LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION

Document Type	**LIGO–T1600115** **VIR-0347A-16**

The LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics
(2016-2017 edition)

The LSC-Virgo Search Groups, the Data Analysis Software Working Group,
the Detector Characterization Working Group and the Computing Committee

WWW: http://www.ligo.org/ and http://www.virgo.infn.it

Processed with LaTeX on 2016/11/10

Contents

1 The LSC-Virgo White Paper on Data Analysis 4
1.1 Searches for Generic Transients, or Bursts . . . 6
1.2 Searches for Signals from Compact Binary Coalescences . . . 8
1.3 Searches for Continuous-wave Signals . . . 10
1.4 Searches for Stochastic Backgrounds . . . 12
1.5 Characterization of the Detectors and their Data . . . 14
1.6 Data Calibration . . . 16

2 Previous Accomplishments 18

3 Search Plans for the Advanced Detector Era 18
3.1 All-Sky Short-Duration Burst Search . . . 19
3.2 Catalogue of Compact Binaries . . . 25
3.3 Astrophysical Distributions of Compact Binaries . . . 27
3.4 Multimessenger Astronomy and Astrophysics with Compact Binaries: GW alerts . . . 27
3.5 Searching for Gamma Ray Burst Counterparts to Compact Binaries . . . 28
3.6 Testing General Relativity with Compact Binaries . . . 29
3.7 Characterizing Exceptional Compact Binary Coalescence Events . . . 30
3.9 Search for GRB Sources of Transient Gravitational Waves . . . 31
3.10 Search for Intermediate Mass Black Hole Binary Coalescences . . . 39
3.11 Search for Eccentric Binary Black Holes . . . 44
3.12 Search for Intermediate-mass-ratio Coalescences . . . 49
3.13 High-energy Neutrino Multimessenger Analysis . . . 55
3.14 Search for transients from Cosmic Strings . . . 60
3.15 Search plan for long-lived gravitational-wave transients . . . 64
3.16 Searches For Transient Gravitational Waves From Isolated Neutron Stars . . . 69
3.17 Gravitational-Waves from Galactic and Near-Extragalactic Core-Collapse Supernovae . . . 77
3.18 Search for transients in coincidence with Fast Radio Bursts . . . 84
3.19 All-sky Searches for Isolated Spinning Neutron Stars . . . 88
3.20 Targeted Searches for Gravitational Waves from Known Pulsars . . . 97
3.21 Directed Searches for Gravitational Waves from Isolated Neutron Stars . . . 102
3.22 Directed Searches for Scorpius X-1 and Other Known Binary Stars . . . 108
3.23 All-sky Searches for Spinning Neutron Stars in Binary Systems . . . 118
3.24 Search for an Isotropic Stochastic Gravitational Wave Background . . . 124
3.25 Directional Search for Persistent Gravitational Waves . . . 130
3.26 Contributions of long transient gravitational waves to the stochastic background search . . . 136

4 Characterization of the Detectors and Their Data 140
4.1 LSC Detector Characterization . . . 140
4.2 Detailed LIGO Detector Characterization priorities . . . 141
4.3 Overarching goals . . . 141
4.4 Characterizing Instrumental Artifacts . . . 141
4.5 Improving search data quality . . . 142
4.6 Essential Software and Automation . . . 143
4.7 Development of New Methods . . . 144
4.8 Ongoing Tasks . . . 145

4.9 Roles 146

5 Calibration 147
5.1 LIGO calibration 147
5.2 LIGO timing diagnostics 148

References 150

1 The LSC-Virgo White Paper on Data Analysis

Gravitational wave searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo collaboration are organized by astrophysical source classification into four working groups. The **Compact Binary Coalescence (CBC)** group searches for signals for merging neutron stars or black holes by filtering the data with waveform templates. The **Burst (Burst)** group searches for generic gravitational wave transients with minimal assumption on the source or signal morphology. The **Continuous Waves (CW)** group targets periodic signatures from rotating neutron stars. The **Stochastic (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin. Joint teams across two or more working groups exist where the science suggests overlap between sources or methods. In addition, the **Detector Characterization (Detchar)** group collaborates with the detector commissioning teams and works to improve searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals.

The *LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics*, which is updated yearly, describes the astrophysical search plans of the LSC-Virgo working groups. This document is its executive summary. For each group, it provides a mission statement and scientific priorities in the Advanced Detector Era, as well as statements from Detector Characterization, Calibration and Hardware Injection teams.

We refer to the Advanced Detector Era (ADE) as the epoch of Advanced LIGO and Advanced Virgo science data acquisition, which began in September 2015 and has already yielded the first direct observation of gravitational waves by the Advanced LIGO detectors [PRL 116, 131103 (2016), PRL 116, 241103 (2016)]. Table 1 shows the planned schedule of science runs, as provided by the LSC-Virgo Joint Running Plan Committee, which includes representatives from the laboratories, the commissioning teams and search groups.

Epoch	Estimated Run Duration	Run Name	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		Binary Neutron Star Range (Mpc)		Number of Binary Neutron Star Detections	
			LIGO	Virgo	LIGO	Virgo		
2015–16	4 months	O1	20 – 30	–	68 – 78	–	–	actual [1,2]
2016–17	6 months	O2	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	projected [3]
2017–18	9 months	O3	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	projected [3]

Table 1: Plausible observing schedule and expected sensitivities for the Advanced LIGO and Virgo detectors. The O1 Burst range is for $\sim 150\,\mathrm{Hz}$ signals, from [1 – arXiv:1611.02972] . The O1 BNS range is from [2 – arXiv:1607.07456]. Projected sensitivity for O2 and O3 will be strongly dependent on commissioning progress [3 – Living Rev. Relativity 19 (2016), 1].

The LSC-Virgo scientific priorities for ADE observations are summarized in Table 2, by search group, in three categories:

- **Highest priority:** searches most likely to make detections or yield significant astrophysical results.
- **High priority:** promising extensions of the highest priority goals that explore larger regions of parameter space or can further the science potential of LIGO and Virgo.
- **Additional priority:** sources with low detection probability but high scientific payoff.

Computing needs and resource allocations are derived from the science priorities presented in this table. Scientific motivations, details on methods and the strategy for result validation are provided in the search plans that constitute the white paper.

We note that the LSC-Virgo Collaboration has adopted a *Multiple Pipeline Policy* [LIGO-M1500027], which calls for all astrophysical results to be validated with a different analysis, using independent methods and tools when possible. In some cases this may require the same data to be analyzed by more than one pipeline for the same science target.

	Burst	CBC	CW	SGWB
Highest priority	All-sky search for generic GW transients, in low latency for EM followup and deep, offline for 4σ detection confidence	Detecting the coalescence of neutron star and black hole binaries and measuring their parameters	All-sky search for isolated neutron stars, both as a *quick-look* on owned resources and as a deep/broad search on Einstein@Home	Directional search for stochastic GW background
	Parameter estimation for the astrophysical interpretation of detected burst events	Characterizing the astrophysical distribution of compact binaries	Targeted search for high value, known pulsars	Isotropic search for stochastic GW background
	Search for GW bursts triggered by outstanding GRB alerts	Responding to exceptional CBC detections	Directed searches for most promising isolated stars (Cas A, Vela Jr etc.)	Constraints of a detected background of astrophysical origin with long transients
	Searches triggered by outstanding astrophysical events (a galactic supernova, neutron star transients, an exceptional high energy neutrino alert)	Multi-messenger astronomy with compact binaries	Directed searches for X-ray binaries SCO-X1 and J1751-305	
	Search for cosmic string kinks and cusps	Searching for CBC-GRB coincidences		
		Testing General Relativity with Compact Binaries		
High priority	Searches triggered by high energy neutrinos, extragalactic supernovae, and GRB observations	All sky search for spinning binary neutron star systems (deep and low latency)	Targeted search for other known pulsars	Long transient follow up of CBC and burst candidates
	Burst search for intermediate mass ratio and eccentric black hole binary systems	Matched filtered search for intermediate mass black hole binary systems	Directed searches for other isolated stars and X-ray binaries	
	All-sky search for long bursts of > 10 s duration			
Additional priority	GRB-triggered search for long-duration bursts and plateaus	Exploring effects of detector noise on parameter estimation	All sky search for isolated stars (alternative approaches)	
	Hypermassive neutron star followup	Searching for sub-solar mass CBC signals	All-sky search for binaries	
	Burst searches triggered by radio transients and by SGR/SGR-QPO	Developing searches for CBC signals with generic spins	Spotlight deep sky-patch search **	
	Burst tests of alternative gravity theories **		Search for Supernova post birth signals **	
			Search for continuous wave transients **	

Table 2: Science priorities of the LIGO-Virgo collaboration, for the four astrophysics search groups: Bursts, Compact Binary Coalescences (CBC), Continuous Waves (CW), and Stochastic Gravitational Wave Background (SGWB). The targets are grouped in three categories (highest priority, high priority, additional priority), based on their detection potential with Advanced Detectors. There is no additional ranking within each category in this table. Critical for accomplishing these science priorities are the detector characterization, calibration and injection activities described in this document.
** Future searches under development, not included in ongoing production computing requests.

1.1 Searches for Generic Transients, or Bursts

The mission of the Burst group is to detect gravitational wave transients, or *bursts*, and gain new information on populations and emission mechanisms of the associated astrophysical objects, as well as to test theories of gravity. Central to the Burst group philosophy is the assumption of minimal information on the source, so that searches for gravitational wave bursts typically do not require a well-known or accurate waveform model and are robust against uncertainties in the gravitational wave signature. Burst searches are, therefore, sensitive to gravitational wave transients from a wide range of progenitors, ranging from known sources such as binary black-hole mergers (in particular the most massive and loudest ones) to poorly-modelled signals such as core-collapse supernovae as well as transients that are currently unknown to science. We refer to this as the “eyes wide open" approach.

For example: the complexity of Supernovae makes it difficult to reliably map the dynamics of a core-collapse into a gravitational wave signal. The merger of precessing intermediate-mass black holes ($\geq 100\,\mathrm{M}_\odot$) produces gravitational wave transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts could be associated with a gravitational wave transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, we need data analysis methods that are able to detect emission mechanisms that have not been envisioned yet.

The Burst group implements a variety of methods to identify instances of statistically significant excess power, localized in the time-frequency domain. To discriminate between gravitational waves and noise fluctuations, the analysis requires the signal to appear coherently in multiple detectors. The confidence of a candidate event is established by repeating the analysis on many instances of background, obtained by shifting the data from different detectors with non-physical delays. In a few special cases when an accurate signal model is available, such as for cosmic string cusps or neutron star ring-downs, a search can be done using matched filtering with a bank of templates.

Although burst search algorithms are designed to detect a wide range of signals, their tuning and interpretation benefit from considering how they perform for plausible astrophysical signals. Therefore, the group’s science program involves an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities.

Many gravitational wave burst sources should also be observable in more traditional channels, from Earth-based astronomical data, through sensitive GRB/X-ray satellite detections, to neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a gravitational wave burst can be used to increase the sensitivity of a triggered burst search compared to an untriggered, all-sky search, and the association with a known astrophysical event may be critical in establishing our confidence in a gravitational-wave burst detection. Most importantly, joint studies of complementary data enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the gravitational wave data, a significant part of the Burst group’s science program involves connecting with other observations and working closely with the astronomy and astrophysics communities.

1. **Highest priority**

   The Burst group is focused on an *eyes wide open* approach to detecting gravitational wave transients. To maximize its discovery potential, the Burst group employs a strategy of multiple searches, overlapping in parameter space to allow for cross-validation of search outputs. Highest priority goals for the analysis of advanced detector data include:

   - a statement on the transient gravitational wave sky, with population studies if we have several detections, a rare-event detection significance if we have one candidate or an upper limit on the

rate of gravitational wave bursts if there is no detection;
- deployment of multiple analyses for cross validation of the all-sky search results, including verifying the significance of any observed events, across a wide parameter space. This is especially important for events that are not matched to a specific source model;
- the astrophysical interpretation of any detected signals, leveraging signal characterization and parameter estimation;
- a prompt analysis, trigger production and sky localization, to enable the electromagnetic follow-up of gravitational wave transients;
- prompt reports on astrophysically significant events, such as nearby gamma ray bursts, soft gamma repeater hyperflares, galactic supernovae as well as exceptional bursts of low (MeV) or high (GeV–PeV) energy neutrinos;
- a dedicated search for gravitational wave bursts originating from cosmic strings.

2. **High priority**

   The Burst group will extend the parameter space of the all-sky search to include longer duration transients ($\geq 10\,\mathrm{s}$) which may originate from various astrophysical sources such as long gamma-ray bursts. Long-duration burst searches share similar complexities with their short-duration counterparts. Since the long-duration search is not as mature as the short-duration one, multiple analyses will be deployed to cross-validate the results.

   The Burst group will also pursue, with the burst analysis approach, some classes of compact binary coalescence sources that are not well covered by the current waveform template banks. These include intermediate mass binary black holes, binary black holes with eccentric orbits and intermediate mass ratio inspirals.

   Finally, the Burst group will pursue multi-messenger searches for gravitational wave bursts in conjunction with signatures such as generic gamma ray bursts, fast radio transients, low- and high-energy neutrino observations, and electromagnetic observations of nearby core-collapse supernovae. The Burst group will use information on the astrophysical event to reduce the parameter space over which searches must be performed, leading to a reduction in the false alarm rate and, consequently, an improvement in search sensitivities.

3. **Additional Priority**

   Additional priorities include the search for gravitational waves in association with neutron star transients (eg. pulsar glitches, type I X-ray bursts and soft gamma ray repeater flares) and testing alternative theories of gravity with gravitational wave bursts.

Several of these science targets – intermediate mass black hole binaries, GRBs, electromagnetic followup – overlap with the CBC group, and joint teams are working together across the two groups on these targets.

1.2 Searches for Signals from Compact Binary Coalescences

On September 14, 2015, one-hundred years after gravitational waves were first predicted, the advanced LIGO experiment detected gravitational waves from the merger of two black holes. This discovery was followed by a second confirmed binary black hole detection on December 26, 2015. With the confirmed existence of a detectable population of stellar-mass binary black hole mergers, we expect many more binary black hole detections in the remaining years of the Advanced LIGO project. Furthermore, we anticipate discovery of entirely new source classes such as coalescing binary systems containing neutron stars within the next few years. The Compact Binary Coalescence group aims to discover new compact binary mergers and to use the gravitational wave signals to advance our understanding of fundamental physics and astrophysics.

The range of scientific activities pursued by compact binary coalescence group requires us to prioritize our goals. In the regime of increasing detection frequency over the coming observing runs, we must strike a balance between exploitation of established classes of sources and preparing for detection of new source classes. Achieving these goals requires the group to prioritize the continued research and development of our tools and methods for source detection, estimation of parameters, inference of rates and populations, probing fundamental physics and modeling of waveforms. We will continue to develop our search pipelines to improve their sensitivity to quiet sources by improvements in detection statistics, understanding of the noise background and rigorous understanding of data quality. We expect a tremendous human effort will be required to develop, deploy, run and interpret the results of low-latency and offline searches as in the context of evolving detector sensitivity and data quality. Additionally, the CBC group maintains an active collaboration with a broader community to enhance the impact of our discoveries on theoretical astrophysics and the electromagnetic and astroparticle observing communities. With this in mind we have outlined the following projects which cover the goals of the group in the coming year.

1. **Highest Priority**

   - **Responding to exceptional events**. We must be prepared to detect and respond to novel sources of extraordinary scientific importance. We define these as sources that yield significant new astrophysics and would warrant a rapid stand-alone publication. These would naturally include the first detection of binary neutron-star, neutron-star black-hole binary or intermediate mass binary systems. We also anticipate examples in which measurement of a source's parameters (e.g. masses and spins) could provide significant constraints on its formation channel or our understanding of stellar evolution (e.g. the possible existence of gaps in the black hole mass distribution, minimum or maximum neutron star mass). Other examples could include sources which are exceptionally loud and allow us to measure the source physics with unprecedented precision, thereby providing exceptional constraints on general relativity, or, for binaries containing a neutron star, measurement of the nuclear equation of state could be made
   - **Detecting the coalescence of compact binaries and measuring their parameters**. We will continue developing and executing the search for coalescence of neutron star and black hole binaries, and the inference of the system's properties. Following the observing run We will produce a summary of all compact binaries detected in order to provide a reference for the astrophysics community with details of the detected source's physical parameters, notable properties, and waveform estimates. This requires a good understanding of systematic errors, including waveform modelling errors. We will continue to reduce our sources of systematic errors by improving our waveform modelling with comparison to numerical relativity simulations. The catalog completeness will be improved by including uncertain signals such as LVT151012, along with their estimated p-value.
   - **Characterizing the astrophysical distributions of compact objects**. As the number of de-

tections increases, we will begin to build a picture of the astrophysical distribution of compact binaries in terms of their masses and spins. This will set novel empirical constraints on the astrophysics of binary evolution. To accurately learn these distributions we need the ability to infer the physical properties of our detected sources and estimate their distribution taking into account the selection effects of our detectors and pipelines.

- **Testing General Relativity**. The final stages of a compact binary coalescence provide a unique window into the behavior of gravity in the strong field, high-velocity regime. We will continue to develop the range of tests we are able to perform on our detections, ensuring their robustness through comparison to numerical relativity simulations where possible. We will develop methods of combining multiple detections to place better constraints on the theory, and test specific predictions in general relativity such as the no-hair and area theorems.
- **Multimessenger astronomy and astrophysics**. The observation of an electromagnetic or neutrino counterpart to a GW signal will be of huge astrophysical importance to the field, so we will continue to pursue multi-messenger astronomy by providing alerts to our observing partners. This requires the continued development of low-latency pipelines for detection and localization of sources, and the infrastructure associated with collating and distributing information about detection candidates.
- **Gamma-Ray bursts** The coincident detection of a gravitational wave with a gamma-ray burst ranks among the highest impact discoveries possible in the compact binary field. We will continue performing a deep coherent search for gravitational waves focussed on the sky position of any known gamma-ray bursts, and pursue joint searches for gravitational wave and GRB signals.

2. **High Priority**

   High priority activities are those which are less certain to produce a significant result in the time-scale of the coming year, but where the potential payoff would be high. These include the development of searches for intermediate-mass ratio binaries and waveforms to describe them. Eccentric binary systems are another potential class of source where the searches and waveforms are less mature and templated searches and unmodelled searches can be combined to allow for the range of eccentricity and robustness of our models.

   Searching for neutron star binaries with significant component spin is also a high priority. Although neutron stars in binary systems have been observed to have small spin, some isolated neutron stars are known to spin significantly. If neutron stars with significant spins do exist in binary systems, then opportunities to detect them could be lost without a dedicated search.

3. **Additional Priority**

   Building more accurate noise models for parameter estimation techniques can dramatically mitigate the effects of non-stationary, non-Gaussian noise on the fidelity of parameter inference. It is a priority to conduct a simulation campaign to study improved noise models for parameter estimation.

   The compact binary parameter space searched in higher priorities is not complete. It covers a plausible range of physical parameters based on observation and stellar evolution models. However, there are other interesting but less plausible parameter spaces which would have a dramatic impact if discovered. Given additional resources, we would consider searching for compact objects below one solar mass. It is possible that neutron stars or black holes could exist with masses down to fractions of a solar mass and be in detectable binary systems. Additionally, although parameter estimation techniques use waveforms that account for orbital precession, detection searches do not presently include precession effects in the templates. Work is ongoing to develop such a search, and with additional resources, we would conduct a precessing binary search in the future.

1.3 Searches for Continuous-wave Signals

The LSC/Virgo Continuous Waves (CW) Group aims to measure gravitational wave signals that are long-lived, nearly sinusoidal and extremely weak, believed to be emitted by rapidly rotating neutron stars in our galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including elastic deformations, magnetic deformations, unstable r-mode oscillations, and free precession, all of which operate differently in accreting and non-accreting stars. Long-term simultaneous gravitational wave and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program.

For known pulsars with measured spin frequencies, frequency derivatives and distances, energy conservation allows setting an upper limit on gravitational wave strain amplitude, known as the *spindown* limit, albeit with significant uncertainties due to poorly understood neutron star astrophysics. Previous searches in LIGO and Virgo data have obtained 95% confidence upper limits well below the spindown limits for the Crab and Vela pulsars. As interferometer sensitivities improve in the Advanced Detector Era, several dozen more known pulsars will become spindown-accessible, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or on estimated accretion rates can also be derived. Such indirect limits are more optimistic for non-accreting stars, but accreting neutron stars are more likely to be emitting near their limits.

Because there is so much astrophysical uncertainty in continuous gravitational wave emission and because electromagnetic astronomers have detected about 2500 of the O(10^{8-9}) neutron stars believed to populate our galaxy, the CW group has established a broad program to search for gravitational wave emission from five distinct source categories, ordered below by decreasing *a priori* information known about the sources: 1) known pulsars with well measured timing; 2) other known or suspected isolated neutron stars with limited or no timing information; 3) known or suspected binary neutron star systems; 4) unknown isolated stars in any direction; and 5) unknown binary stars in any direction.

This ordering of categories corresponds to ordering by source strain sensitivity. Targeted searches using known ephemerides from radio, X-ray or γ-ray timing measurements can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans with minimal trials factor corrections. Directed searches using known sky locations but having no *a priori* frequency information (e.g., *Cassiopeia A*) are degraded by trials factors that depend on the band size searched and on the assumed age of the source (which affects the number and range of higher-order spin derivatives to be searched). The sensitivity achievable with all-sky searches is still further limited by the need to make sky-location-dependent corrections for Doppler modulations of detected source frequency due to the Earth's motion (daily rotation and orbital motion). The number of sky points to search to maintain accurate demodulation grows rapidly with coherence time used in the search (time scale over which the signal is assumed to follow a precise phase model). The effect is severe enough to preclude all-sky searches using coherence times equal to the full observation spans of data runs. Adopting semi-coherent summing of data makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Directed searches for suspected neutron stars in binary systems with unknown source frequency must make similar sensitivity tradeoffs, and all-sky searches for sources in unknown binary systems define the current extreme in sensitivity tradeoff for tractability.

In the case of known objects, we have identified sources that seem to be the most promising, and should priorities need to be set because of limited resources (labor or computing), those sources will receive the highest priority. With these considerations in mind, the CW group plans a comprehensive search program in the Advanced Detector Era for all of these source categories, with the following priorities:

1. **Highest priority**
    - Targeted searches for the Crab and Vela pulsars and any other stars for which the spindown limit is likely to be beaten to within a factor of two. High-interest stars likely to fall in this category include PSR J0537–6910 and PSRJ1813–1246, among many others, as detector sensitivities improve. These analyses will include searching at the stellar spin frequency and twice that frequency.
    - Directed search for Cassiopeia A which is the youngest known neutron star in the galaxy, but for which the spin frequency is unknown. (This choice of primary source is under reconsideration; Vela Jr. may be more promising, under some astrophysical assumptions.)
    - Directed searches for the X-ray binaries Scorpius X–1, Cygnus X–3, PSR J1751–305 and 4U 1636-536. The first two are especially bright in X-rays, and in the torque-balance model, GW luminosity scales with X-ray luminosity, while there is evidence in the last two objects for sharp X-ray periodicities that may indicate an r-mode oscillation.
    - All-sky searches for unknown isolated stars. These searches necessarily suffer from degraded strain sensitivity relative to what can be achieved in the targeted and directed searches, but they cast a very wide net, offering a reasonable prospect of discovery.
2. **High priority**
    - Targeted searches for known pulsars for which the spindown limit is unlikely to be beaten, according to conventional theory, but which are extreme astrophysical objects of great interest.
    - Directed searches for young supernova remnants other than Cassiopeia A, including Supernova 1987A, for sources near the galactic center, for sources in nearby globular clusters and for unidentified γ-ray sources with pulsar-like spectra.
    - Directed searches for additional X-ray binaries.
3. **Additional priority**
    - All-sky searches for unknown binary stars. Because of the additional unknown orbital parameter space to search, these searches are most computationally demanding and must make the greatest tradeoffs in strain sensitivity for tractability.
    - All-sky searches for unknown isolated stars, using alternative algorithms.

For every type of search, the CW group supports at least two independent methods (pipelines). This redundancy provides greater robustness against incorrect assumptions in signal modeling and against non-optimum handling of instrumental artifacts. The robustness against incorrect signal modeling is especially important for accreting sources, such as Scorpius X–1, where the time span over which the coherence of the signal model can be safely assumed is uncertain. In fact, that time scale is likely to vary in response to fluctuations in accretion rate.

There is some overlap in the CW search space with searches carried out in the Burst and Stochastic working groups. Long-lived transients can be considered to be short-lived CW sources. A small joint subgroup with members from both the CW and Burst groups is carrying out work in this area. CW sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the “radiometer” method in use by the Stochastic group. Tradeoffs among search methods for such sources are being explored in a joint CW/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.4 Searches for Stochastic Backgrounds

The prime objective of the Stochastic Gravitational Wave Background (SGWB) group is to measure the stochastic background. A stochastic gravitational-wave background is formed from the superposition of many events or processes that are too weak and/or too numerous to be resolved individually, and which therefore combine to produce a stochastic background. A stochastic background can arise from cosmological sources such as inflation, cosmic strings, and pre-Big-Bang models. Alternatively, it can arise from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars.

Comprehensive searches have been carried out using data from initial LIGO and Virgo. No signal was detected, but our results constrain the energy density of the stochastic background to be $\Omega_0 < 5.6 \times 10^{-6}$ at 95% confidence. Advanced detectors are expected to have about $10\times$ better strain sensitivity than the initial detectors, as well as to extend the sensitive band from 40 Hz down to 10 Hz. These improvements and wider bandwidth will enable breakthroughs in searches for the stochastic background, with a potential sensitivity of $\Omega_0 < 6 \times 10^{-10}$. The detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. Simulations studies show the detection of an astrophysical background is not unlikely, and it would be of great interest as a probe of the evolution of the Universe since the beginning of stellar activity.

The SGWB group has built on the cross-correlation infrastructure, originally designed to carry out searches for isotropic stochastic backgrounds, to diversify and to carry out a wide range of interesting analyses. The SGWB directional search provides a method of distinguishing between different stochastic sources using sky maps of gravitational-wave power; the narrowband radiometer has been used to search for gravitational waves from Scorpius X-1, the Galactic Center, and SN 1987A. The radiometer provides an important tool for gravitational-wave astronomy when there is significant uncertainty in the phase evolution of a neutron star signal (as is the case with the low-mass X-ray binary source, Scorpius X-1). The radiometer limits on Scorpius X-1 from initial LIGO remain the most constraining to date over a portion of the observing band, and the SGWB Group continues to develop the search, in collaboration with the Continuous Waves Group.

The SGWB group has developed a cross-correlation pipeline to search for very long-lived gravitational-wave transients lasting hours to weeks. It may be possible for neutron stars to emit transient gravitational waves on these time scales. Moreover, exotic models allow for the possibility of a seemingly persistent signal to start or stop during an observing run, also leading potentially to very long transient signals. An efficient very-long-transient detection algorithm will have other useful applications: it can establish if an apparently persistent source, e.g., observed in a stochastic background search, exhibits variability in time, and it can be used to understand the behavior of detector artifacts on timescales of days to weeks.

The SGWB group is actively involved in detector characterization efforts. Much of this work has overlap with both the Detector Characterization and SGWB groups. For example, the SGWB group uses Detector Characterization measurements of correlated magnetic noise in order to find solutions that minimize contamination in stochastic searches. Correlated noise, e.g., from Schumann resonances, can create coherence in widely separated detectors, which is possible to mistake for a stochastic background signal, thereby introducing a bias. The group is also developing a stochastic data-quality monitor to track search sensitivity in real time and to identify problematic sources of noise.

1. **Highest priority**

   The highest priorities of the SGWB group are the isotropic search, the directional search, and the search for very long transients. The isotropic analysis is the original *raison d'être* for the SGWB working group, and the detection of a stochastic background is the group's most compelling scientific deliverable. The directional search—which employs both a radiometer algorithm and a spherical harmonic decomposition algorithm—generates sky maps (and strain spectra), which can be used to identify cosmological or local anisotropies as well as point sources. This long-established analysis is an important tool for distinguishing between different sources of the stochastic background (e.g., isotropic signals vs. signals clustered in the galactic plane). While the directional search assesses the contribution to stochastic signals from different directions and from different frequency bins, the search for very long transients assesses the contribution from different times. The three searches together provide a complete understanding of the origin of any observed signal. We carry out a number of activities in support of these three searches including mock data challenges, modeling of different sources of the stochastic background, parameter estimation, folding of data into a sidereal day, detector characterization, and an extension to the isotropic search to look for non-standard polarization modes in the stochastic background.

2. **High priority**

   We designate as high-priority a program to follow up on CBC and burst detection candidates with a low-cost cross-correlation search. The search produces spectrograms showing the detection candidate in cross-correlated data and is designed to provide useful diagnostic tools for visualization and characterization of candidate events. For compact binary coalescence signals in particular, it offers a low-cost, independent verification of detections made by matched-filtering pipelines while filling in potential gaps caused by data-processing corner cases. In addition, this method offers a useful visualization of the GW signal in spectrograms.

3. **Additional priority**

   Additional priorities for the SGWB Group includes studies that are at a less mature stage than those listed above, such as measurements of non-Gaussianity of the stochastic background and a search for r-modes from neutron stars.

There is overlap in the SGWB group's search for very long-lived transients with searches being carried out in the Burst and Continuous Wave search groups. Continuous wave sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the radiometer method in use by the SGWB group, or methods being developed in the continuous wave search group. Trade-offs among search methods for such sources are being explored in a joint Continuous Wave/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.5 Characterization of the Detectors and their Data

LIGO: LIGO's sensitivity to gravitational-wave signals is limited by noise from the instruments and their environment. Continued detection, the vetting of candidate signals, and the accuracy of parameter estimation is *crucially* dependent on the quality of the data searched and the collaboration's knowledge of the instrument and environment. The LIGO Detector Characterization group is focused on working together with the astrophysical search groups and the detector groups to (i) deliver the data quality information necessary to clean the data sets, veto false positives, and allow candidate follow up for gravitational-wave searches and (ii) characterize the early Advanced LIGO detectors to help to identify data quality issues early enough that they can be addressed in the instruments to improve future instrument and search performance.

Search Data Quality: LIGO data contain non-Gaussian components such as noise transients and quasi-periodic lines that have a negative impact on astrophysical searches. Transient noise in the detector data can mimic or mask transient signals from Compact Coalescing Binaries and more generic Burst sources, interfering with detection and the accuracy of the source parameters recovered. To minimize these negative effects, LIGO data must be cleaned of transient data quality issues. The primary forms of data quality information that must be delivered to the astrophysical search groups are: *state segments* that indicate which data should be analyzed, based on the state of the instrument and its calibration; *veto segments* that indicate periods of poor quality data; and *data quality triggers* that identify short durations where the data are likely to contain a non-astrophysical disturbance. Searches will use veto segments and data quality triggers to either ignore problematic data or to reduce confidence in any search triggers associated with these times. For continuous-wave and stochastic backgrounds searches, frequency bins that are contaminated by non-astrophysical disturbances must be identified and removed, and low-level, broadband contamination from correlated magnetic noise must be mitigated.

Automation of Data Quality assessment: With the anticipated signal rate for O2, and the need for low-latency data to support multi-messenger astronomy, the Detector Characterization group must develop automated approaches to respond to items on the Detection Checklist. The objective is to reduce to a minimum the amount of manual sorting through signals, flagging of problems, and identification of sources of defects in the data. This will be the main focus of the group during O2, with partners in the astrophysical search groups collaborating on both identifying pipeline needs and sensitivities to data defects.

aLIGO Instrument Characterization: The Detector Characterization group works with the detector commissioning and engineering groups to identify and resolve issues in the aLIGO subsystems related to glitch and noise contamination, channel signal fidelity and robustness, etc. This work has led to early data quality improvements and helped to train a wider pool of scientists who are familiar with the instruments. Continued work aims to facilitate aLIGO detections by ensuring that the detectors are well understood and that fixes for data quality issues are aggressively pursued.

1. **Highest priority.** The highest priority of the LIGO Detector Characterization group is to provide timely data quality information to the LSC-Virgo search groups that designate what data should be analyzed, remove egregious data quality issues, and identify periods/frequencies of poor data quality. Automation is central to success in this activity.

2. **High priorities.** Complement and collaborate on commissioning with tools and insights to help find sources of transient and CW data defects. Use the non-interferometer sensors to find, quantify, and mitigate coupling to the environment. Maintain and extend the software infrastructure required to provide needed data quality information to online searches.

3. **Priorities.** Develop improved methods to uncover the causes of the noise transients which most impact the searches, with the goal of mitigating them or producing vetoes. Pursue, when motivated, exploration of new approaches to data quality issues.

To accomplish these priorities, the LIGO Detector Characterization group requires

- search group participation to call out sensitivities in the pipelines to data defects
- data quality experts to identify data defects and establish relationships to instrument events
- code developers to establish both infrastructures and specific modules to recognize and flag defects
- instrument characterization experts to quantify the sensitivity of the instrument to the environment, establish coupling coefficients, and to identify mitigation where needed

Virgo

Noise mitigation, spectral lines identification, glitch reduction and data quality vetoes are the main tasks of the Virgo detector characterization group. Responsibilities include working with the commissioning team to track down any limitation to the detector's sensitivity, working with the calibration team to maintain the calibration and timing accuracy to an acceptable level for GW searches, and providing noise information and vetoes to the data analysis groups and commissioning team. During past science runs and commissioning periods, the Virgo detector characterization team has provided several investigation and monitoring tools, and data quality vetoes which impacted positively both commissioning activity and astrophysical searches.

Search Data Quality: A new Virgo data quality model has been developed and is currently implemented. This model defines workflows and procedures the group will follow to provide data quality products to searches. In particular, emphasis is made to produce and deliver search-specific data quality vetoes. On top of this, a new and ambitious online architecture is being implemented to provide vetoes to online search pipelines. We have developed with LIGO a common data quality segment database, to benefit Burst and CBC groups. It has been moved to production. Additional data quality needs specific to CW and Stochastic search groups include the identification of noise source contributions to spectral lines or non stationary and non linear features. For this, we use automatic spectral lines identification tools already well tested, and a line database.

Early AdvVirgo Characterization: The Virgo detector characterization team will begin noise and glitch studies on each commissioned sub-system as soon as they come online, in close collaboration with sub-system hardware coordinators and commissioners. A system of shifts has been organized. Periodically, a team of two shifters is on watch. They study transient and spectral noise using analysis tools developed by the group.

1. **Highest priority**
   The highest priority of the Virgo Detector Characterization is to find and mitigate the sources of noise and to provide data quality information to the LSC-Virgo search groups in order to reduce the impact of the remaining noises.

2. **High priority**
   Our current high priorities are the development of useful tools for commissioning and an early characterization of each sub-system of Advanced Virgo in order to reduce the need of vetoes in future searches. This will imply a coherent system of monitoring web pages, a spectral line database catalogue, identification of non stationary lines and a software infrastructure to provide useful online data quality information.

3. **Additional priority**
   Additional priorities for Virgo detector characterization are to develop improved methods to uncover the paths and the sources of the noise transients which most impact the searches, and to implement automated noise classification tools.

1.6 Data Calibration

LIGO Calibration

Calibration of the LIGO interferometer data is critical to the success of the searches and to the confidence in their results. This is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. Calibration is provided both in the frequency domain, as a frequency-indexed response function to be applied to the Fourier transform of the gravitational wave channel, and in the time-domain, as a derived digital time series representing strain as a function of time. The time domain calibrated data, along with an accompanying error budget, is the main calibration product. Critical calibration activities include:

- measurements of instrument transfer functions and calibration model parameters,
- development and improvement of instrumental measurements,
- estimation and reduction of the errors in the calibration data products,
- use of the photon calibrator as the primary source for the accuracy and precision of all calibration,
- use of alternative configurations of the interferometer and lock-acquisition systems as independent cross-checks of the calibration,
- development and improvement of time-domain data generation techniques, including use of gstlal and the aLIGO front-end system,
- development of pre-processed h(t) products, such as whitened, cleaned, and coherent data streams,
- developing injection techniques to validate calibration measurements,
- expanding data monitoring tools related to instrument calibration,
- development of on-line tools to monitor calibrated data quality, and
- a comprehensive review of entire calibration procedure.

LIGO Timing Diagnostics

Traceable and closely monitored timing performance of the detectors is mission critical for reliable interferometer operation, astrophysical data analysis and discoveries. The advanced LIGO timing distribution system provides synchronized timing between different detectors, as well as synchronization to an absolute time measure, UTC. Additionally, the timing distribution system must provide synchronous timing to subsystems of the detector. Timing distribution system's status is monitored, and periodically tested in-depth via timing diagnostics studies.

Critical timing tasks include:

- verifying traceable performance of the timing distribution system,
- verifying the validity and accuracy of the recorded time-stamp,
- verifying the accuracy of the distributed timing signals,
- expanding the capabilities of data monitoring tools related to timing,
- availability of timing diagnostics for various subsystems,
- measuring and documenting the timing performance,
- reviewing the physical/software implementation and documentation of the timing distribution and timing diagnostics components.

Virgo Calibration

During the Virgo science runs, the calibration measurements have been automated and extended to have some redundant data. It includes measurement of the absolute time of the Virgo data, measurement of the transfer function of the dark fringe photodiode readout electronics, measurement of the mirror and marionette actuation transfer functions and monitoring of the finesse of the arm cavities. The calibration output are then used (i) in the frequency-domain calibration, resulting in the Virgo sensitivity curve, (ii) in the time-domain calibration, resulting in the h(t) strain digital time series and (iii) for the hardware injections. Independent cross-check of the reconstruction has been done systematically during VSR4 using a photon calibrator.

The methods used for Virgo will still apply for AdV after some tuning for the new configuration. Simulations have been carried on for the a priori most challenging measurements, i.e. the measurement of the mirror actuation response. They confirm that the Virgo methods can still be applied, putting some constraints on the minimum force to be applied on the AdV arm mirrors. In parallel a conceptual design of the new photon calibrator to be developed for AdV is being finalized before the setup is built and then installed in 2015. Critical calibration activities are:

- development and improvement of instrumental measurements (in particular with the digital demodulation electronics of the photodiode readout),
- prototyping and installation of a photon calibrator,
- development of online tools to monitor the Virgo timing permanently,
- upgrade the h(t) reconstruction method after the study of the impact of some parameters that were neglected during the Virgo era.

LIGO and Virgo Hardware Injections

Hardware injections are simulated gravitational wave signals added to LIGO and Virgo strain data by physically actuating on the test masses. They provide an end-to-end validation of our ability to detect gravitational waves: from the detector, through data analysis pipelines, to the interpretation of results. The hardware injection group is tasked with the development, testing, and maintenance of hardware injection infrastructure. This includes on-site software to carry out the injections at specified times. We also work with the search groups to maintain the software that generates gravitational waveforms suitable for injection.

Each data analysis group works with the hardware injection team, in different ways: Burst and CBC groups provide transient waveforms and determine suitable injection rates, the CW group selects the parameters for neutron star signals, which persist throughout the science run, and the SGWB group typically carries out one or two $\approx$10 min injections during each science run. The search groups analyze hardware injections during science and engineering runs to identify and solve problems as they come up, and the results of these studies are reported back to the hardware injection team so that adjustments can be made.

While most injections are known to the LSC, there are also blind injections, for a blind test of the analysis. Although blind injections are performed by a separate team, the hardware injection group is in charge of maintaining the blind injection infrastructure, nearly identical to the regular injection one, and provides training.

2 Previous Accomplishments

This section has been removed from the 2016-2017 version of this white paper.

3 Search Plans for the Advanced Detector Era

This section collects the plans formulated by the astrophysics search groups for Advanced LIGO and Advanced Virgo. These plans connect the science case, analysis methods, criteria for result validation and publication, software development plans and resource needs for each search.

Contents

3.1 All-Sky Short-Duration Burst Search . . . 19
3.2 Catalogue of Compact Binaries . . . 25
3.3 Astrophysical Distributions of Compact Binaries . . . 27
3.4 Multimessenger Astronomy and Astrophysics with Compact Binaries: GW alerts . . 27
3.5 Searching for Gamma Ray Burst Counterparts to Compact Binaries . . . 28
3.6 Testing General Relativity with Compact Binaries . . . 29
3.7 Characterizing Exceptional Compact Binary Coalescence Events . . . 30
3.9 Search for GRB Sources of Transient Gravitational Waves . . . 31
3.10 Search for Intermediate Mass Black Hole Binary Coalescences . . . 39
3.11 Search for Eccentric Binary Black Holes . . . 44
3.12 Search for Intermediate-mass-ratio Coalescences . . . 49
3.13 High-energy Neutrino Multimessenger Analysis . . . 55
3.14 Search for transients from Cosmic Strings . . . 60
3.15 Search plan for long-lived gravitational-wave transients . . . 64
3.16 Searches For Transient Gravitational Waves From Isolated Neutron Stars . . . 69
3.17 Gravitational-Waves from Galactic and Near-Extragalactic Core-Collapse Supernovae 77
3.18 Search for transients in coincidence with Fast Radio Bursts . . . 84
3.19 All-sky Searches for Isolated Spinning Neutron Stars . . . 88
3.20 Targeted Searches for Gravitational Waves from Known Pulsars . . . 97
3.21 Directed Searches for Gravitational Waves from Isolated Neutron Stars . . . 102
3.22 Directed Searches for Scorpius X-1 and Other Known Binary Stars . . . 108
3.23 All-sky Searches for Spinning Neutron Stars in Binary Systems . . . 118
3.24 Search for an Isotropic Stochastic Gravitational Wave Background . . . 124
3.25 Directional Search for Persistent Gravitational Waves . . . 130
3.26 Contributions of long transient gravitational waves to the stochastic background search 136

3.1 All-Sky Short-Duration Burst Search

3.1.1 Abstract

Supernovae, long gamma-ray bursts, and soft-gamma repeaters are among the variety of violent astrophysical phenomena that are expected to produce bursts of gravitational waves. These waves are ripples in spacetime, and carry the signature of the complicated physical processes that produced them. The detection of gravitational-wave bursts could therefore provide a direct probe of these relativistic systems, help us unravel the mechanism behind supernova explosions and reveal the inner workings of gamma-ray bursts.

We present plans for searching for gravitational-wave bursts using data acquired by the advanced LIGO - advanced Virgo network during the next Observing Runs. This search targets bursts of any form, without restriction to a particular signal type. We aim to cast the widest possible net for gravitational-wave transients and infer the properties of any observed signal which may originate from a wide variety of astrophysical phenomena ranging from known gravitational wave progenitors phenomena (eg. binary black hole mergers) to sources that are, at present, entirely unknown to science.

Parameter estimation algorithms will be used to estimate the morphology of observed gravitational-wave burst signals and their parameters. A key part of this search is the estimation of the position on the sky of possible gravitational-wave signals within minutes of data taking. This will allow partner telescopes to search for an electromagnetic counterpart, which could be vital to interpreting the nature of the source. The joint identification of a system in light and gravitational waves would be a watershed moment in multi-messenger astronomy.

3.1.2 Scientific Justification

Relativistic astrophysical systems such as supernovae, long gamma-ray bursts, and soft-gamma repeater giant flares are expected to produce bursts of gravitational waves. These systems are difficult to model, due in part to their complicated dynamics, and to the fact that the equation of state of matter at neutron-star densities is not known. Therefore, searches for gravitational-wave bursts from these systems cannot rely on an accurate signal model. Instead, methods must be developed that are capable of distinguishing weak gravitational wave (GW) signals from the cacophony of background noise fluctuations in our data *without* prior knowledge of the signal shape. This is in contrast to searches for GWs from, e.g., neutron star coalescences or isolated pulsars, which rely on precise models to separate signals from noise.

The all-sky short-duration burst search targets GW bursts of generic waveform in the advanced detector bandwidth, without assumptions on the signal's origin, direction, or time of arrival. While past all-sky burst searches have focused on signal durations of up to approximately one second, such searches in the advance detector era will extend to durations of 10 seconds which covers the parameter space of some gravitational wave emission models for supernovae and neutron star oscillations. Searches for unmodelled signals of durations between 10 seconds and 10 hours are covered in the long-duration Burst search plan. Potential sources of GW bursts include gamma-ray bursts, choked or low-luminosity gamma-ray bursts, core-collapse supernovae, soft-gamma repeater bursts, ringdowns of perturbed neutron stars or black holes, the coalescences of intermediate-mass black holes or highly eccentric binaries, and potentially as-yet-unknown systems. Burst search techniques are particularly useful for signals with compact time-frequency volume, where they are known to achieve sensitivities comparable to matched filters. They are also valuable for systems such as highly eccentric binaries where the number of templates required for a matched filter search is prohibitive. For the compact binary coalescence sources where burst methods are an efficient option, the work will proceed jointly with relevant the CBC group; see §3.10.

In the absence of robust signal models, predictions of detection rates cannot be made with any certainty[1].

---

[1] We note that the rate of binary neutron star detections, which is the best-modelled GW source for the advanced detectors, is

The astrophysical impact of a positive result would greatly benefit from the reconstruction of the signal's characteristics (both waveform and source location), and the identification of counterparts in the electromagnetic or neutrino sector. The interpretation of null results will need to rely on some parametrisation of the burst signal, particularly the frequency range and total energy content. For example, burst searches of first-generation LIGO and Virgo data showed a typical sensitive range of $7\,\mathrm{Mpc}\,(E_{\mathrm{GW}}/10^{-2}\mathrm{M}_{\odot})^{1/2}$ for standard sirens that emit energy E_{GW} isotropically in the 100-200 Hz band. This corresponds to a rate density limit of approximately $4 \times 10^{-4}\,\mathrm{Mpc}^{-3}\mathrm{y}^{-1}\,(E_{\mathrm{GW}}/10^{-2}\mathrm{M}_{\odot})^{-3/2}$. This performance was shown to be robust across a variety of signal morphologies. [1]

In the advanced detector era, the chances of detection for the strongest GW sources ($E_{\mathrm{GW}} \geq 10^{-2}\mathrm{M}_{\odot}$) will scale as their detectable volume, since the average source density approaches homogeneity at the sensitive distance scales. For weaker sources, the chances of detection depend on the distribution of mass in the local universe. In particular, for sources whose initial LIGO and Virgo range was approximately 0.01 Mpc to 0.1 Mpc, the detection chances will increase less than the detectable volume due to the absence of significant additional mass on the 0.1 Mpc to 1 Mpc scale. The detection of GWs or their associated electromagnetic counterparts in the nearby universe may be aided by the use of galaxy catalogs as source priors. In addition, we note that the extension of the sensitive frequency band of the detectors to lower frequencies will also make new sources available, in particular higher-mass systems.

Historically, the burst group has performed many specialized searches targeting particular astrophysical transients or specific signal classes. In the advanced detector era, the all-sky short-duration Burst search will be the reference used to benchmark other burst searches for signals of similar duration. An assessment of the improvement offered by new approaches will be essential in deciding how or if such new searches will lead to LVC publications. The all-sky search results from low-latency analysis will also be used to trigger follow-up studies in electromagnetic channels, and as a first rapid check for GW counterparts to external triggers such as gamma-ray bursts.

3.1.3 Search Description

All-sky searches for GW bursts scan a broad parameter space which can overlap with the parameter spaces described in other search plans. Generic GW burst searches require techniques that can distinguish signals from background noise fluctuations without prior knowledge of the signal waveform. The "gold standard" in this field is *coherent analysis*, in which the data from all the detectors in the network is combined using both amplitude and phase information before being searched. A GW signal in the data stream of each detector will build up coherently when those streams are combined, while coincident noise fluctuations can be eliminated based on their (non-)correlation between detectors. The analysis is typically done by performing a time-frequency decomposition of the data using wavelets or short Fourier transforms, and identifying candidate signals as clusters of "hot" pixels in the time-frequency maps.

Several independent pipelines based on these ideas have been used in the analysis of initial LIGO - Virgo data, including coherent waveburst (CWB) [2, 3, 4], X-PIPELINE [5], and STAMP [6]. Of these, only CWB has been used to date for all-sky short-duration Burst searches due to the computational cost of coherent analysis and the superior speed of CWB. However, development work continues on all three pipelines, and additional pipelines are under development. These include: the GSTLAL Excess Power (EXCESSPOWER) [7], which processes detector data streams separately ("incoherently") and looks for coincident transients; omicron+LAL Inference Burst (LIB), which also searches incoherently [8] to trigger a coherent MCMC followup; and BAYESWAVE [9], which performs Bayesian MCMC followups.

Given the unmodelled nature of GW bursts and the potentially large discovery space in the event of a detection, the all-sky search strategy aims to support multiple analyses that will offer both complementarity

---

uncertain to three orders of magnitude; see §**??**.

and redundancy. Multiple all-sky pipelines will allow for cross validation of search outputs and help the review our science results. In particular, by being subject to different systematics, additional all-sky analyses are expected to increase our confidence in the coverage for unexpected signal morphologies. We note further that, historically, the direct comparison of two or more pipelines has spurred improvements in each. Therefore, we will adopt at least two pipelines to perform all-sky searches. The baseline all-sky search pipeline will be coherent WaveBurst CWB2G (see §3.1.6).Additional pipelines will need to be reviewed by the start of each Observing Run.

In addition to these search pipelines, there are several pipelines that focus on the analysis of data from auxiliary and environmental channels to generate required veto and data quality information. Two such pipelines are KLEINE-WELLE and OMICRON. More details on pipeline development plans are given in §3.1.6.

For the coming Observing Runs, CWB2G, omicron+LIB and CWB2G+BAYESWAVE will be deployed to search all science data with two or more detectors operating at reasonable sensitivity. A minimum of two detectors is required to reject background noise fluctuations. Each search pipeline will actively work to improve their performance in preparation for improved detector sensitive in subsequent Observing Runs and tune their search parameters accordingly. The search will identify and rank candidate events, using GW correlation tests and data quality checks to reduce the noise background. The same time-lag method used in previous burst searches will be used to assess the background and thus the significance of candidate events. In this approach, search thresholds will initially be tuned using a small set of time lags before a larger, different set of time lags are used to estimate the background and, thus, the significance of zero-lag events. The significance estimated by each all-sky search pipeline will be combined to give a single, joint estimate, particularly for loud triggers which may be identified as candidate GW events. Should no GW events be identified, the combined significance estimate will be used to construct the rate upper limit.

Parameter estimation follow-ups of the loudest triggers will also be performed. BAYESWAVE will choose a CWB2G significance threshold so that it follows up background and zero-lag triggers at an average rate of once per week. LIB will choose a significance threshold so that it follow-up zero-lag triggers at an average rate of once per day. These analyses aim to estimate the signal properties for any detected gravitational-wave burst. Additionally, BAYESWAVE aims to characterise background trigger properties. Since parameter estimation work is a relatively new aspect of the all-sky search, outputs from all parameter estimation analyses, including CWB2G signal parameter estimates, will be compared to determine the operational characteristics of each algorithm. Should the observed GW signal originate from a source targeted by other search plans, the Burst group will coordinate with relevant groups to characterise the signal.

As in O1, online minute-latency analyses will be used to provide alerts of significant events to electromagnetic observatories. The offline analyses will initially run on a small subset of all available livetime to identify any issues that many cause errors or delays in the computing time. This smaller run will also feed into data quality studies and data monitoring tasks. The definitive analysis will be performed offline using the best calibration, data quality, and other relevant information available.

3.1.4 Results validation plan

The coherent Waveburst search pipeline has had past experience analysing data from LIGO and Virgo and its upgraded successor, coherent Waveburst 2G (CWB2G), has been used as the baseline analysis during O1 run. The cWB2G pipeline with few modifications including improved computing efficiency and waveform reconstruction is planed for use during the O2 run. In addition to CWB2G, there will be two other measures of significance for each event: the results of the omicron+LIB pipeline and the BAYESWAVE follow-ups to CWB2G triggers. In the case that a pipeline sees a short duration transient, signficant events from one pipeline will be cross validated with events observed in the other pipelines. The additional validation pipelines will increase the robustness of the search by providing an independent analysis of the data. In particular, by being subject to different systematics, validation searches are expected to increase our confidence in the coverage for unexpected signal morphologies. It will also provide a significant opportunity for cross-checking and reviewing of results. Additionally, we will ensure the redundancy and cross-checks contribute to validation of any scientific results reported in an all-sky short-duration Burst search publication.

3.1.5 Publication plan

If the all-sky short-duration burst search identify gravitational wave signals, the Burst group aim to have an article ready for publication within 3 months of the identification of any candidates. The all-sky short-duration burst search is likely to detect binary black hole mergers (BBH). If only BBH signals are found, the Burst group expect to publish an observational results paper for short-duration bursts following each advanced detector Observing Run, stating the null result with respect to non-BBH signals and reporting on the sensitivity of burst searches to BBH coalescences.

In case of non-BBH GW detection candidates, we consider $3\,\sigma$ to be a *minimum* significance threshold for an “evidence for” statement. Based on past experience, we expect that confident detections will require improvement in our background rejection techniques. Currently these rely on single-detector characterization and data quality, and the tuning of coherent tests in network data analysis. Advanced methods for data cleaning and signal/background discrimination are under development, as described in §3.1.6.

Null results will be interpreted as typical sensitive distance and rate density limits for standard-candle sources. We will also compute limits based on standard-candle populations folded with galaxy catalogs when applicable, i.e., when the sensitive range is of order a few megaparsecs to a few tens of megaparsecs.

For each GW detection candidate, all burst pipelines report bulk information such as duration, bandwidth, and amplitude. In the absence of an *a priori* signal model, more refined statements about the properties of a candidate, such as reconstructed $h_{+,\times}(t)$, will rely on robust parameter estimation tools for generic bursts. Such tools are under active development, as discussed in §3.1.6. We will also explore schemes to classify GW candidates into pre-determined signal classes. This will allow us to set a statistical confidence conditional to a signal class of astrophysical interest. Finally, the inclusion in a publication of any multi-messenger information on candidates will depend on the nature of that information, and following the procedures set out in the relevant MoUs.

Our minimum goal is to complete the analysis of each run and the corresponding publication before the start of subsequent run. We will review in advance the analysis methods, as well as a few standard parts of the publication, to speed up the final internal review process. In the case of long observations, we aim to complete the offline analysis for a given data set within one month of fixing the calibration and data quality information. Our ultimate goal is to circulate a paper within the LSC and Virgo collaborations not more than 3 months after the calibration and data quality information is finalised.

3.1.6 Technical requirements and development plan

coherent WaveBurst:
The same version of the CWB2G pipeline running during the O1 run can be also used during the O2 run. The (cwb pipeline features of particular interest include: a modular structure, allowing the plug-in of user-definable modules; an input data cleaning stage by regression of auxiliary channels; multi-resolution reconstruction of signal candidates using time-frequency pixels from different wavelet resolutions; and the ability to perform different post-processing using the same input trigger set (e.g. for specialised analyses targeting different polarization states). This version of the pipeline has been already reviewed. In addition an updated version of the pipeline with better computational efficiency, waveform reconstruction and background rejection will be deployed before or during the O2 run and replace the current cwb version. A new version of the pipeline both for the online and offline analysis will be tested in ER10. It will require a review of updated pipeline modules which can be complete before the O2 run or shortly after its start. Ongoing tests include the re-analysis of the O1 data. Other tests focus on questions including: the ability of regression to reject glitches which survive the standard data quality checks; how much signal reconstruction has improved; how much the confidence of candidates improves by classification into pre-determined signal and glitch classes; and optimal tuning using the false alarm rate density statistic [2].

Additional pipelines:
A feasibility study of all-sky analysis of initial LIGO data is currently underway, and advanced time-frequency clustering techniques are being explored [6]. EXCESSPOWER has been developed primarily for use in detector characterisation studies, but can be used for GW searches by applying coincidence criteria to triggers from different detectors using the infrastructure for the cosmic string analysis [10]. It has already been integrated into the existing online data transfer and analysis infrastructure and is partially reviewed as a consequence of the gstlal_inspiral review. The omicron+LIB pipeline has been tested by offline running over ER4,5 and S6/VSR2,3 data. BAYESWAVE has been applied to follow up background events identified by CWB2G as well as simulated signals, both in ER5 and S6/VSR2,3 data.

Mock Data Challenge (Simulation) infrastructure:
Burst simulations will be created using the lalsimulations infrastructure. The new code developed for generating burst injections has already been tested against the traditional burst simulation infrastructure, GRAVEN/BURSTMDC. GRAVEN/BURSTMDC will be be maintained in the near term as a reference with which to validate simulation engines until the lalsimulation infrastructure is fully deployed.

Glitch rejection and signal parameter estimation:
Improved glitch rejection is crucial for the all-sky search. In addition to the data cleaning and multi-resolution reconstruction efforts in CWB2G, the LIB and BAYESWAVE parameter estimation pipelines are being developed based on MCMC techniques. To quantify their performance, a parameter estimation challenge has been proposed[3]. Focusing on the all-sky background of the S6/VSR2,3 CWB search, this challenge will assess the glitch rejection and waveform reconstruction capabilities of the various pipelines.

Future searches:
The all-sky searches can also be adapted to perform future searches for signatures of alternative theories of gravity or bursts with memory. Alternative theories of gravity can be tested by modifying the all-sky burst search code to allow for polarization modes other than the plus and cross modes present in GR. Preliminary studies have focused on searching for scalar-mode GW bursts. Such research will be pursued more in the future, especially when a network with more GW detectors allows different polarization modes to be better separated.

---

[2] See https://dcc.ligo.org/LIGO-T1300869.

[3] See https://wiki.ligo.org/Bursts/AllSkyPE.

3.1.7 Resources

Detector Characterization:
All-sky searches have relied on data quality information to help reduce the noise background. While improved glitch-rejection capabilities are being developed, we expect that data quality will remain a key component of the all-sky search.

Calibration:
To meet our publication schedule, the offline search will require "final" calibrated $h(t)$ from three months after the beginning of each run (within two months for the 2015 run). All tests to date have shown that the calibration uncertainties will not have a significant impact on the analysis provided they are of the level already achieved in the S5-6 and VSR1-3 runs[4].

Review:
The CWB2G pipeline will require review of its modifications and it is expected to complete before the start of O2 run or shortly after. Given the relevance of the pipeline the review team is made up of 5 reviewers. The review of BAYESWAVE is underway, while the LIB review has been completed. The omicron review will begin soon though it is not expected to an onerous review since omicron shares many components with the Omega pipeline which has previously been reviewed.

---

[4] for detailed requirements, see `https://dcc.ligo.org/LIGO-T1300950`

3.2 Catalogue of Compact Binaries

Stellar-mass BBHs have been directly measured by Advanced LIGO to merge with a rate of approximately 9–240 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ [11]. Advanced LIGO has established two confirmed binary black hole detections, GW150914 and GW151226 and a strong third candidate LVT151012 [11], with an overall range of masses $\sim 7-36\,\mathrm{M}_{\odot}$. From these observations, the mass distribution of black holes in binary systems can be estimated to be a power law with the primary mass m_1 distribution $p(m) \propto m_1^{-2.5}$ [11], although the power law index is still very uncertain with so few observations. To date, spins have been difficult to constrain from gravitational waves, but are consistent with small effective spins.

The binary massess detected through gravitational wave observations are larger than those of black hole candidates identified by X-ray observations, which yield BH masses $5 \leq M_{\bullet}/\mathrm{M}_{\odot} \leq 20$, confirmed with dynamical mass measurements for 16 BHs. An apparent lack of BH masses in the range 3–5 $\mathrm{M}_{\odot}$ (the "mass gap") [12, 13, 14] has been ascribed to the supernova explosion mechanism [15, 16]. Further BBH observations with Advanced GW detectors will begin to give us a clearer picture of the mass distribution of coalescing BBHs, allowing comparisons to be made with galactic BH distributions and probing the existence of a mass gap. Population synthesis based on recent stellar wind models allows for isolated black hole masses up to $\sim 80\,\mathrm{M}_{\odot}$ [16, 17]. Common envelope binary evolution [18] may reduce the maximum expected component mass and total mass to $\lesssim 100\,\mathrm{M}_{\odot}$ [19], however stellar BH with mass above $100\,\mathrm{M}_{\odot}$ are conceivable [20], overlapping the range associated with IMBH formed by repeated mergers.

X-ray observations of accreting black holes indicate a fairly uniform distribution of spins over the entire range allowed by general relativity, $0 \leq S/m^2 \leq 1$ [21, 22, 23, 24, 25, 26, 27]; both low (∼0.1) [28] and high (> 0.85) values [29] are represented. The microquasar XTE J1550-564 [30] and population synthesis models [31] indicate small spin-orbit misalignment in field binaries. For massive field binary progenitors, the common envelope phase and mass transfer [32] are expected to cause strong correlations between spins and masses of the two BHs in field binaries [33]. However, no such correlations are expected for dynamically formed BBH.

Population synthesis models constrained by radio observations of double neutron star (NS) systems in the Milky Way, provide an indirect estimate of the gravitational wave (GW)-driven binary neutron star (BNS) merger rate of $0.01\mathrm{Mpc}^{-3}\mathrm{Ma}^{-1}$ to $10\mathrm{Mpc}^{-3}\mathrm{Ma}^{-1}$. This gives an expected BNS detection rate of 0.4—1000 per year for Advanced LIGO at design sensitivity [34]. The detection or non-detection of BNS systems in future observing runs will allow us to constrain the models of the BNS rate.

The masses of known NSs are reported to be in the range $0.7\mathrm{M}_{\odot}$ to $2.7\mathrm{M}_{\odot}$ with a mean mass of $\sim 1.4\mathrm{M}_{\odot}$ [35], though the lower value, $0.7\mathrm{M}_{\odot}$, comes from an imprecise measurement of a single system that is also consistent with a higher mass. NSs in BNS systems have a more narrow observed mass distribution of $(1.35 \pm 0.13)\mathrm{M}_{\odot}$ [35]. Theoretical models support the production of a population of NSs formed in binaries through electron-capture collapse of O-Ne-Mg cores, and predict masses which are consistent with these observations [36, 37]. Lower mass Fe cores are predicted to lead to NSs with masses almost as low as $1\mathrm{M}_{\odot}$ [38].

Current astrophysical understanding indicates that the older NS in a binary system can be spun up through mass-transfer from its companion, which can increase the spindown timescale. However, this process is not completely understood, and it is not clear how efficient the spin-up process can be. The observed dimensionless spins (J/m^2) for NSs in BNS systems (e.g., J0737-3039) are ≤ 0.04 [39], however the fastest known NS spin is 0.4 [40].

NSs contain the highest densities of matter in the observable universe. The internal structure of NSs is constrained by nuclear experiments and astrophysical mass-radius measurements, which help to constrain the possible equation of state (EOS) of nuclear matter [41]. As binary NSs coalesce, the EOS will determine both tidal interactions during late inspiral and matter effects during merger. These effects are encoded in the gravitational waveform [42]. In cases where an electromagnetic (EM) counterpart can be identified, further information can be used to understand the physics of the merger [43, 44]. There are several plausible EM counterparts to BNS mergers [45].

Neutron star - black hole binary systems are thought to be efficiently formed in one of two ways: either through the stellar evolution of field binaries or through dynamical capture of a neutron star by a black hole [46, 47, 48, 49]. Though no neutron star black hole binarys (NSBHs) systems are known to exist, one likely progenitor has been observed [50]. Rates for the coalescence of NSBH systems are not well known, however a "realistic" estimate from population synthesis of field binaries is given as 0.03 Mpc^{-3} Myr^{-1} [51]. A "pessimistic" estimate is given as 6×10^{-4} Mpc^{-3} Myr^{-1} and an "optimistic" estimate as 1 Mpc^{-3} Myr^{-1} [51]. These yield observation rates for Advanced LIGO and Advanced Virgo of 0.2 - 300 yr^{-1}.

The mass distribution of NSBH systems is not well constrained. However, it is possible to place estimates on the mass and spin ranges by using the properties of neutron stars and black holes observed in other systems, such as the NS and BH systems described above. The microquasar XTE J1550-564 [30] and population synthesis models [31] indicate small spin-orbit misalignment in field binaries. Dynamically formed NSBH systems, in contrast, are expected to have no correlation between the spins and the orbit.

Fully general-relativistic numerical simulations of NSBH systems have been performed (for e.g. [52, 53, 54, 55, 56, 57]) and show that certain combinations of mass, spin, and NS equation of state (EOS) parameters can cause the neutron star to tidally disrupt before coalescence. These systems could power the central engines of short gamma ray bursts (GRBs) or produce other types of prompt or delayed electromagnetic (EM) counterparts [58].

In the O2 observing run we expect to detect around ten compact binaries. Providing a comprehensive summary of the detected systems will be one of the main publication goals of the CBC group. To this end, we will catalogue our detections made during O2 and release a detailed description of all detected systems, covering their detection and physical parameters, inferred using the best available waveform models.

In O2 we will conduct a deep search for compact objects from $1\,M_\odot$ to a maximum mass dictated by the instrument sensitivity (likely not to exceed $\sim\ 1000\,M_\odot$). For detection, spins aligned with the orbital angular momentum will be considered. For components below $2\,M_\odot$, spin magnitudes up to 0.04 will be searched for. Otherwise, up to maximal spins of 1 will be considered. For parameter estimation, waveform models that capture the most complete dynamics available of any binary system will be used. Two independent search codes, pycbc and gstlal, will be run on the data. In O1 we conducted a joint search with the burst group for IMBH systems separately from BNS, NSBH and stellar mass BBH. In O2 we will include binary black holes detected by burst pipelines in the catalogue alongside those detected with modeled CBC pipelines.

For each event, both clear and marginal detections, we will provide estimates of the physical parameters of the source using the best available waveform models, and provide an estimate of the systematic error through comparing parameter estimation using different waveform families or through comparison to numerical relativity simulations. This information is an input to the study of astrophysical rates and distributions.

The published results from this project should represent the best available information on the detected sources during O2, using final vesions of data quality and calibration. In coordination with the LIGO Open Science Center we will produce an electronic data release to go alongside the publication.

O2 deliverables

1. A publication detailing significant signals detected during O2. These will include
    - clear detections,
    - marginal events which cannot be invalidated through data quality or other means,

  - and may also include single-detector events which have significant probability of being true signals.

2. Parameter estimates for each event, including an eventual electronic data release
3. Probability of astrophysical origin for each event
4. Estimates of the gravitational waveform for each event, including in electronic format

3.3 Astrophysical Distributions of Compact Binaries

The detection of GW150914 and GW151226 firmly established the existence of stellar-mass binary black holes (BBH), with a coalescence rate of 9-240 Gpc^{-3} yr^{-1}, high enough to make them a primary source for future observing runs. In the O2 run we expect to detect between 0 and 10 such events, depending on detector performance, duty cycle and the actual rate of BBHs. Binary black holes can be produced by several astrophysical formation channels including isolated binary evolution and dynamical formation in dense stellar environments. The direct observation of BBHs using GWs allows us to measure the mass and spin of individual systems. Combining these individual detections into a statement about the population requires knowledge of the selection function of the GW detectors, searches and parameter estimates. The resulting knowledge of the astrophysical population can be used to improve models of binary evolution and determine the relative importance of the various formation channels.

O2 deliverables

1. A catalogue of detected events in coordination with the Catalogue project
2. Astrophysical event rates
   (a) Up to date compact binary event rate estimates including all feasible sources of uncertainty and, if possible and mature, $\frac{dN}{dV dM}$.
   (b) Constraints on BNS and NSBH rates in lieu of detection.
3. Astrophysical mass distribution of coalescing binary black holes
4. Astrophysical spin distribution of coalescing binary black holes
5. Data release of BBH population

3.4 Multimessenger Astronomy and Astrophysics with Compact Binaries: GW alerts

The National Science Foundation has recently name “Window on the Universe: The Era Multi-messenger Astrophysics" as one of its “big ideas". Gravitational waves along with electromagnetic and astroparticle observations could help us to unravel the mystery of some of the Universe’s most spectacular transient phenomena.

We will conduct low-latency analyses that aim to detect and localize gravitational waves from compact binary sources across the full parameter space in near real time. Observations will be sent to the gravitational wave candidate database and propagated to external observers in a timely fashion according to LVC policy. These observations will also be correlated with incoming external triggers from e.g., gamma ray observations and neutrinos.

02 deliverables

1. Rapid alerts for CBC signals containing
   (a) Sky position
   (b) Distance
   (c) Basic classification (EMbright probability or similar)

3.5 Searching for Gamma Ray Burst Counterparts to Compact Binaries

The coalescence of a neutron star with a neutron star or black hole is a probable candidate to be the progenitor of short gamma-ray bursts (sGRBs). A detection of GWs in coincidence with a GRB would be a major scientific result, confirming this progenitor model and demanding a rapid publication. Any possible association should be communicated to MOU porters with low latency to enable follow-up observations of any GRB of interest.

In O1 we successfully ran triggered search pipelines for BNS and NSBH progenitors in online mode, and provided results with a latency of a few hours. We also analysed our data offline to provide a final collection of results for the O1 GRB search. We will continue this plan in O2.

O2 deliverables

1. Communication of online search results to MOU partners. This will require the following:
   (a) Continue to run low- (RAVEN) and medium-latency (X and pyGRB) pipelines, as for O1, but with updates.
   (b) Continue to use the online frame files at Caltech, as for O1.
   (c) Complete the infrastructure to communicate online results to MOU partners via approval processor, etc (in progress as of Oct 17, 2016)
   (d) Adding Virgo data (sometime in O2) needs to be tested. X and pyGRB successfully ran with Virgo in S6, so not a problem, in principle.
2. Rapid publication of a GW detection associated with a GRB.
   (a) Communications with MOU partners would give best, vetted, but perhaps not final, results available at that time.
   (b) The group should develop a publication template.
   (c) Significant non-detections would presumably also fall into this category, but presumably with faster collaboration approval; and we have several paper templates from GRB 070211, GRB 051103, and GRB 150916B.
3. Publication of complete set of GRB search results. This may result in two papers:
   (a) A “classic" upper limits paper which includes promptly available GRBs, typically those published in the public GCN plus IPN GRBs if available quickly.
   (b) A second results paper which includes results from the emerging sub-threshold analyses using the Fermi GBM or possibly other detectors, such as the Integral-only GRBs. If the IPN GRBs are not available promptly, they would also be included in this paper. The sub-threshold analyses would require new reviewing efforts.

3.6 Testing General Relativity with Compact Binaries

Both GW150914 and GW151226 allowed us to constrain deviations from GR, and place bounds on the mass of the graviton. As GW151226 had lower masses, we observed many cycles of the inspiral of the two black holes, but given the SNR of the source, the merger-ringdown did not provide much information. In contrast, GW150914 was a more massive binary, and while we saw the end of the inspiral, most of the information came from the merger-ringdown. Using both signals we set limits on the deviation from GR in the post-Newtonian (PN) regime governing the inspiral phase, and in the phenomenological model of the merger-ringdown. In addition, the GW150914 analysis established that the final remnant's mass and spin, as determined from the low-frequency (inspiral) and high-frequency (post-inspiral) phases of the signal, are mutually consistent. Furthermore, the data following the peak are consistent with the least-damped quasi-normal mode of the remnant black hole.

In O2, we expect new detections of BBHs, and detections of both BNS and BHNS systems to further tighten the constraints from O1. If a deviation from GR is detected, we would like to be able to say what this corresponds to. However, this is something that we are unlikely to do. The phenomenological tests are a “top-down" methodology which allow us to signal a deviation from GR, but not the underlying alternative theory. Furthermore, due to the lack of waveform models arising from alternative theories of gravity, specific theory tests do not seem possible in O2.

In addition to the concrete O2 deliverables listed below, the detection of an intermediate mass ratio inspiral (IMRI) would allow us to also place constraints on deviations from GR as the inspiral of the smaller companion would produce more GW cycles than a comparable mass system. These extra cycles could be used to confirm that the more massive object is indeed a Kerr black hole as predicted by GR. Our inability to establish the accuracy of IMR waveforms in this regime could hinder such tests. In addition, from the O2 events, we might also be able to constrain the possibility of black hole mimickers, the electric charge of the black holes, etc.

O2 deliverables

1. *Constraining deviations from GR during the PN inspiral phase:* Lower mass BBH, as well as BNS and BHNS sources, will have longer inspiral phases. Combining posteriors from multiple events in O2 should allow us to progressively strengthen the constraints on deviations from PN theory.

2. *Constraining deviations from GR during the merger-ringdown phase:* More massive binaries should produce most of the detectable SNR in the merger-ringdown phase. By using improved IMR and EOB waveforms, we should be able to place tighter constraints on the phenomenological parameters that govern the merger-ringdown.

3. *Measurement of quasi-normal modes:* Sufficiently loud signals from massive BBHs should provide conclusive evidence of quasi-normal modes. Measurement of multiple quasi-normal modes will allow us constrain the no-hair theorem of GR.

4. *Consistency between the inspiral, merger and ringdown:* A consistency test between the mass and spin of the remnant black hole estimated from the inspiral and post-inspiral parts of massive BBHs will allow us to detect certain departures from GR. Combining posteriors from multiple inspiral-merger-ringdown events should allow us to strengthen these constraints.

5. *Dipole radiation:* With signals that provide a long inspiral phase, we should be able to conduct a phenomenological test for dipole radiation. If dipole radiation exists, its effects would be visible at the -1PN order in the phase and frequency of the waveforms. An ideal source for testing for dipole radiation will be the inspiral phase of a BNS.

6. *Bound on the mass of the graviton and constraining Lorentz violation*: A further constraint on the graviton mass from the increased number of events in O2 and constraints on generic Lorentz violations (by considering modified dispersion relations for propagating GWs).

3.7 Characterizing Exceptional Compact Binary Coalescence Events

In future observing runs, we expect to detect a broad range of compact object merger scenarios. Many of these will be exceptional events, e.g., the first confirmed neutron star binary, systems with definitive spin precession, etc. Such systems will warrant specific attention to be determined only once confirmed.

O2 deliverables

1. A detailed analysis of exceptional events with parameter estimation and astrophysical interpretation.

3.9 Search for GRB Sources of Transient Gravitational Waves

3.9.1 Abstract

Extremely energetic bursts of gamma-rays from cosmological sources are observed by orbiting satellite detectors at a rate of about one per day. These extra-galactic events are generally referred to as GRBs. Astrophysical evidence has led to the hypothesis that GRBs herald the creation of a compact object (a black hole or neutron star) by way of two distinct pathways, corresponding to two phenomenologically recognized GRB categories: short-duration (<2 s) bursts with generally harder spectra, and long-duration (>2 s) bursts with generally softer spectra. Both progenitor categories, collapsars for long GRBs and mergers of compact binary systems for short GRBs, are expected to be sources of transient gravitational waves (GWs). The detection of a GW signal in coincidence with a GRB would provide tremendous insight in the astrophysics of these systems. A GW signal associated to a long GRB would give new astrophysical insight into long GRB progenitors, which in general are not expected to be efficient GW radiators, but some models do predict significant GW emission. A merger signal associated to a short GRB would confirm the compact binary merger nature of the engine and allow for measurements of the binary components masses and spins, as well as constraints on the beaming angles and the neutron star equation of state. A collection of joint short GRBs with redshift and GW measurements will enable a relatively systematics-free measurement of the Hubble parameter at low redshift, which would provide constraints on cosmological models.

Since the GWs would be observable within seconds of the onset of the gamma-ray detections, we plan to perform sensitive *triggered searches* with two distinct algorithms. Optimal searches with GW waveform templates will be sensitive to short GRBs out to ~ 400 Mpc for NS-NS mergers and ~ 1 Gpc for NS-BH systems in advanced detectors at full sensitivity. Because of the astrophysical uncertainty of the long GRB mechanisms, the GW emission cannot yet be modeled *a priori*, so a *burst* algorithm is also employed for GW searches triggered by both long and short GRBs. The space and time constraints for mergers which are associated with a GRB allow for a *coherent* version of both types of searches. We plan to run archival searches on the refined data samples available after a few weeks, as well as a more computationally costly search focused on long-duration GW signals associated with long GRBs.

3.9.2 Scientific Justification

GRBs are generally associated with systems which are also expected to be GW sources: compact binary coalescences for short GRBs, with gamma-ray duration $< 2\,\mathrm{s}$ and harder spectra, and collapsars for long GRBs, which typically last $> 2\,\mathrm{s}$ and have softer spectra. The cosmological distance of GRBs remains the principal challenge for detecting GWs associated with GRBs with advanced detectors.

Cosmological short GRBs likely result from mergers of binary systems consisting of two neutron stars (NS-NS) or a neutron star and stellar mass ($< 10\,\mathrm{M}_\odot$) black hole (NS-BH). At full sensitivity, they are potentially observable by advanced GW detectors to $\sim 400\,\mathrm{Mpc}$ for NS-NS or $\sim 1\,\mathrm{Gpc}$ for NS-BH at a rate of $\sim 1\,\mathrm{yr}^{-1}$ for each [59, 60]. Short GRBs can also result from soft gamma-ray repeaters (SGRs) of galactic or near-galactic origin (*e.g.* the likely progenitors of GRB 070201 and GRB 051103).

It is widely believed that binary mergers are the progenitors of short GRBs. The recent detection of a possible kilonova associated with a short GRB [61] has further supported this association. However, it is only the observation of a GW signal that will conclusively show that the progenitor is a binary merger. While the merger scenario is preferred and at least one NS is required, both NS-NS and NS-BH progenitors are possible; GW observations will allow us to determine which of these it is. A population of GW-GRB observations will allow us to measure the fraction of GRBs associated with each progenitor type. The degeneracy between distance and inclination angle means that it will be difficult to measure the GRB beaming angle based on measurement of a single system. However, with observations of a population of binary merger sources, with and without GRB counterparts, we can constrain the average opening angle.

Long GRBs are associated with the gravitational collapse of massive stars, also termed collapsars, but perhaps with multiple sub-pathways and astrophysical details which are far from being fully understood. They are detected more frequently than short GRBs, are typically brighter in gamma rays, and are observed to larger distances. Their observable distance in GWs is unknown, but is unlikely to be as large as short GRBs. For basic stellar collapse, the GW range is likely to be galactic or near-galactic. Collapse leading to rotational instabilities or core fragmentation could be observable to 200 Mpc. Long GRBs associated with accretion disk related mechanisms could produce long-duration GW emissions, perhaps observable to tens of Mpc. The estimated rate for long GRBs within 100 Mpc is $\sim 1\,\mathrm{yr}^{-1}$ [62, 63]. The hypothesized population of low-luminosity long GRBs [64] would also have a rate of $\sim 1\,\mathrm{yr}^{-1}$.

Long-duration GRBs are expected to be dominantly associated with collapsar models – rapidly rotating massive stars which collapse to BHs (or NSs). The long GRBs reveal themselves with a wide range of observable properties, leading to speculation that there may be sub-classes involving different mechanisms. In addition, some models predict GW emission associated with the accretion disk itself, or with a post-collapse proto-neutron star, which would give rise to long-duration (> 1 s) GW emission. The observation of X-ray "plateaus" following the GRB on timescales of tens of minutes to hours after the main burst, has suggested that GRB central engines may live longer (1000 s) than previously thought. Given the mysteries associated with long GRBs, it is clear that any significant GW detection would greatly contribute to our understanding of the underlying astrophysics. Finally, a low-luminosity population of long GRBs would benefit from lower-threshold gamma-ray triggering.

The association between GWs and GRBs also impacts fundamental tests and cosmology. For example, the speed of gravity can be probed to $\sim 10^{-16}$, and "dark matter emulator" models, which allow MOND-like models to fully eliminate the need for dark matter, can be effectively ruled out with the first observation of a coincident GRB-GW event [65].

After some number of years of running near design sensitivity, it may be possible to accumulate a sufficient number of GW detections in association with short GRBs to make meaningful statements about cosmology. A well-measured binary inspiral waveform can determine the luminosity distance D_L which is absolutely calibrated, up to GW detector calibration uncertainties, and independent of the electromagnetic distance ladder [66]. However, to probe the cosmological expansion, one also needs the redshift, thus a joint observation of gravitational waves and electromagnetic afterglow for the GRB.

The potential science outcomes of such joint observation include testing the EM cosmological distance ladder for z up to 0.1 or 0.2 and setting dark energy constraints. With enough short GRBs a few % measurement of the Hubble constant H_0 will be possible [67]. A precise measurement of H_0, along with the CMB, tightly constrains models of cosmological expansion and addresses the question of continued acceleration into the current epoch. The dark energy figure of merit [68] is used to quantify the worth of future constraints, by testing deviations from a pure cosmological constant: even after the next generation of BAO measurements from WFIRST, a 1% measurement of H_0 will improve the figure of merit by $\sim$ 40% [68].

3.9.3 Search Description

The nature of GRB progenitors enables a GW *triggered search*: a search restricted to short on-source time windows that are defined by the gamma-ray detections. The source position derived from gamma-ray observations, constrains the possible delays in the GW arrival time in the LIGO and Virgo observatories. Together, knowledge of the time and location of the event are powerful handles for the reduction of accidental background in GW searches, which translates to a larger maximum distance ("horizon distance") for a GW detection [69, 60]

In addition, the existence of a GRB trigger significantly reduces the search parameter space, for example with the source orientation, spin, or binary mass ratio, which allows us to deploy a fully coherent analysis restricted to (near-)circularly polarized signals that would is be possible in the all-sky searches for bursts, NS-NS, or NS-BH.

A number of different searches will be deployed in the search for gravitational wave signals associated with GRBs. We will run an un-modelled burst search, a templated inspiral search and a search for long duration transients. For the templated search, we will cover a similar parameter space as for the NS-NS and NS-BH searches combined, as we require at least one neutron star in the system to produce a GRB. Numerical models can predict the range of masses and spins of the black hole in an NS-BH system that may lead to a GRB; if the black hole is too massive, the NS is swallowed whole and no GRB can be formed [70]. Taking this into account allows us to reduce the number of templates searched.

Both searches — for short and long GRBs — will be promptly initiated, within about two to thirty minutes following a GRB detection notice, and results from the GW searches should be available within a few hours. The results that will be provided, in order of increasing latency, are:

- As soon as possible after the announcement of a GRB, we will provide details on which of the detectors were operational, as well as an estimate of the network sensitivity in the direction of the GRB.
- Low latency analyses will look for coincidences between events in the online burst, BNS and NSBH searches (described in those plans) and GRBs. These have the advantage of being very low latency, and of requiring a little additional computational cost over the existing all sky searches. The results from these searches will be ready in minutes after the GRB and will give a preliminary indication of any candidate event and associated significance.
- We will run two fully coherent analyses around the time of the GRBs, as was done for the S5-6 and VSR1-4 searches: the X-PIPELINE burst algorithm on all GRBs [71], long or short, and the PYGRB binary merger search on any GRBs that are identified as short, or possibly short [72, 73] These searches will be initiated as soon as possible after the GRB alert, and we will endeavour to produce first results from this analysis within hours of the GRB alert, so that these can be shared with the broader astronomical community. For both analyses, in the initial run we will calculate a minimum of 1,000 background trials to enable us to quote a 1 in 1,000 false alarm probability for any significant event. Subsequently, we will refine the search results by performing more background trials, if necessary, to better estimate the significance of any event and by performing injections to test the sensitivity of the search. These follow-up runs will be performed in the offline/archival framework. The final results will be available within a few days.
- We will run an archival search with a latency of around a month. This will be a rerun of the data with the final data quality, calibration, etc. It will be the result that is used in non-detection publications, much as has been done in the past. Additionally, at this time we will run a search for longer duration signals with the STAMP pipeline.

3.9.4 Results validation plan

Validation searches for the different GRB analyses will be done by using the all-sky triggers produced by others plans:

- cWB for the long GRBs analyzed with X-PIPELINE
- pyCBC for the short GRBs analyzed with pyGRB
- the long duration transient search (Stampas, Sphrad,...) for the long transient GRBs

The coincidence search will de bone with the Raven pipeline currently developed for the low latency follow-up of GRB events.

3.9.5 Publication Plan

As a general rule, we plan to share anything of interest in low latency with MOU partners in the GW-Electromagnetic Follow-up program. Combined GW–gamma-ray sky maps are an example of such information. We also plan to release public GCN notices or GCN circulars, similar to the one reported by IceCube on GRB130427A [74], where we acknowledge there was an event of interest and we provide basic detector status information (on/off, antenna response, etc.). The Fermi GBM team has volunteered to include such status information in their GCN notices. They would presumably read the LIGO-Virgo status from a web page or equivalent.

Detection confidence for the GRB triggered searches will be increased if the associated GW sky map overlaps the GRB error box. Otherwise, we expect detection confidence to be analogous to that of the all-sky CBC or burst analysis, as the case applies. The publication plan will depend on the detection and astrophysical scenario as follows:

- **A significant non-detection.** (like GRB 070201 [75]) We plan to publish with a goal of ~2 weeks after the GRB. This would apply to (nearby) GRBs for which there is a reasonable expectation of GW detection. For a short GRB this can be well defined, *e.g.* when the distance is known and is within the current NS-BH horizon. For a long GRB, we have no expectation, except perhaps for a galactic or local neighborhood GRB. We must keep in mind that most GRBs do not have an associated redshift and we know that the gamma-ray brightness is not a good indicator for distance. For this quick turnaround, we need pre-reviewed pipelines and pre-reviewed paper templates.
- **Early detection.** If one or more of the first several detections is a GRB, we would then plan to publish one paper per event.
- **End of run upper limits.** If the average exclusion distance upper limit is at least twice that of the current published result (currently S6/VSR2-3), we will then publish a paper including all vetted GRBs from Fermi, Swift, and IPN on a time scale of 3 to 6 months.
- **Sub-prime GRB search.** A search focused on a population of low-luminosity GRBs would benefit from a gamma-ray trigger sample obtained with a lower than usual threshold. If no significant GW detection results from this search, the results can be included in the end of run paper.

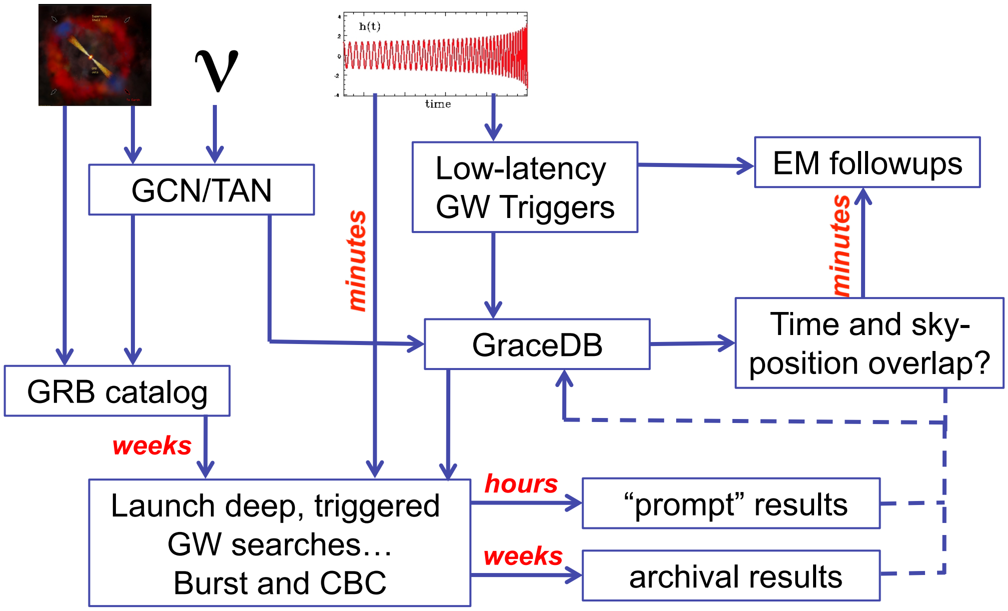

Figure 1: Flow of gamma-ray and GW data for the GRB searches. There are three main time scales, each having an associated search: Low-latency (minutes), prompt triggered (hours), archival (weeks). The ν indicates that a galactic supernova with a corresponding SNEWS alert could be handled similarly to the GRB bursts search.

3.9.6 Technical Requirements and Development Plan

The GRB searches involve 5 pipelines and 3 analysis timescales, as shown in Fig. 1.

Low latency analysis. The low-latency (∼minutes) all-sky pipelines are developed by the Burst and CBC groups. Candidates from these analyses can be compared to the GRB triggers to provide additional evidence by way of time coincidence and spatial overlap, using GW sky maps and GRB error boxes.

Triggered GW pipelines. (∼hour, or *prompt*, and ∼week, or *archival* timelines)

- **Bursts.** The X-PIPELINE [?] is a coherent search which has been used for almost all of the GRB searches in the initial detectors era. The code is stable, known, reviewed, and can be used *as is*. A steady program of updates was applied to improve it, including efforts to speed up the code. A recent version using multivariate analysis, for higher efficiency and lower computational cost, is in development but has not been reviewed yet. Its performance on the next engineering run will determine which version will be used in the first science run and whether a review of the modifications is needed.
- **CBC.** PYGRB is a fully-coherent search employing matched filtering to target NS-NS and NS-BH waveforms in association with GRBs [72, 73]. This pipeline was used in S6/VSR23 GCN searches and in S56/VSR123 IPN searches. The pipeline searches for GW signatures in a 6 s window around the time of the GRB and uses O(1000 s) of data around the central time to estimate the significance of events seen in the 6 s window. A number of enhancements were added to the code since S6. For example, the ability to do time slides has been added, the NS-BH template bank has been reduced by excluding target sources in which the NS cannot be tidally disrupted, and the low-frequency cutoff has been reduced to 15 Hz. In addition, the pipeline generator has been rewritten within the PYCBC

framework, although the underlying coherent search code is largely unchanged. The code is now able to run on GRBs where only short stretches of data are available, and to use longer stretches of data when these are available.

- **Promp triggered search infrastructure.** The coherent Bursts (X-PIPELINE) and CBC (PYGRB) GRB pipelines will be run in prompt triggered mode, to give relatively quick feedback from our most sensitive searches, on $\sim$hour timescale. In ER5, both pipelines were operating in immediate triggered mode and sending triggers to GRACEDB.
- **Long Duration GW bursts.** The STAMP pipeline targets GW signals lasting 10–1000 s. It has been applied to initial LIGO data to constrain extreme models of stellar collapse [76]. The pipeline is reviewed and can be applied "as is" to advanced detector data. More recent work has focused on the development of the seedless clustering algorithm **stochtrack**, which can improve the reach of STAMP by as much as a factor of 2 [77]. Stochtrack is not at present reviewed, but it is a relatively small subroutine called by the otherwise reviewed STAMP pipeline.
- **GRB plateaus.** An analysis technique is in development to target secular bar-mode signals of duration $\sim$1000 s, triggered by GRBs that show evidence for longer-lived energy injection (*plateaus*). The plan is to develop a search with a sensitivity that is intermediate between matched filtering and un-modeled searches. This analysis could complement the burst search with tools that extract astrophysics information from the results of an un-modeled search.

3.9.7 Resources

Number of events

The computing needs of prompt and archival triggered searches are driven by the number of GRBs in the samples. We will assume that the GRB rate for the early ADE will be the same as that of the S6/VSR2-3 runs, in which the rate was dominated by the Fermi-GBM, with significant contributions by the Swift-BAT and the other IPN detectors. As the IPN detections are not conveyed promptly via the GCN, they are only considered for the archival searches. Table 3 summarizes these rates.

Table 3: S6/VSR2-3 detected GRB rates

Fermi + Swift (GCN) GRBs	350/year
short GRB fraction of above	17%
IPN GRBs not in GCN sample	85/year
short GRB fraction of above	10%

We will ask to retrieve the low latency alerts from GCN through a Web Marshall (GRACEDB) getting triggers to start analyses with a medium latency ($\sim$ 30 minutes). Past analyses were run on 50% of the received GRB triggers, asking for at least 2 IFO and sufficient data around the trigger time. On a longer timescale we need to insure getting all triggers from offline catalogs with the vetting procedure described below.

Data needs

The prompt triggered search aims to launch an analysis within $\sim$ 10 minutes of receiving the GCN trigger notification. Thus, online frames with $h(t)$ calibrated data, gathered from shared memory, will need to be used with a circular buffer of at least 24 hours. Additional needs include:

- The archival searches using X-PIPELINE, PYGRB or STAMP will use standard offline frames.
- The infrastructure will need to retrieve the data on the cluster, i.e. a metadata service that maps the scientific description of detector data to frame file locations (diskcacheAPI, ligo_data_find).
- The low-latency search only requires an analysis of the data products of the low-latency, all sky searches; it does not require frame data.
- All the pipelines use the typical job submission system and therefore will then need the workflow planning and execution environment (Pegasus, DAGMan, Condor).
- The results of the analyses will be gathered and shared with the LIGO.ORG authenticated web severs (auth project, LDG).
- Low and medium latency analyses plan to store results in the Web Marshall system (GRACEDB).

Detector Characterization:

We will need to retrieve detector status and data quality information before the search start in order to determine which periods are to be excluded around the GRB time. This will require: infrastructure to generate detector state and data quality information (ODC, DMT); metadata service that provides information about when the detector data is analyzable (DQSEGDB, ligolw_segment_query_dqsegdb, segments_from_cats) within 15 min; method to locate veto trigger files from detector characterization.

Calibration:

If subsequent modifications to the offline calibration result in a significant change of results, as defined by the criteria for the corresponding all-sky analyses, a full rerun will be performed on all of the GRBs.

Review:

- For the X-PIPELINE, the expected review will depend on the configuration selected as the multivariate configuration, which has not been reviewed yet. Otherwise, most of the modifications done recently have been reviewed for different analysis projects.
- For PYGRB, review will be needed on the different upgrades foreseen, see *Technical Requirements and Development Plan*.
- The core of the STAMP pipeline has already been reviewed for previous searches. Some parts will also be reviewed for on-going projects on the burst and stochastic sides. We anticipate short review times for this project.
- As we plan to have a short time scale to publish a significant detection, we plan to have paper templates reviewed before the start of the first run of the Advanced Detectors.

Documentation:
This will be one of the main projects, as we would like to have any member of the collaboration able to act as GRB *advocate* of a GW analysis, or to check the online results. We then need to insure that all the proper documentation will be available to start the analysis, monitor the processing and interpret the results.

3.10 Search for Intermediate Mass Black Hole Binary Coalescences

3.10.1 Abstract

Intermediate Mass Black Holes (IMBHs) are conjectured to occupy the mass space between stellar-mass and massive black holes, roughly 100 to $10^5\,\mathrm{M}_\odot$. The coalescence and merger of IMBH binaries with masses of a few hundred solar masses is one of the promising sources of gravitational waves for Advanced LIGO and Advanced Virgo. A single detection of an IMBH binary merger would provide the first unambiguous proof of IMBH existence. Searches for these sources have already been conducted on data collected by the initial GW detectors during the S5/S6 and VSR1-VSR3 runs; no IMBH binaries were discovered. The established upper limits on the IMBH binary merger rates, $\sim 10^{-7}$ Mpc^{-3} yr^{-1} for binaries with $\sim 100\,\mathrm{M}_\odot$ companions, are a few orders of magnitude higher than the expected optimistic rates, $\sim 10^{-9} - 10^{-10}$ Mpc^{-3} yr^{-1}. Preliminary studies show that detection of a few IMBH binary mergers is plausible at advanced detector sensitivities.

3.10.2 Scientific Justification

Stellar-mass black holes, originating from core collapse of massive stars, have been observed in the mass range up to ~ 30–$50\,\mathrm{M}_\odot$. Massive black holes, exceeding $10^5\,\mathrm{M}_\odot$, appear to be generic in galactic centers. Intermediate-mass black holes (IMBHs) occupy the mass range between these two. IMBHs with a mass of a few hundred solar masses may generically exist in globular clusters [78, 79]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [80], or as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [81]. A large number of IMBH mergers may be a generic feature of some mechanisms of structure formation, although these are likely to occur at high redshifts [82]. IMBH binaries could also form as a result of evolution of isolated binaries with very high initial stellar masses [83].

No IMBHs in the mass range of interest ($\lesssim 1000\,\mathrm{M}_\odot$ for advanced detectors) have been detected so far. Thus, a single detection will be revolutionary, as it will prove unambiguously that black holes exist in the mass range between stellar-mass and massive black holes. IMBH binary detections will also serve as probes of globular cluster dynamics, and, potentially, as probes of structure formation and growth of massive black holes. IMBH binary measurements could also inform our understanding of the formation and evolution of the most massive stars. On the other hand, the lack of confident IMBH observations to date and the complexity of modeling the evolution of very massive stars mean that little is known about these objects. It is impossible to quote lower limits on the IMBH binary merger rate, which may, in fact, be zero.

If IMBHs in this mass range do merge in binaries, little is known about their mass distribution. However, we do expect that merger and ringdown will make a very significant contribution to the signal-to-noise ratio of observed gravitational waves from such systems, because most or all of the inspiral for massive systems will occur at frequencies below the detector band. Therefore, waveforms that include merger and ringdown phases, such as (S)EOBNR [84], will be necessary to accurately model IMBH binaries. Similarly, little is known about the spin distribution of IMBHs; they may have high spins, and because of the dynamical interactions likely involved in IMBH binary formation, the spins are likely to be misaligned, leading to precession.

We can very crudely estimate optimistic IMBH binary merger rate predictions as follows. For IMBH binary mergers in globular clusters, it is very unlikely to have more than $O(1)$ merger per history of globular cluster. The space density of globular clusters is approximately 3 Mpc^{-3}, and a typical cluster is about 10 Gyr old, leading to an upper limit on the IMBH binary merger rate of 3×10^{-10} Mpc^{-3} yr^{-1}. IMBH binary formation from very massive isolated stellar binaries in galactic fields could yield rates a few times higher than this, but there are many uncertainties. This optimistic rate is a factor of several hundred lower than the upper limits obtained in previous LIGO-Virgo searches [85].

A search for IMBH binaries would thus have a chance of yielding a detection once $\sim 3 \times 10^9$ Mpc$^3 \cdot$ yr (comoving volume $\cdot$ surveyed time). Assuming the $\sim$ 3$-$month O1 run operates at the high-sensitivity version of the early aLIGO noise spectrum, it will reach approximately this sensitivity, providing a chance of making the first IMBH detection. IMBH binaries with a "redshifted" mass of $M(1+z) \sim 260\,\mathrm{M}_{\odot}$ could be detected to a luminosity horizon distance of ~ 4.8 Gpc. Larger detection volumes are possible for spin-aligned systems.

Previous searches covering the IMBH binary parameter space included the coherent-WaveBurst search [86, 85] and the CBC ringdown search [87]. This search will have some overlap in mass space with the CBC search for binary black hole systems. The Burst all-sky search will also be sensitive to some IMBH binary mergers.

3.10.3 Search Description

IMBH binaries (IMBHBs) can be effectively searched for with both template (CBC) and unmodeled (Burst) techniques. We propose to carry out both types of searches over all data with two or more detectors operating in coincidence, starting with the O1 run, and combine the results of several pipelines into joint publications.

Due to the large binary mass ($\mathrm{M_T} > 50\,\mathrm{M}_{\odot}$), the IMBHBs merge at low frequencies ($f_{merger} \sim 1/\mathrm{M_T}$ < 200 Hz) and the IMBHB waveforms are dominated by the late inspiral, merger and ringdown phases. The IMBHB signals detectable by second generation GW detectors are relatively short, lasting less than a few seconds in band, which allows the use of un-modeled or weakly-modeled excess power (Burst) searches. The Burst searches do not require templates and provide a robust IMBHB detection, which is insensitive to the waveform uncertainties. Matched-filtering searches should be optimal under the assumption that the source waveforms are known perfectly. The requirements to both searches are discussed in §3.10.6.

The coherent WaveBurst (cWB) burst search is well established [3]. Two IMBHB burst searches have been performed with data from initial LIGO and Virgo [86, 85]. For the IMBHB search with Advanced Detector data the upgraded cWB pipeline (called CWB2G) will be used. The efficiency of the CWB2G pipeline to the IMBHB sources is expected to be comparable to the original cWB pipeline, with significant improvements in background rejection and computational performance. The CWB2G upgrade is nearly complete, the first stable version is available.

The CBC search has previously covered the total mass range above $50\,\mathrm{M}_{\odot}$ with ringdown-only template searches [87], while binaries with a total mass up to $100\,\mathrm{M}_{\odot}$ were searches for with full inspiral-merger-ringdown searches [88, 89]. Also, during Engineering Run 3, a successful search over the IMBHB mass parameter space was carried out with the inspiral-merger-ringdown templates via the streaming matched-filtering gstlal pipeline [90]. The gstlal pipeline is particularly relevant for advanced detector BNS searches, as it has been developed with long-duration templates and low latencies in mind. These features are not critical for the IMBHB search, where templates are relatively short and the low-latency detection is not an issue; however, other features of gstlal, such as accurate estimation of false alarm probability without the need for large numbers of time slides, are still relevant. Also, the ability of gstlal to search for binary black holes with aligned spins has been successfully demonstrated [91]. However, further work will be necessary (see §3.10.6) to tune the gstlal pipeline for IMBHB sources.

The results of these two searches will be combined by using the False Alarm Density (FAD) statistic [92], which has been already used in the burst IMBHB search [85]. This search will cover IMBH binaries with a total mass $\geq 50\,\mathrm{M}_{\odot}$ and a mass ratio $0.1 \leq q \leq 1$, where q is the ratio of the smaller component mass to the larger one.

3.10.4 Result validation plan

We will have two searches, the CBC gstlal search and the Burst cWB search, running on the same data. These are completely independent searches, and as such will provide the robust means for an independent validation of search results. While we do not require that both search pipelines find the candidate to be significant, the preferred signal interpretation (i.e., inferred signal parameters) and our studies of the relative sensitivity of the two searches will make it possible to determine whether the results are consistent with an astrophysical interpretation. Similarly, parameter estimation follow-up with the LALInference pipeline [93], a parameter estimation pipeline written with in the LAL library (see **??**), will provide an additional check on the candidate events.

3.10.5 Publication Plan

Any IMBH binary detection will be very exciting, since they are likely to be the first definitive proof of the existence of intermediate-mass black holes. Upper limits will, in general, be less informative than for other binary types, because of the uncertainties in formation scenarios. Therefore, the focus of this search is on detections. Rather than committing to a paper for every science run, we will publish a paper either when there is a single confident detection, an accumulation of one or more marginal detections before a break in detector operations, or a significant improvement over existing upper limits, as specified below.

Confident detection. In the case of a clear detection, such as the S6 blind injection with false alarm probability $\sim 7 \times 10^{-5}$, we aim to submit observational papers within 6 months of the first detection, and within 3 months for subsequent detections. Based on past experience, this timeline is contingent on the technical and resource requirements outlined in §3.10.6 and §3.10.7. The S6 blind injection manuscript, LIGO-P1000146-v16 [94], is a good model for what we expect from a first detection paper, including calculation of the event significance and estimation of the event parameters. Where necessary, subsequent collaboration papers may provide more details about the events, such as tests of general relativity carried out on these events.

Marginal detections. If one or more significant but not outstanding detection candidates, based on their false alarm probability, are found prior to a break in data collection, we will submit a paper describing the analysis and providing the details of any marginal candidates. This will include follow-up studies on these candidates. The goal is to submit this paper within 6 months of the end of data collection.

No detections. If there is a break in detector operations and the accumulated data allows us to significantly improve existing upper limits, either by lowering upper limits in previously covered regions of the parameter space by an order of magnitude or more, or by covering a previously unexplored region of parameter space, we will submit a paper with updated rate upper limits within 6 months of the end of data collection. This will be reduced to 3 months after the first joint upper limits paper.

In all cases, we will submit a single paper combining the results of all searches covering the IMBH parameter space and described in Section 3.10.3. Because of limited prior experience with such joint publications, we are budgeting for somewhat longer times for the first paper, to be reduced for future publications. Upper limit papers may include an overlap in the covered parameter space with other searches (e.g. the CBC BBH search); this would provide a confirmation of the sensitivity of different techniques.

3.10.6 Technical Requirements and Development Plan

Pipelines. Both the CWB2G and gstlal pipelines should satisfy general IMBHB analysis requirements: detect IMBHB sources with high efficiency comparable to an optimal matched filter and establish significance of detected events at the FAR level of 1 event per several thousands years. Both pipelines should be ready for the first aLIGO data taking runs as outlined in the Milestones, Table **??**. The gstlal algorithm requires validation that its template bank is covering the IMBHB mass parameter space and that there is no significant loss of efficiency due to the BH spins and spin precession. The CWB2G algorithm is much less dependent on the model of the IMBHB sources and provide a robust detection in the full IMBHB parameter space accessible by aLIGO. However, for both searches the waveform uncertainties may bias the estimation of the search sensitivity (range), source parameters, upper limits and measured astrophysical rates. The bias and the corresponding systematic errors due to the model uncertainties have to be estimated with the different waveform families. These studies should be performed as part of the mock data challenge (MDC), which will provide a platform for the end-to-end testing of the CWB2G and gstlal analysis infrastructure. The MDCs will also validate the application of the FAD statistic to combining the results of the two searches. Low-latency analyses and EM-follow-up are not of a high priority for the IMBHB search, since EM counterparts are not expected to accompany IMBH binary mergers. Therefore, the main analysis mode is offline. However, both pipelines are designed for the low-latency analysis and can be run online.

Waveforms. In general, the burst search does not require very accurate waveforms: the existing family of EOBNR waveforms is expected to be adequate for the burst IMBHB search. The CWB2G pipeline will allow for a robust (model-independent) estimation of the source parameters, such as sky location, polarization and total mass (by reconstructing the ringdown phase of the IMBHB merger). However, the CBC gstlal search and modeled parameter estimation require accurate waveforms. To estimate the CWB2G and gstlal detection efficiency and systematic errors due to waveform uncertainties, several waveform families will be used in the analysis, including SEOBNRv2, IMRPhenomP, and ROM surrogates.

Mock Data Challenges. To prepare for aLIGO/AdV runs, the Burst and CBC groups are using Mock Data Challenges (MDC), MDCs will be a critical component of testing prior to the first science runs. IMBHB injections into S5/S6/VSR1-3 noise recolored to aLIGO/AdV noise spectra are used to test pipeline performance and data analysis infrastructure. The pipeline performance is evaluated based on the False Alarm rate Density (FAD) figure of merit [92]. MDC studies serve to validate the performance of search pipelines on IMBHB injections and the FAD method for combining pipeline outputs.

Data quality. Data Quality is a critical-path issue for the IMBHB search. The IMBHB signal is expected at low frequencies ($\lesssim 100$ Hz), which are strongly affected by non-stationary instrumental and environmental noises. The IMBHB signal may have just a few cycles in-band, which makes it difficult to distinguish from noise glitches. A significant fraction of glitches can be rejected with the coherent network analysis (performed by CWB2G) or with template matching and signal-based vetoes (CBC analyses), but background rejection provided by the pipelines usually is not sufficient. For the initial detector data, the false alarm rate of the burst pipeline was dominated by the spike glitches — sine-Gaussian-like signals at frequencies below 200Hz with FAR of ~ 1 event per 30 years. The source of these glitches is not understood and it is likely that similar glitches will be present in the aLIGO data as well, affecting confident detection of GW signals. Therefore, interaction with the DetChar and commissioning groups and development of advanced detector characterization methods is critical for the IMBHB searches. As aLIGO/AdV sub-systems are commissioned, the Burst and CBC group will collaborate with the Detector Characterization and Commissioning groups to ensure the best data quality possible for the IMBH search.

3.10.7 Resources

Development and Simulation studies 3 FTEs are required for the development of the IMBHB searches and for the MDC studies. Of these, 2 FTEs are needed for simulations. This includes generating MDC data sets, running CWB2G and gstlal jobs, and analyzing the resulting triggers . This also includes post-processing the CWB2G and gstlal triggers and finalizing the statistical procedure for the estimation of trigger significance. The development needs are 0.1 FTE for CWB2G (studies of IMBHB-specific constraints) and 0.9 FTE for gstlal (finalizing the IMBH template bank and search statistic).

Analysis of aLIGO data 3 FTEs will be required to maintain and run the searches.

Detector Characterization & Data Quality As discussed in 3.10.6, data quality, particularly at low frequencies, is critical for the IMBHB search. We will work with the detector characterization and commissioning teams to identify and eliminate sources of transient noise at low frequencies. We will quantify the effect of these transients on our search sensitivity. One of the primary engineering run goals will be to develop the tools and techniques to effectively identify and mitigate glitches in the data. During data taking runs, we will examine the data on a daily and weekly basis for detector characterization. The IMBHB analysis will require 2 FTEs to carry out data quality studies.

Calibration requirements We will require calibrated data over the sensitive band of the detectors (from the low-frequency wall to 1kHz). Both Burst and CBC IMBHB search groups plan work together with the CBC waveform sub-group on simulating calibration errors to test calibration requirements.

Review We will need review teams for the following search components: IMBH-specific details of the search pipelines, post-production code for combining their results, waveforms (where not reviewed elsewhere) and parameter estimation (aspects specific to IMBHB parameter estimation – LALInference code has been reviewed and upgrades are continuously reviewed). Most of the review effort is not IMBHB specific; we do not anticipate that IMBHB-specific aspects of the review to require more than 0.5 FTE years. We expect that Data Quality and Calibration will be reviewed as part of the aLIGO baseline CBC BNS and Burst All-sky analyses.

3.11 Search for Eccentric Binary Black Holes

3.11.1 Abstract

Compact binary coalescences (CBC), containing some combination of neutron stars (NS) and black holes (BH), are the most promising sources for first detection with advanced gravitational wave (GW) detectors. Compact binaries formed from stellar binary progenitors, which have historically been considered the most probable sources, are expected to circularize due to gravitational-wave emission prior to reaching the sensitive band of advanced detectors. However, other types of dynamically formed CBC sources covering a large range of component masses, spins and eccentricities are also possible. For example, dynamically formed compact binaries may retain significant residual eccentricity when they enter the sensitive band of Advanced LIGO and Advanced Virgo. The inspiral and merger-ringdown (IMR) of these eccentric binary black holes (eBBH) may therefore be a promising candidate for gravitational-wave detection. A detection of these sources would provide information regarding the viability of several proposed dynamical formation mechanisms, and a measurement of the eccentricity would help discriminate among those scenarios. However, standard CBC searches using quasi-circular IMR waveforms from stellar-mass binaries will not detect these systems for eccentricities $e >\sim 0.05$ [95], so a dedicated search for these potential sources is required. The expected event rate for eccentric binary sources varies wildly, from a negligibly small event rate up to rates that exceed the expected rates for quasi-circular binaries. This uncertainty illustrates the underlying uncertainty in the astrophysics governing the various proposed formation mechanisms, and serves to justify a dedicated eBBH search exploring the CBC parameter space not covered by existing CBC searches.

3.11.2 Scientific Justification

The focus of previous gravitational-wave searches for compact-object (CO) binaries has centered on quasicircular systems, since gravitational waves are known to circularize binaries, and there is ample time to circularize if the system was formed from a stellar binary progenitor. However, more recent theoretical work has suggested that galactic nuclei and globular clusters may be promising settings for the formation of dynamical capture binaries. Since these systems can form with large eccentricities and very small initial separations, there is good reason to expect that a significant amount of eccentricity will remain when the binaries evolve into the Advanced LIGO (aLIGO) band. In galactic centers, mass segregation around the central massive BH can lead to large densities of stellar mass BHs. The Fokker-Planck model used in [96] suggests that our galactic nucleus should have ~ 2000 BHs and ~ 400 NSs in the central 0.1 pc. In [97, 98], the event rate for the formation of BH-BH binaries from GW capture in this setting was estimated to be between 0.01 and 1.0 yr^{-1} Gpc^{-3}, with corresponding Advanced LIGO detection rates of $\approx 1 - 10^2$ yr^{-1}. The formation of BH-NS binaries is estimated to be $\sim 1\%$ of this rate [97].

Dynamical capture binaries may also form in globular clusters (GCs) that undergo core collapse [99, 100]. In [101], it was estimated that binary formation through tidal capture would result in a NS-NS tidal capture rate that would peak at ~ 50 yr^{-1} Gpc^{-3} at $z = 0.7$, falling to ~ 30 yr^{-1} Gpc^{-3} by $z = 0$. They also provide a scaling to BH-NS and BH-BH mergers which gives rates that peak at ~ 70 yr^{-1}Gpc^{-3} and ~ 20 yr^{-1}Gpc^{-3} for BH-NS and BH-BH mergers, respectively.

There is also the possibility that eccentric mergers could result from hierarchical triples through the Kozai mechanism. This has been suggested to occur in BH-BH mergers in GCs [102, 103, 104] and CO mergers around supermassive BHs in galactic nuclei [105], as well as in coevolved or dynamically formed BH-NS or NS-NS binaries [106]. Efforts to understand this mechanism in the general-relativistic regime are ongoing (see e.g. [107]), and the event rates of these systems are not well known (though see [108]).

To estimate the fraction of dynamical capture binaries that retain high eccentricity, we first note that the relationship between impact parameter b and pericenter distance r_p is $r_p \approx b^2 v^2/2M$. In other words, the cross section $\sigma \propto b^2$ scales *linearly* with r_p, rather than quadratically as one might expect. If the initial periapse is $r_{p,i}$, and we consider the repeated burst phase to end at a periapse of $r_{p,f}$ with eccentricity e_f, then from [109], $r_{p,i} \approx 0.57 r_{p,f}(1+e_f)e_f^{-12/19}[1+O(e_f^2)]$. For example, if a binary with $e_f > 0.1$ by $r_{p,f} = 10M$ can be considered to have a significantly eccentric inspiral phase, then this corresponds to all systems with $r_{p,i} < 27M$. In galactic nuclei, this is between 60% and 80% for mass ratio $q = 1 - 0.1$, so the majority of systems from the aforementioned rate estimates will have significant eccentricity with a repeated burst phase occurring in band. This fraction is significantly lower in globular clusters due to the smaller velocity dispersion, such that more systems will form with large periapses.

For all of these scenarios, the event rates for Advanced LIGO are very uncertain, and range from effectively zero to exceeding the predicted event rate for quasicircular binaries. A null result will significantly constrain the efficiency of the aforementioned mechanisms, and the fact that a very large event rate remains a viable possibility necessitates a concerted effort to search for these specific signals.

3.11.3 Search Description

The purpose of the eBBH search is to explore the CBC parameter space not covered by the CBC searches planned for aLIGO. One possible approach would be to extend the CBC template banks to cover the corresponding part of the eBBH parameter space. Such template bank should cover not only eccentric waveforms, but spinning waveforms as well, because many anticipated sources are binary black holes where the spin effects can be significant. This is a very challenging task, which is unlikely to be realized in the immediate future. Therefore, the eBBH search will be conducted with the cWB2G burst pipeline, tuned for eBBH sources. This tuning is required for improving the cWB2G performance for low mass eBBH sources, which could be formed dynamically in galactic nuclei. Typical total masses for such binaries are expected to be in the range of 5 – 100 $M_\odot$. GW signals from more massive BH-BH systems are dominated by the merger and the ring-down phases where the effects of eccentricity are less important and the detection of such sources is covered by the IMBBH burst searches. The cWB2G IMBBH search should efficiently detect high mass systems even if they retain residual eccentricity.

After the cWB search pipeline identifies and reconstructs candidate signals, we will also apply parameter estimation algorithms to characterize the source parameters. Such source characterization is critical in the eBBH search to understand the eBBH formation mechanism. For example, if the event followup analysis reveals that there are repeating bursts before the BH-BH merger and/or multi-chirp structure (high-order modes), this would be a signature of a highly eccentric binary formed dynamically in a galactic nucleus. The cWB2G pipeline already has a chirp reconstruction algorithm implemented, which needs to be extended for reconstruction of multi-chirp signatures.

Apart from the minor algorithmic details and different tuning strategy, the eBBH analysis uses the same search algorithm as the All-sky and IMBBH searches, which are extensively validated with the other search pipeline: Omicron+LIB and GSTLAL respectively. Also, for validation of the eBBH candidates and better parameter estimation the BayesWave pipeline will be used. BayesWave coherently models transient events in LIGO data as a linear combination of wavelet basis functions [110]. The number of basis functions needed in the analysis is a parameter of the model and is determined through Bayesian model selection. BayesWave calculates relative probabilities that excess power in the data is due to a gravitational wave or an instrument artifact, In addition, for the signal model, BayesWave provides parameter estimates. The most basic implementation of BayesWave uses a uniform prior in the time-frequency plane for the location of basis functions and has shown promise in standard burst analyses in S6/VSR2 and ER5 data. The sensitivity of BayesWave can be improved by adopting more informative priors in the time-frequency location of wavelets, which are motivated by a particular signal morphology, such as eBBH signals. Numerical evolutions of eBBH waveform models provide predictions for the time-frequency locations of GW bursts emitted at pericenter passages. While the simulations are not accurate enough to construct templates for matched filtering, they are ideally suited as priors for signal recovery in BayesWave [111]. Ultimately, we will use the $f(t)$ predicted by these simulations to guide where in time-frequency new wavelets can be added to the signal model resulting in a “happy medium” between an eyes-wide-open burst search and a strict template-based matched filtering analysis, but initially, we will use leading order expressions for $f(t)$ [109]. The $f(t)$ track itself is a function of the eBBH system parameters. By simultaneously varying the track parameters along with the basis functions in the model, we will simultaneously produce estimates for the physical parameters of the system such as mass, spin, and eccentricity. A proof of concept study using $f(t)$ priors from post-Newtonian waveforms to perform dedicated analysis of CBC signals and provide estimates of the binary mass and spin parameters using BayesWave is under way [112] and is naturally extensible to eBBH searches.

3.11.4 Publication Plan

The eBBH search covers the same mass parameter space as the high-mass CBC BH-BH search. However, it will be sensitive to a wider class of BH-BH sources with arbitrary spins and eccentricities. The eBBH publication plan is described below and depends on the possible outcomes of both searches.

Confident detection. In the case of a clear detection with a false alarm probability of 10^{-4} or lower, we aim to submit a paper within 6 months of the first detection, and within 3 months for subsequent detections. It will be an observational paper, if the event is not observed (or observed with low significance) by the CBC BH-BH search. In the event that the same circular BH-BH events are observed by both the eBBH and CBC BH-BH searches, we aim to write a followup paper to the CBC detection. Based on past experience, this timeline is contingent on the technical and resource requirements outlined in §3.11.5 and §3.11.7. Where it is necessary, subsequent collaboration papers may provide more details about the events and their refined astrophysical interpretation.

Marginal detections. If one or more significant, but not outstanding, detection candidates (false alarm probability $\sim 10^{-3}$) are found prior to a break in data collection, we will submit a paper describing the analysis and providing the follow-up studies of any marginal candidates. The goal is to submit this paper within 6 months of the end of data collection.

No detections. If there is a break in detector operations and the accumulated data allows us to significantly improve the existing upper limits, we will submit a paper with the updated rate upper limit within 6 months of the end of data collection.

3.11.5 Technical Requirements and Development Plan

There are two main technical requirements for a successful execution of the eBBH search: a) confident detection of BH-BH sources with a wide range of source eccentricities and spins and b) reconstruction of BH-BH sources and unambiguous identification of eBBH signatures.

The first requirement is satisfied by using the cWB2G pipeline, which is proven to be sensitive to eBBH sources. However, additional optimization of the cWB2G eBBH analysis will be necessary to improve the detection of eBBH sources. To capture long eBBH waveforms, the cWB2G pipeline extracts principal components from the multiresolution time-frequency data. Currently, the extraction of principle components is sub-optimal and needs improvement. Also, the reconstruction of the binary chirp mass provides a powerful selection cut for background rejection. The current reconstruction procedure needs to be updated to account for the higher chirp modes (multi-chirp) in the eBBH signal.

The second requirement is important to understand the astrophysical origin of detected events. Both the cWB2G and BayesWave need to be updated to be able to identify the multi-chirp structure of detected waveforms, provide measures of eccentricity and spins, and identify the trailing sequence of periodic bursts typical for dynamically formed binaries with large in-band eccentricities. In the case of BayesWave, a prior on $f(t)$ that uses leading-order expressions for eccentric binaries will be implemented and tested, to estimate the size of parameter biases that result from using a lower-order prior to model injected signals that contain higher order contributions. This study will be completed in advance of O1. Beyond O1, development will be required to implement our knowledge of higher order contributions to $f(t)$ in the prior calculation performed in BayesWave.

Implementing a search that can address all of the aforementioned astrophysical questions will require improvements to the existing model for binary black-hole systems on orbits with arbitrary eccentricity. The model that has recently been implemented within lalsimulation [113] is a frequency domain model that is capable of generating faithful frequency-domain inspiral waveforms for BNS sources with $e < 0.4$ at 10 Hz. The range of eccentricity over which this model can provide faithful templates increases with the total mass of the binary, so that, for instance, a $(6+6)\mathrm{M}_\odot$ BH-BH binary can be modeled faithfully for $e < 0.6$ at 10 Hz. This version of the code will be stress tested through simulations across the relevant parameter space and comparison with existing models in the appropriate limits, and then it will need to undergo code review. The code will then be used for generation of eccentric injections to assess the sensitivity and performance of cWB and BayesWave (as well as any other existing search pipelines) to the eccentric regime.

For BH-BH sources with larger masses, the late inspiral and merger-ringdown portions of the waveform contribute nonnegligibly to the amount of available match-filtered SNR within the band. For this reason, a key area of model development will be the development and implementation of a frequency-domain merger-ringdown waveform. The merger-ringdown model will be a frequency-domain version of a separate, time-domain model for sources with large eccentricities that has already been used to test and tune the cWB2G pipeline [111]. By improving the accuracy of the inspiral model at ever larger eccentricities through the inclusion of higher order post-Newtonian effects, and the addition of an accurate merger-ringdown model that can be attached to this (or, in principle, to any other) inspiral model, we plan to maximize the range of source eccentricities and masses that can be faithfully approximated with a single waveform model.

The suggested waveform model has been optimized for speed and it is a natural candidate for use as a template generator for CBC search algorithms like gstlal. Also we will investigate other approaches for EBBH detection, such as nested sampling [114]. However, nested sampling and the development of eBBH templates that span the full range of possible eccentricities and masses are the longer term projects with an uncertain time scale.

3.11.6 Milestones

Both cWB2G and BayesWave will be ready for the O1 all-sky analysis. The same software is used for the eBBH analysis. However, our plan is to conduct the full eBBH analysis starting with the O2 run. There are two reasons for that: a) for the two-detector Livingston/Hanford network there are small differences between the ALLSKY and the EBBH cWB2G settings. These searches become significantly different when the Virgo detector joins the run, and b) the eBBH simulation work may not be finished before O1.

3.11.7 Resources

Development and Simulation studies 2 FTEs are required for the development of the eBBH search and for the MDC studies: 1 FTE to run cWB2G analysis and 1 FTE to run BayesWave. This includes generating MDC data sets, running CWB2G and BayesWave jobs, and analyzing the resulting triggers . The development of CWB2G is complete. The development of BayesWave is nearly complete. The remaining development items are reconstruction of eBBH waveforms in BayesWave, demonstration of reconstruction of the eBBH signals with BayesWave, and review of both algorithms will be finished before the O1 run. An additional 1 FTE is required for development of eBBH templates that can be used by the gstlal pipeline.

Analysis of aLIGO data 2 FTEs will be required to maintain and run the eBBH cWB2G search and the BayesWave followup.

Detector Characterization & Data Quality As with other burst searches, the data quality (DQ) is critical for the eBBH search. Most of the DQ work will be conducted in the scope of the all-sky and IMBBH searches. No additional DQ resources are required for the eBBH search.

Calibration requirements We will require calibrated data over the sensitive band of the detectors (from the low-frequency wall to 1kHz). The eBBH calibration requirements are the same as for the cWB IMBBH search and they are investigated as part of the IMBBH search proposal.

Review The analysis software used in the eBBH search is reviewed as part of the all-sky and IMBBH proposals. The review of the cWB2G pipeline is in progress and will be completed in early 2015. The BayesWave review has start in the end of 2014. We expect that the majority of the analysis will be reviewed prior to the beginning of the O1 run. The additional review items include the eBBH-specific details of the analysis (both in cWB2G and BayesWave) and the review of the existing frequency domain inspiral eBBH waveforms. It is envisioned that the review of all of the additional components could begin in the second half of 2015. We expect that Data Quality and Calibration will be reviewed as part of the aLIGO baseline CBC BNS and Burst All-sky analyses.

3.12 Search for Intermediate-mass-ratio Coalescences

3.12.1 Abstract

There is some observational evidence that intermediate mass black holes (IMBHs), with mass in the range 100–$1000 M_\odot$ may be present in globular clusters. In these dense stellar environments, encounters between the IMBH and other stellar objects in the cluster could lead to the capture of a compact object and the formation of a binary with mass ratio of $1 : 10$ or smaller. The subsequent gravitational-wave driven inspiral and merger of the compact object with the IMBH could generate gravitational waves detectable by Advanced LIGO and Advanced Virgo. These systems are usually referred to as intermediate-mass-ratio inspirals (IMRIs) in the literature, and we will refer to them as IMRIs in the following, but we have used "coalescence" in the search title to emphasise that the merger and ringdown phases could also contribute significantly in the LIGO/Virgo band. The event rate for IMRIs is highly uncertain, given the uncertainty in the number density of IMBHs in particular. However, the IMRI rate could be comparable to or higher than the rate of IMBH-IMBH mergers. Detection of a single IMRI could provide the first direct proof of the existence of IMBHs and constraints on their number density. Any observations would have profound implications for our understanding of black holes and the evolution of globular clusters, since these systems are currently highly speculative and virtually unconstrained observationally. These systems also have strong potential as probes of fundamental physics. A search for these sources poses various complications, which is why they require a dedicated analysis. They lie outside the usual parameter range of current searches, the sources sweep through a relatively narrow range of frequencies, and the systems lie in a regime where accurate modelling of the gravitational waveforms is particularly difficult. However, several approximate models of IMRI signals have been proposed in recent years which can now be used to assess the efficiency of pipelines. Given the uncertainty in waveform modelling, we propose to use both burst and template based search techniques. We will use the coherent WaveBurst [3] with tuning for the appropriate mass range and a template based search with gstlal [90]. The performance of both techniques will be assessed using the best available models in the IMRI mass range.

3.12.2 Scientific Justification

There is some observational evidence that IMBHs of a few hundred solar masses may exist generically in globular clusters [78, 79]. Various scenarios have been suggested for IMBH formation in these environments, including the runaway collision of massive stars, mergers between stellar-mass black holes that sink to the centre of globular clusters through mass segregation, gas accretion onto a black hole seed early in the cluster's lifetime or direct collapse of low-metallicity pop-III stars. Numerical simulations suggest that in the dense environments of globular clusters, IMBHs could merge with many compact objects over their lifetime. After dynamical capture, an IMBH-compact object binary is hardened through three-body interactions with other stars in the cluster until it becomes sufficiently hard that gravitational-wave emission takes over and drives the binary to coalesce [115]. This gradual hardening mechanism means that the binary is likely to have sufficient time to circularize. In [115], an upper limit on the Advanced LIGO IMRI rate of $\sim 30\text{yr}^{-1}$ was estimated, with more realistic rates of ~ 1 every 3 years if the inspiraling compact objects are primarily $\sim 1.4 M_\odot$ neutron stars or ~ 10 per year if the typical compact object is a $\sim 10 M_\odot$ black hole. More recently, the discovery of several very massive stars in the Large Magellanic Cloud has indicated that IMBHs do not necessarily need a dense stellar environment to form [83], opening up a possible new channel for IMRI formation.

The observation of one or more IMRIs would have significant astrophysical implications. The detection of an IMBH in an IMRI (or IMBH-IMBH binary) would provide the first direct evidence for the existence of black holes in the intermediate-mass range. This would have profound implications for our understanding of stellar evolution in the dense environments of globular clusters, which are the most likely hosts of such black holes. The rates of IMRI events and the parameters of the observed systems encode information about the physical processes occurring in globular clusters and the relative efficiency of the sequence of segregation, capture and hardening that most likely gives rise to IMRI events. In addition, IMRI sources can be used as probes of fundamental physics, in particular to test the no-hair property of the IMBH [116, 117]. A $1.4 + 100 M_\odot$ non-spinning IMRI system generates approximately $340/85/5$ waveform cycles between a frequency of $10/20/40$Hz and plunge, throughout which time the compact object is within $8/5/3.5$ Schwarzschild radii of the IMBH [118]. These strong-field waveform cycles encode a map of the strong-field space-time structure just outside the horizon of the IMBH which can be used to verify that the multipole structure of the spacetime obeys the no-hair theorem expected for Kerr black holes in general relativity. We note that, although the detection of an IMRI event is extremely uncertain, due to the very uncertain number density of IMBHs in the Universe, the scientific pay-off both for astrophysics and for fundamental physics of just one IMRI observation would be immense.

There are several reasons for having a dedicated IMRI search, rather than subsuming this search into one of the existing CBC or burst searches. IMRIs are outside of the parameter space included in conventional inspiral searches. The mass ratios and chirp masses are much smaller than usually considered in the CBC high-mass search and in the proposed IMBH-IMBH binary search. The templates are also much longer than IMBH-binary templates due to the lower mass ratio. Spin effects are likely to be more important for IMRIs as all of the observed cycles will be in the strong-field regime where spin effects are most important. The size of precessional effects will be suppressed due to the low mass ratio, but these will accumulate over the large number of observed waveform cycles and so it might also be necessary to use precessing templates. Therefore, an IMRI CBC search will require the construction of a dedicated template bank. An additional complication for the IMRI search is that IMRI waveforms are difficult to model, lying between near-equal mass systems that can be described by PN and numerical waveforms and extreme-mass ratio systems that can be described by perturbation theory. An IMRI search will have to tolerate greater uncertainty in the templates than other searches. A dedicated IMRI burst search will also be required since the necessary background rejection strategy will be different for IMRIs than existing burst searches for higher chirp mass systems.

Given that both the prospects for IMRI detection and the scientific pay-off of any IMRI observations are significantly enhanced by a lower low-frequency cut-off and that significant effort is required to realise this search we propose to have this search ready for O2 [119]. We plan to run a version of the search, with all the most up-to-date reviewed code available, in O1 as a detection search only. If an event candidate is identified it will be followed up, but if not we will not plan to publish an upper limit since any pipeline used in O1 will not be optimised.

3.12.3 Search Description

We will use both template based searches (gstlal) and burst search techniques (cWB) to identify candidate signals. These will be followed up using parameter estimation codes in LALInference for IMRI waveform models. The template based search will employ a dedicated IMRI template bank, covering the relevant parameter range and tuned to be effective for IMRIs. This search will cover binaries with a total mass $\geq 20\,\mathrm{M}_\odot$ and a mass ratio $0.1 \geq q$, where q is the ratio of the smaller component mass to the larger one; the lowest companion mass we will include is $1\,\mathrm{M}_\odot$, while the upper mass cutoff will depend on the sensitivity of the detectors. The lower cut off in total mass was chosen to ensure a sufficient overlap with other CBC searches so that no events are missed, but not too much overlap. While a $20\,\mathrm{M}_\odot$ black hole is not an IMBH, if such a black hole merges with a neutron star the mass ratio is ~ 0.05, which is in the IMRI range where no numerical simulations are available and therefore is subject to the same modelling uncertainties that will be the focus of much of the IMRI search development. It is highly likely that it will be necessary to include spin effects in the templates. Theoretical work suggests that in the IMRI range the spin of the larger object is very important and, while the effect of the spin of the smaller object is instantaneously suppressed due to the small mass ratio, the effect of precession accumulates over the large number of observed waveform cycles and therefore precessing templates may be needed [120, 121]. The template bank will therefore ultimately need to employ non-precessing spinning waveform models to increase coverage and it may even be necessary to use a precessing waveform model. Nonetheless, non-spinning waveform models should provide some sensitivity in the IMRI range and since such models are already reviewed and available we will use these initially. As more complex waveform models become available these will be used to improve the search and assess the effectiveness of the simpler templates. To cover the IMRI parameter range using TaylorF2 3.5PN templates with a low frequency cut-off of 10 Hz requires $\sim 50,000$ templates (estimated using $pycbc\_geom\_nonspinbank$, though stochastic template bank placement will probably be used for the actual search). Using this template bank with EOBNRv2 non-spinning templates and injections has been shown to be effectual. However, this number will change as investigations into the necessity of including spin effects are completed. Nonetheless, the IMRI parameter space should be coverable with $O(10^5 - 10^6)$ templates, which could be pre-computed if necessary. In addition, the templates will be considerably shorter than binary-neutron star templates due to the higher primary mass which will make the evaluation of this bank computationally much simpler. The IMRI template search may also require the use of a more relaxed chi-squared veto to allow for waveform uncertainties. Understanding these issues is part of the development plan described below.

The burst search will be needed to pick up events that the gstlal search misses, for instance due to the use of poor waveform models. The burst search will use cWB to identify triggers in the usual way, but background rejection will be tuned for the IMRI parameter range using the best available IMRI models for injections (see waveform discussion in “Technical Requirements” section). The additional costs of the IMRI search with cWB are small as it will borrow from the all-sky and IMBH binary searches (see computational requirements below). We will use both burst and inspiral pipelines to improve coverage and handle uncertainty. The short duration of IMRI signals for the highest mass systems in the early Advanced LIGO era will make a burst search quite sensitive to these systems, but they will be less sensitive to the longer inspirals expected for lower mass IMBHs and IMRIs observed in later science runs. The current uncertainty in IMRI waveforms also means that the template based search will potentially not be as effective, as the templates could have moderately large mismatches with astrophysical signals. The results of these two searches will be combined by using the False Alarm Density (FAD) statistic [92], which has been already used in the burst IMBHB search in initial-detector data [85], and is being developed as a technique for combining Burst and CBC searches as part of the joint CBC and Burst IMBHB search.

Parameter estimation follow-up will use the LALInference parameter-estimation pipeline and IMRI waveform models included in LAL. Robustly identifying an event as being an IMRI will require measurement of the mass ratio. This parameter should be measured more precisely in the IMRI range than it is for more comparable mass systems due to the large number of observed strong-field waveform cycles [122]. IMBHB parameter estimation has been demonstrated to mass ratios of 1:10, on the edge of the IMRI range [123], and there have been some (unpublished) efforts to extend this further into the IMRI range. However, this was only preliminary work for a very small number of mass ratios, spins and other parameters, so further work will be required to explore the efficiency of parameter estimation codes and the likely precision of parameter estimation over the full parameter space of IMRIs. Current work has also ignored the effects of waveform uncertainty which must be understood. This will be handled by performing inference with multiple waveform models or using uncertainty-marginalisation techniques currently under development.

The search for IMRI-like triggers will be applied to all data. Neither the cWB search nor the inspiral search is expected to be particularly computationally demanding so this should be possible in practice.

3.12.4 Result validation plan

We will have two searches, the CBC gstlal search and the Burst cWB search, running on the same data. These are completely independent searches, and as such will provide the robust means for an independent validation of search results. While we do not require that both search pipelines find the candidate to be significant, the preferred signal interpretation (i.e., inferred signal parameters) and our studies of the relative sensitivity of the two searches will make it possible to determine whether the results are consistent with an astrophysical interpretation. Similarly, parameter estimation follow-up with the LALInference pipeline [93], a parameter estimation pipeline written with in the LAL library (see **??**), will provide an additional check on the candidate events.

3.12.5 Publication Plan

We aim to have an IMRI search operating during O1 on a best-effort-available basis, to facilitate serendipitous discoveries. No upper limits will be published until all elements of the search have been fully developed and the impact of waveform uncertainties in particular has been properly understood. We aim to have a full IMRI search operating in O2.

Confident detection. If we have a confident detection of a system with IMRI-like mass and mass ratio, which has been followed up using parameter estimation codes, this will be a significant astrophysical result. In the case of a clear detection, such as the S6 blind injection with false alarm probability $\sim 7 \times 10^{-5}$, we aim to submit observational papers within 6 months of the first detection, and within 3 months for subsequent detections. We will publish a detection statement and parameter measurements, including both statistical and systematic uncertainties. The former include any parameter degeneracies intrinsic to these systems, while the latter arise from waveform model uncertainties.

Marginal or no detections. If only marginal candidates (defined as events with false alarm probability above some threshold, say 10^{-4}) or no candidates are found then we we will submit a paper describing the analysis, providing the details of any marginal candidates and an upper limit. The first paper will be based on a minimum of 6 months of data and the analysis will be performed only after the IMRI search has been fully implemented and reviewed. There will be an additional requirement that the sensitive volume of the IMRI search is at least a factor of ten better than the part of the IMRI parameter space covered previously (e.g., [88]). The paper will be submitted within 6 months of the search review being completed. Subsequent improved upper limits will be published if there is a break in detector operations and the accumulated data allows us to significantly improve existing upper limits, either by lowering upper limits in previously covered regions of the parameter space by an order of magnitude or more, or by covering a previously unexplored region of parameter space. For these subsequent papers, we will submit a paper with updated rate upper limits within 3 months of the end of data collection (or 6 months if previously unexplored regions of parameter space have been added). In the absence of detections from the IMBH binary searches, we would consider a joint upper limit paper from the two searches since both contribute statements about the number density of IMBHs and their environments.

3.12.6 Technical Requirements and Development Plan

The development of an IMRI search will have various elements. The inspiral search and any parameter estimation follow-up will rely on the existence of templates for IMRI waveforms. IMRIs are very difficult to model, as they spend many cycles in the strong-field regime, which makes post-Newtonian and numerical techniques inappropriate, but have mass ratios that are too large for perturbation theory to be applicable [124]. Several waveform models are now available which make predictions in the IMRI range — EOBNR(v2) [125, 126], SEOBNR(v2) [127], Huerta & Gair [122], Callister & Gair [128], etc. While none of these models are likely to be correct, they will capture the main features of IMRI waveforms and the differences between the models will be characteristic of the size of the difference between astrophysical IMRI waveforms and any one of these models. A necessary first-step to understanding the effect of waveform uncertainties on IMRI searches is to have multiple models available for injections and templates, extending the analysis of [129] to explore the impact of waveform uncertainty on the χ^2 veto as well as the effectiveness of parameter-space coverage. Implementation of these models in LAL has begun; in particular, Callister & Gair waveforms can now be used in LAL.

The only developments required for the cWB IMRI search are in the tuning of post-processing of triggers to reject background efficiently in the IMRI regime. This will be done using each of the IMRI models to understand the impact of waveform systematics.

For the template-based search in gstlal several developments are needed:

- Construct template banks in the IMRI range. Test their efficiency for IMRI detection.
- Explore which waveform models are needed. In particular, is it necessary to use a precessing-waveform template bank? Can template banks constructed for one of the IMRI waveform models detect injected IMRIs described by one of the other models?
- How much do standard vetoes reduce our search efficiency in the IMRI range and how do we modify them to recover the lost efficiency? For instance, an uncertain waveform may have a poor effective SNR or fail a χ^2 test as the model will not perfectly match the data. Tuning of the detection statistic may be required to optimise search efficiency.
- Tune the gstlal pipeline in the IMRI range to maximise the detection efficiency.

For parameter-estimation of IMRI systems, studies of the effectiveness of existing PE codes within LALInference for the characterisation of IMRIs are needed. Tuning of theses pipelines for the IMRI parameter space may be required. The best way to include systematic uncertainties from waveform differences in parameter estimates must also be investigated. This is particularly important for IMRIs, given the uncertainties that exist in our understanding of IMRI models. The development of techniques for folding such uncertainties into parameter estimates is underway and will be used here. The utility of template-free parameter estimation techniques, such as STAMP or BayesWave, to characterise IMRI signals, will also be explored.

3.12.7 Resources

Some of the challenges of developing the joint matched filtering and unmodeled search for IMRIs are the same as those for the IMBH binary coalescence search. Since that search is at a further stage of development at the time of writing, we rely on the Intermediate Mass Black Hole (IMBHB) search preparation to address some of the common challenges, such as using the False Alarm Density statistic to combine Burst and CBC search results. The resources required here are therefore only additional resources *on top* of those requested in the IMBHB search plan.

Development and Simulation studies The biggest challenge for the IMRI search is producing credible waveforms in the IMRI regime and assessing the accuracy of existing waveforms.

Detector Characterization & Data Quality Data quality, particularly at low frequencies, is critical for the IMRI search. As discussed in 3.10.6, we will work with detector characterization and commissioning teams to identify and eliminate sources of transient noise at low frequencies.

Calibration requirements We will require calibrated data over the sensitive band of the detectors (from the low-frequency wall to 1kHz). We will need to confirm that IMBHB calibration requirements are sufficient for IMRI searches. Following this, we will provide more detailed feedback to the calibration team on the level of calibration accuracy required for the IMRI search. The desired calibration should be available for the analysis shortly (1-3 months) after the beginning of each science run.

Review We will need review teams for the following search components: IMRI-specific details of the search pipelines, post-production code for combining their results, waveforms (where not reviewed elsewhere) and parameter estimation (aspects specific to IMRI parameter estimation – LALInference code has been reviewed and upgrades are continuously reviewed). We expect that Data Quality and Calibration will be reviewed as part of the aLIGO baseline CBC BNS and Burst All-sky analyses.

3.13 High-energy Neutrino Multimessenger Analysis

3.13.1 Abstract

Some dynamical processes with strong gravitational-wave (GW) emission, such as compact binary mergers or stellar core-collapse with rapidly rotating cores, can drive relativistic outflows that result in the emission of high-energy neutrinos. Detecting both messengers from a common source would provide the unique opportunity to develop and fine-tune our understanding of the connection between the central engine, its surroundings, and the nature of relativistic outflows. A joint search also increases the sensitivity compared to GW-only or neutrino-only searches, and can be especially interesting for sources that are difficult to detect electromagnetically.

We present the plans for the multimessenger search for GWs and high-energy neutrinos using the advanced LIGO - advanced Virgo network (c.2015+) as well as the IceCube detector. This search targets (i) GW bursts of any form, without restriction to a particular signal type, as well as (ii) GWs from compact binary mergers, both in coincidence with one of more high-energy neutrinos. The presented search plan closely follows the GW+neutrino multimessenger search performed for initial detectors. It will combine the time of arrival, significance and point spread function from neutrinos and GWs, along with a blue-luminosity-based weight and direction of galaxies in the local universe, to determine the significance of multimessenger event candidates.

3.13.2 Scientific Justification

Many of the most violent and interesting phenomena producing GW transients are also thought to be sources of high-energy neutrinos [130, 131, 132, 133, 134, 135]. These non-thermal, GeV-PeV neutrinos neutrinos are thought be produced in relativistic outflows driven by central engines also responsible for GW emission [136, 137, 138, 139, 140, 141, 142, 143]. The progenitors of both long and short gamma-ray bursts (GRBs), core-collapse supernovae with rapidly rotating cores, and highly magnetized neutron stars (magnetars) are thought to produce GWs and high-energy neutrinos that may be detectable out to relevant distances [135]. A particularly interesting development is the recent detection of astrophysical PeV-energy neutrinos [144], which will be an important science target for multimessenger observations.

Studies indicate that multimessenger searches with advanced detectors will be able to probe the characteristic parameter space for GRBs [134]. For compact binary mergers, which are the likely progenitors of short GRBs, we expect GW emission detectable out to $\sim 450\,$Mpc for optimal direction and orientation, and even farther for BH-NS mergers, with advanced detectors at design sensitivity. Core-collapse supernovae with rapidly-rotating cores, which are the likely progenitors of long-GRBs, low-luminosity GRBs and choked GRBs, may be detectable out to $\sim 200\,$Mpc upon the emission of $10^{-2}\mathrm{M}_\odot \mathrm{c}^2$ via, e.g., non-axisymmetric instabilities of the millisecond proto-NS that forms upon core-collapse. Neutrino emission is uncertain, but is expected to be comparable to the observed gamma-ray emission of $\sim 10^{51}\,$erg for some sub-photospheric and collisionless shock models.

Search results can be used to constrain joint emission models [134]. Upon non-detection, the source rate will be constrained to a rate comparable to or below the core-collapse supernova rate of $\sim 10^5 - 10^6\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for characteristic emission parameters (above). The expected rate of joint GW+neutrino sources will probably be between the core-collapse supernova rate and the rate of long GRBs.

There are multiple scientific benefits of simultaneously observing GWs and high-energy neutrinos from a common source: (i) The combined information from GW and high-energy neutrino observatories can greatly enhances our confidence in a joint detection [130, 131, 132, 133, 134, 135, 145, 146]. (ii) GWs and high-energy neutrinos both carry information from the depth of their source that is, to a large extent, complementary to the information carried by electromagnetic radiation. While the GW signature of cosmic events is characteristic of the dynamics of their central engine, a high-energy neutrino flux is reflective of the presence of hadrons in the relativistic outflow generated and driven by the central engine. (iii) The emission of high-energy neutrinos is tightly connected to the creation of high-energy photons (gamma rays) by the outflow. There are specific cases in which the source optical thickness is large and prevents the gamma-rays from leaving the source. One of the most interesting prospects of joint GW - high-energy neutrino searches are common sources that are dark in gamma rays. Prominent sources of this type are choked GRBs [138, 147, 148] or low-luminosity GRBs. These sources are difficult to detect with electromagnetic observatories, and hence provide an exciting opportunity to joint GW+high-energy neutrinos searches that can discover them and/or constrain their population [133, 134, 146].

The IceCube neutrino detector [149], from which reconstructed neutrinos will be taken for the joint search, is already under operation, and will be in operation during ADE. Additionally, IceCube is planned to be extended during early ADE, and will be operating with further increased sensitivity.

The ANTARES neutrino detector operates in its complete configuration since mid 2008. It will be in operation during the currently planned period for O1 (end of 2015). It will cease operation in 2016 and will be gradually superseded by KM3NeT. KM3NeT is currently in its construction phase 1 aiming at 24 and 7 lines installed close to Sicily and Toulon respectively. Phase 1 should be completed in 2016. Few lines of KM3NeT could be operating already end of 2015. The ANTARES/KM3NeT detectors will also be used for joint searches.

In short, GW+high-energy neutrino observational results have already proved to produce exciting scientific results [134, 145], while the projected constraints [134] and expectations (e.g., [150]) suggest that multimessenger GW+high-energy neutrino searches will be a fruitful direction of research during ADE.

3.13.3 Search Description

The multimessenger GWHEN pipeline aims to identify GWs and neutrinos emitted from a common transient source. It uses GW event candidates identified by searches in LIGO-Virgo data, and neutrinos identified by IceCube or other neutrino telescopes. The goal is to find GWs and neutrinos of common origin. In the initial detector era, a multimessenger search pipeline was developed to search for temporally and directionally coincident GW and neutrino signals [151, 133, 146]. The search pipeline additionally allows for the use of galaxy catalogs, as many of the target phenomena are expected to be occurring from within or near galaxies other than the Milky Way. Other astrophysical catalogs or distributions also present an interesting option, while general all-sky searches are also important. The search pipeline was developed to be directly applicable to multimessenger searches in ADE. The corresponding code, developed and used in initial searches, will be used for ADE searches. While it makes use of available directional information, it is also effective with limited or no directional information. This scenario can be particularly useful

1. in the early ADE when only 2 detectors are available
2. with neutrino cascade events that are poorly localized
3. other cases in which neutrino information have no localization

The joint analysis uses a test statistic for GW+neutrino event candidates, which combines the significance and directional distribution of GW and astrophysical neutrino event candidates, and optionally galaxies. We only consider a GW and neutrino for analysis if they arrive within a time window of 500 s. For GWs, we measure the significance of an event candidate by adopting the test statistic of the used GW pipeline, and comparing it to the background distribution. The background distribution is estimated as standard for the used GW pipelines, using time-shifted data for cWB2G and other techniques not requiring time shifts for CBC. To estimate sensitivity, the search will adopt standard simulated signals for which test statistics are determined by the GW pipelines. For high-energy neutrinos, we calculate the significance of a neutrino by comparing the reconstructed energy of the neutrino to the distribution of the reconstructed energies of all detected neutrinos (implicitly assuming that most of them are background events). The background distribution for neutrino events is estimated as standard for neutrino searches, using the reconstructed direction and energy of detected neutrinos. We calculate the significance of a galaxy using its blue luminosity and its distance, assuming that the source rate in a given galaxy is proportional to its absolute blue luminosity. We then combine the point spread functions of GWs, neutrinos and galaxies. For GWs, we take the point spread function, the so-called skymap, from the used GW pipeline. For neutrinos, we calculate the point spread function form the reconstructed neutrino direction and directional uncertainty. We finally combine the GW, neutrino and galaxy significances, as well as the p-value derived from the combination of the point spread functions, using Fisher's method, i.e. we consider the logarithm of the product of the p-values. The background distribution of the GW-neutrino joint test statistic is obtained by time-shifting the data streams of GW detectors relative to each other and by randomly permuting the neutrino times of arrival, while keeping the neutrinos' directions relative to the detector and energy fixed.

The search will receive GW triggers with high false alarm rate threshold from an all-sky GW search that is being run on ADE data. We will adopt a FAR of 10/day or the FAR provided by the GW pipeline. GW signal injections will be used to determine the search sensitivity and to set upper limits in the case of non-detection. The pipeline will take a GW test statistic, time of arrival, and directional information (skymap) for each trigger. For more detailed information see [151].

The search will receive neutrino events from a neutrino transient search developed by the respective neutrino collaborations (IceCube, ANTARES, KM3NeT). The pipeline will take a neutrino test statistic, time of arrival, and directional information (skymap) for each trigger. For more detailed information see [151].

We will carry out two GW+neutrino searches, one for exceptional events and one for regular events. An event will be considered exceptional if it has sufficient significance such that it could be beneficial to follow the event up with electromagnetic of other observations, or if the event is a possible detection by itself. The specific significance threshold for considering an event exceptional will be determined based on available follow-up capabilities, latency from GW and neutrino searches, and the events likelihood of being an astrophysical event, or if this can be determined with additional observations. All other events that do not satisfy this exceptionality criterion will be considered regular.

Both analyses for exceptional and regular events will be carried out by the GWHEN group using the method described in [151] for all joint triggers. All data that is analyzed by the all-sky searches will be analyzed in the GWHEN search. Data quality will be taken into account by the GW searches themselves. The GWHEN pipeline will adopt the output of GW pipelines, therefore it will not additionally consider data quality.

The GWHEN search will use GW event candidates from the cWB2G pipeline, as well as the standard CBC pipeline. cWB2G will provide triggers covering unmodeled transients expected, e.g., from the progenitors of long GRBs, while the standard CBC search will provide triggers covering compact binary mergers, the likely progenitors of short GRBs. For the CBC-neutrino analysis, both binary NS and NS-BH templates are relevant as potential short GRB progenitors. Both types of sources are interesting for joint GW+neutrino detections.

We will carry out a search that identifies exceptional GW+neutrino events. These events will be a subject to low-latency analysis on an event-by-event basis. Some of these events may be subjected to EM follow-up (the latency of these will be determined based on the GW and neutrino latencies. The latency due to GWHEN will be much smaller.). We will communicate with the EM follow-up group to arrange a proper follow-up of the identified GWHEN events (e.g., by email).

Additionally, we will carry out an analysis for regular GW+neutrino events. These events will be analyzed in ensemble (i.e. the results will be interpreted for all of the regular GW+neutrino events within a measurement duration, similarly to the initial searches).

Low-latency joint GW+high-energy neutrino searches will constitute an interesting new direction for the advanced detector era. Both GW and high-energy neutrino detectors and their implemented event reconstruction algorithms will be able to provide low-latency events that in turn can be used in low-latency joint searches. As both GWs and high-energy neutrinos can arrive prior to the onset of electromagnetic emission from sources such as GRBs, joint GW+high-energy neutrino events may be primary targets for electromagnetic follow-up searches. Additionally, due to the sub-degree direction reconstruction available with neutrino detectors, joint events will exhibit significantly improved localization compared to GW-only triggers, further aiding EM-followup searches.

3.13.4 Publication plan

For GWHEN detection candidates, we consider the "$3\,\sigma$" threshold to be a *minimum* threshold on the significance to be considered for a possible "evidence for" statement. This $3\,\sigma$ is calculated for the whole analysis period. In the case of a clear first detection ($> 3\,\sigma$) of a multimessenger GW - high-energy neutrino event, we will aim to publish results within 3 months of identifying the candidate.

As the sensitivity of the detectors improve, we expect more detections. Upon regular detections, we foresee the publication of a short detection summary after each GW science run. We will aim to publish results within 3 months following the end of a science run.

Upon no detection or marginal detection, we expect to publish a multimessenger GW and high-energy neutrino search results following each ADE science run. This will involve the determination of source rate upper limits. Similarly to the expected increase of the expected observable number of sources between each science run, we require a source rate upper limit improvement of at least 2-3 in order for the results to merit a separate publication. We will aim to publish results within 3 months following the end of a science run.

3.13.5 Technical requirements and development plan

The ADE search will use the multimessenger search pipeline developed for joint searches with IceCube [151]. The same pipeline can be used for ANTARES and KM3NeT searches as well. The development of the pipeline is finished and reviewed, and it is ready to be used for ADE searches.

As the pipeline is built on the foundations of utilizing GW triggers from all-sky GW searches, its adaptation to ADE will be done on the all-sky-search level, and no adaptation is needed in the pipeline itself. The search will use the online triggers generated by the cWB2G GW pipeline, as well as CBC triggers by processing the time, test statistic and skymap from these events by the GWHEN pipeline. GW triggers from cWB2G will be acquired through direct access to the LDAS server. The same triggers will be used as in the online CBC and cWB2G analyses. The data stored on the server is of essentially identical to the data used in the reviewed GWHEN analysis, therefore no additional review is necessary. Low-latency trigger notifications will be received via gracedb with an expected latency of $\sim$ minutes. The received triggers will be automatically received by a special-purpose "alert code", and will be automatically processed by the reviewed pipeline. CBC triggers will be accessed via gracedb by the alert code. The alert code will be a standard software that will automatically receive incoming GW and neutrino trigger alerts, and feeds these alerts to the GWHEN pipeline.

The IceCube collaboration, as well as ANTARES and KM3NeT will provide readily usable triggers for the search, for which no development is needed. Low-latency trigger notifications will be received via gracedb by the alert code with an expected latency of $\sim$ minutes. The received triggers will be automatically processed by the reviewed pipeline.

The low-latency joint search pipeline will be tested using GW and neutrino signals generated by the GW pipelines (engineering run) and IceCube (real observations) in an identical data format as for ADE, and will be accessed identically to the access during ADE.

3.13.6 Resources

The multimessenger search requires low-latency GW triggers from an all-sky search pipeline (along with low-latency neutrino triggers). Beyond this, there is no requirement for the search. Running the pipeline is computationally cheap. The low-latency reception of GW triggers with direction reconstruction is important.

The multimessenger search requires 0.5 FTE for running and maintaining the search and its infrastructure, as well as the organization of publication efforts.

For the search the MOU between IceCube and the LVC needs to be renewed. Similarly, the MOU between ANTARES and the LVC needs to be renewed. An MOU needs to be signed between KM3NeT and the LVC. IceCube is already generating the data products required for this search.

Personnel: IceCube GWHEN search development/testing will need up to 0.1 FTE, while running will need up to 0.1 FTE. ANTARES/KM3NeT GWHEN search development/testing will need up to 0.5 FTE, while running will need up to 0.1 FTE.

3.14 Search for transients from Cosmic Strings

3.14.1 Abstract

Powerful bursts of gravitational waves (GWs) are expected to be produced by cosmic string cusps and kinks. The search for GW signals from cusps was performed on initial detectors' data and was published in 2014. We propose to conduct the same search using the data of Advanced LIGO and Advanced Virgo detectors. In addition, we plan to search for kink signals as well.

3.14.2 Scientific Justification

A cosmic network of strings may form as a result of phase transitions in the early Universe [152]. When a U(1) symmetry is broken in multiple causally disconnected spacetime regions, one-dimensional topological defects, i.e., strings, are expected to form [153]. For a long time, cosmic strings were considered candidate sources for structure formation in the early Universe [154]. Cosmic microwave background (CMB) experiments, however, have shown that cosmic strings can only contribute up to a few percent of the overall anisotropies observed [155, 156, 157, 158, 159]. More recently it was realized that strings can also be produced within the framework of string theory inspired cosmological models and grow to cosmic scales [160, 161, 162, 163, 164]. Cosmic strings produced in string theory motivated models (dubbed "cosmic superstrings") have received much attention since they could provide observational signatures of string theory [165, 166].

Observational constraints on cosmic string models are often given as bounds on the string tension $G\mu$ ($c = 1$), where G is Newton's constant and μ the mass per unit length. Such constraints have been derived from direct searches for line discontinuities in the CMB temperature maps [167, 168, 169] and from simulations of string-sourced CMB anisotropies [155, 156, 157, 158, 170, 171]. These analyses, based on various assumptions about the string network, set upper limits on $G\mu$ in the range of 10^{-7}–10^{-6}. The recent results from the Planck mission [159] constrain $G\mu$ to be lower than 1.5×10^{-7} and 3.2×10^{-7} for Nambu-Goto and Abelian-Higgs strings, respectively.

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational wave (GW) emission from loops [172, 173]. When two string segments meet, they exchange partners or intercommute with a probability p. For superstrings, the reconnection probability can be less than unity ($10^{-4} < p < 1$ [174]) while field theory simulations show that topological strings will essentially always reconnect. This is partly due to the fact that fundamental strings interact probabilistically. Furthermore, superstring models have extra spatial dimensions so that even though two strings may meet in three dimensions, they miss each other in the extra dimensions. When a string intercommutes with itself, a closed loop breaks off. The loop oscillates, radiates gravitationally, and decays (see [175] for a review of the dynamics of cosmic string loops).

Special points on the cosmic string loop play important roles – cusps and kinks. Cusps are points along the string with large Lorentz boosts. Kinks are loop discontinuities that forms in particular every time inter-commuting occurs. Both produce powerful bursts of gravitational radiation [176].

We propose to perform searches for such GW transient signatures from cosmic strings in data from the advanced LIGO and Virgo gravitational wave detectors.

The GW emission by cosmic strings depends on the loop size, which is often written as a fraction of the horizon at the time of formation $l = \alpha t$, where t is the cosmic time. Early simulations such as Ref. [177] suggested that the size of loops is set by gravitational backreaction and $\alpha \leq \Gamma G\mu$, where $\Gamma \sim 50$ [153]. More recent simulations favor cosmic string networks where the size of loops is dictated by the large scale dynamics of the network, in which case $\alpha \lesssim 1$ [178, 179]. We parametrize $\alpha = \varepsilon \Gamma G\mu$ with $\varepsilon < 1$ following the convention of Ref. [172].

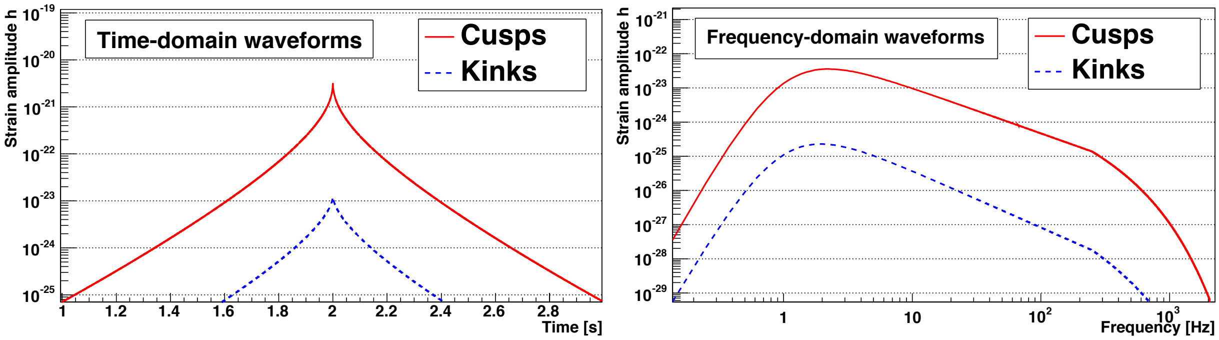

Figure 2: Time-domain (left) and frequency-domain (right) waveforms for gravitational waves produced by cusps (red plain curve) and kinks (blue dashed curve). These waveforms have been computed with the same set of cosmic string parameters: $G\mu = 10^{-8}$, $\varepsilon = 10^{-5}$, $z = 1$ and $f_h = 250$ Hz.

The possibility of direct detection of GW bursts from cosmic string cusps was first suggested in 2000 by Berezinsky *et al.* [180]. Shortly after, Damour and Vilenkin showed that the stochastic GW background generated by oscillating loops is strongly non-Gaussian [176]. Occasional sharp bursts of GWs produced by cusps are expected to stand out above the stochastic background [176, 181, 172]. Damour and Vilenkin predict that the GW burst signal produced by cusps is linearly polarized and the expected waveform in the frequency domain (using logarithmic Fourier transform) is $h_{cusp}(f) = A_{cusp} f^{-4/3}$ ($h_{kink}(f) = A_{kink} f^{-5/3}$) with an exponential decay that sets on at some high-frequency cutoff f_h. Figure 2 shows an example of such a waveform for a given set of parameters. The signal amplitude A_{cusp} is determined by the string tension, the loop size, and the propagation distance. Direct searches for these signatures such as the one proposed here explore the parameter space $(G\mu, \varepsilon, p)$.

Constraints on cosmic string parameters obtained from the search for GWs produced by cusps have been published in 2014 [10]. The next generation of ground-based GW detectors will probe the cosmic string parameter space further. The improved sensitivity of Advanced LIGO [182] and Advanced Virgo [183] will eventually allow us to search for cosmic strings with an order of magnitude lower tension.

Recent studies shows that GWs produced by cosmic string kinks might also be of interest for LIGO and Virgo. The signal amplitude is smaller than for cusps (see Fig. 2) but a proliferation mechanism could offer a production rate several order of magnitude larger [184] see Fig. 3). In the future, it is planned to search for GWs associated to both cusps and kinks and to publish combined results.

3.14.3 Search Description

The search for GW bursts from cosmic strings begins with a matched-filter analysis of strain data from each detector separately [185]. It consists of projecting the whitened data onto an overpopulated [5] template bank defined by a set of cusp waveforms with a high-frequency cutoff spanning from 75 up to 8192 Hz. This procedure results in a time series for the signal-to-noise ratio (SNR) for each template. An event is identified when the SNR > 4 and only the template with the largest SNR is retained when several templates are triggered at the same time. A set of five variables is used to characterize an event. The event time t_e and the SNR ρ are determined by the point where the SNR time series is maximum. The triggered template provides the high-frequency cutoff f_h and the amplitude A. In addition, a χ^2 parameter can be computed to characterize the match between the event and the signal waveform in the time domain [186].

To discriminate true signals from background events, we apply the multivariate technique described in Ref. [187], which uses a set of simulated GW events and typical noise events to statistically infer the

---

[5] the maximal mismatch between two consecutive templates is 0.001.

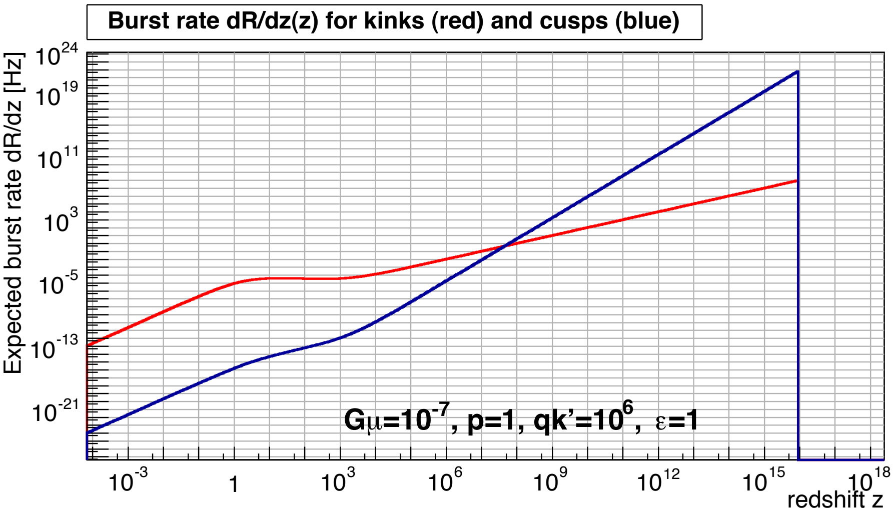

Figure 3: Predicted rate of GW bursts produced by cosmic string cusps and kinks. The proliferation mechanism, parameterized by $qk' \gg 1$, favors the kink event rate over a wide range of redshifts.

probability for a candidate to be signal or noise.

Figure 4 displays the region of the cosmic string parameter space that is excluded by the analysis of initial detectors' data [10]. For comparison, we also show limits, fixing p at 10^{-3}, derived from constraints on the GW stochastic background spectrum. These limits were computed adopting the same cosmic string model and using the same parameters $(G\mu, \varepsilon, p)$. Our result improves the indirect CMB bound [188, 189] by a factor 3 for intermediate ε values. It nicely complements existing limits provided by pulsar timing experiments for large ε [190, 158] and by the LIGO stochastic search in the very small loop regime [189].

3.14.4 Results validation plan

If an event is found to significantly differ from what is expected from background, we will immediately trigger the following procedure:

- we will ping the detector characterization groups to investiagte detector noise at the time of the event.
- We will compare the results of our search with the untriggered all-sky searches (CWB2G, EXCESSPOWER, and omicron+LIB).

3.14.5 Publication plan

We will run the cosmic string pipeline over O1 data to search for both cusp and kink signals. O1 data will be analyzed in a detection-only mode. Even if the O1 sensitivity is improved by some factor, this will not impact the upper-limits significantly enough. The O1-only analysis is indeed penalized by the low livetime and the presence of only 2 detectors. The O1 analysis will lead to a publication only if a detection is made. In this case, a paper for LVC consideration should be ready within 6 months after the run ends.

In case of non detection, the plan is to publish combined cusp and kink upper limit results of O1/2/3.

3.14.6 Resources

Detector characterization Studies performed over S5 data showed that data quality vetoes had a low impact on the events of this search as the background distribution was found to be almost Gaussian. In

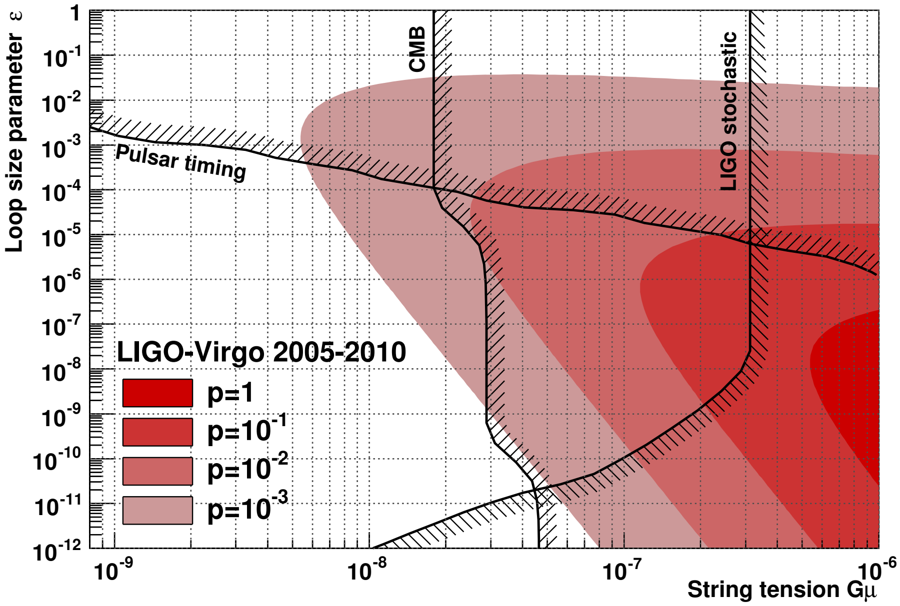

Figure 4: This plot presents existing constraints on cosmic string parameters: the string tension $G\mu$, the loop size parameter ε and the probability p that two string segments interact when they meet. The S5-6/VSR1-2-3 analysis is able to reject the regions filled in red. For comparison, other constraints derived from searches of a GW background from cosmic strings (pulsar / CMB / LIGO stochastic) are given fixing p at 10^{-3}.

the future, it is planned to carefully select useful vetoes for this type of search and not to apply the vetoes blindly.

Calibration The cosmic string search is sensitive mostly in the bucket of the detectors. Special care should be taken to insure the best calibration uncertainties at these frequencies.

Review The cosmic string search pipeline was already reviewed. The review process of the furture analysis is expected to be straight-forward and to require little manpower

3.15 Search plan for long-lived gravitational-wave transients

3.15.1 Abstract

Unmodeled long-lived gravitational-wave transients (lasting $\gtrsim$ 10–$10,000\,\mathrm{s}$) are an interesting class of signals for advanced detectors. Such long-lived transients have been linked to the death of massive stars. In one class of models, gravitational waves are emitted by a rapidly spinning protoneutron star, which may be spun up through fallback accretion. In another class of models, the signal comes from the motion of clumps in an accretion disk. In either case, the signals are long-lived, narrowband, and may occur with a sufficiently high rate so as to be observed with advanced detectors. Other possible scenarios for long-lived gravitational-wave emission include protoneutron star convection, rotational instabilities in merger remnants, r-mode instabilities associated with glitching pulsars and type I bursts from accreting pulsars, eccentric binary systems, and, of course, surprises. A targeted long-transient search with initial LIGO data has been published, as well as a second all-sky search. Future searches for long-lived transients will require coordination with various LIGO-Virgo subgroups and search plans. This search plan describes the scientific justification for long-transient searches and the technical description and requirements for such searches. These searches will carried out using the STAMP-AS pipeline, X-PIPELINE, and CWB2G. All three pipelines are sensitive to gravitational-wave signals in this long-duration regime, and their results will contribute to both this search effort and verification if a signal is detected.

3.15.2 Scientific Justification

Sources of long-lived (lasting $\gtrsim$ 10–$10000\,\mathrm{s}$) gravitational-wave transients are reviewed in [191]. The most promising sources fall into two categories, both of which begin with the death of a massive star.

Protoneutron stars. The first scenario relies on the formation of a protoneutron star. If the protoneutron star is born spinning rapidly, it may develop an instability (e.g., a bar mode), leading to the strong emission of long-lived, narrowband gravitational waves [192]. A protoneutron star can also be spun up through accretion of stellar remnant fallback such that an instability sets in [193]. The resulting gravitational-wave emission can last for $\approx$ 40–$3100\,\mathrm{s}$ [194]. Advanced LIGO might detect rotational instability signals from protoneutron stars out to to distances of up to $\approx 40\,\mathrm{Mpc}$ [195, 196]. The rate of observed supernovae in this volume is on the order of $\approx$ 10–$30\,\mathrm{yr}^{-1}$ [194], though the fraction of these stellar explosions that might result in an accretion fallback signal is currently unknown. Nonetheless, a single such detection would provide an unparalleled glimpse into the moments following stellar collapse and the birth of a neutron star or black hole.

Accretion disks. The second scenario relies on the formation of an accretion disk following stellar collapse. A central spinning black hole drives turbulence in the accretion torus, which leads to the formation of clumps. The motion of these clumps emits long-lived narrowband gravitational waves [197, 198, 199], on the time-scale reaching 10^3 sec. Alternatively, clumps may form through accretion disk fragmentation, also leading to the production of gravitational waves [200]. The rate and energy budget of accretion disk instability signals are debated. However, we estimate that advanced LIGO can observe accretion disk instability events out to distances of $540\,\mathrm{Mpc}\,(E_{\mathrm{gw}}/0.1M_\odot)^{1/2}$ where E_{gw} is the gravitational-wave energy budget [195, 196]. We note that long gamma ray-bursts are observed at a rate of about $0.3\,\mathrm{yr}^{-1}$ within this radius (and many are likely to be missed due to beaming) [201]. A single detection would provide unprecedented information about the environment following the collapse of a massive star and could shed light on the mechanics of long gamma-ray bursts.

Other sources. Other scenarios for the production of long-lived gravitational waves include protoneutron star convection [202], rotational instabilities in merger remnants [191], and eccentric binary systems [203]. While these sources are associated with signals on the time-scale of 1 minute to 1 hour, much longer transient signals (on the time-scale of days) are also possible, for example in glitching pulsars or in accreting fast millisecond pulsars. The subfield of theoretical investigations into long-lived transients is fluid, and it is prudent to have a search dedicated to whatever long-lived transient signals may be awaiting discovery: predicted models, yet-to-be-predicted models, and total surprises.

Relationship to other searches. This search plan complements the burst all-sky search for short-duration signals [204] by extending the parameter space to longer durations. We will coordinate with the short-duration search teams to determine the complementarity of the two searches and the overlap in sensitivity of the pipelines involved. For example, benchmark tests performed in 2015 have indicated that STAMP-AS, CWB2G (with a long-burst search configuration), and X-PIPELINE have comparable sensitivities for signals with duration 10–500 s while CWB2G (with a short-burst search configuration) has better sensitivity below 10 s. This search also overlaps with triggered searches for long-lived transients described in the GRB search plan 3.9 and the neutron star transient search plan 3.16. We will work with these other ongoing efforts to study long-lived transients, and collaborate to identify the advantages and complementarities of different pipelines.

This search also overlaps with efforts in the CW group to look for long-lived transient signals from neutron stars. More recently COCOA, a cross-correlation based pipeline to search for intermediate duration signals bridging the gap between continous waves and transient searches has been proposed [205]. We will coordinate with the CW group to identify overlapping interests. Finally, this work overlaps ongoing work in the Stochastic group in which STAMP is used to study the time dependence of a stochastic background signal and, in doing so, to identify very long-lived ($\gtrsim$ 10 hours) signals [206]. The two projects are complementary as they focus on different time scales, and the stochastic search is primarily concerned with the effect of transient phenomena (astrophysical or due to noise) on the stochastic background search, whereas this search is concerned with studying astrophysical long-lived transient signals.

3.15.3 Search Description

This search proposal describes using advanced LIGO and advanced Virgo data to conduct an all-sky, all-time search for long-lived signals from 10–10^4 s. We plan to carry out these searches using STAMP-AS, X-PIPELINE, and CWB2G. Each of these pipelines uses a distinct approach to the analysis, providing for robustness and cross-validation of the searches in this relatively unexplored region of parameter space.

STAMP-AS

STAMP-AS [191, 207, 201, 195, 196] is an all-sky extension of the STAMP matlab based library[6] developed initially by the Stochastic group and also used for detchar purposes. The pipeline cross-correlates the output of any combination of detectors. While fully coherent the analysis remains computationally affordable thanks to a series of compromise (reduced sky grid for instance) and specific developments (pixel based clustering adapted for hundreds of second long signals). The S5 and S6 LIGO data have been analyzed and the results published [209] using STAMP-AS to search for transient signals of duration up to 600 sec in the 40–1000 Hz frequency band. Some of the outputs include: managing the computational cost of the search, understanding the background and minimizing the effect of noise transients to a level approaching Gaussian noise, and investigating the applicability of the search to eccentric binary waveforms [210, 211]. The pipeline has also been verified via a comprehensive review.

For O1/O2 we apply a hierarchical strategy to select the most significant events without wasting computional resources. We run the STAMP-AS standard configuration (Zebragard clustering algorithm) with 200 time slides to reveal the presence of significant events at 2.8-σ level for a single search. We will then determine if it can be explained in terms of a detector artifact. If the candidate is promising, we will present the results to the burst group and estimate its significance running more time slides using a quicker time slide code (semi coherent method) and using alternative analytical methods to time slides [212]. The parameter

---

[6] STAMP-AS resides in the Matapps svn repository [208]

space has been increased to 24-2000 Hz. Starting with O1, STAMP-AS will also be run with the seedless clustering algorithm STOCKTRACK. The goal is to measure the complementarity of STOCKTRACK with the seed-based clustering pipelines for the shorter signals and prepare the very ylong transient search pipelines (days-weeks).

X-PIPELINE

X-PIPELINE [71, 69] performs coherent burst searches of data from arbitrary networks of detectors and has been used in many externally triggered searches [213, 214, 215, 216, 217, 218]. Recently, X-PIPELINE has been extended to an all-sky pipeline by replacing the sky-grid based analysis by a spherical radiometer analysis [219, 220]; this technique allows correlations between detectors to be computed quickly for signals with durations longer than $\sim$1 s. The spherical radiometer formulation also provides a fundamentally different approach to all-sky searches than the traditional grid-based approach used by other burst pipelines.

Our search strategy is to perform an initial analysis with enough time slides to tune for maximum sensitivity at the 3-σ detection level for a single pipeline. In the case of a loud on-source event, additional time slides will be run to estimate significance to the 3-σ level with a trials factor of 3 (accounting for the CWB2G and STAMP-AS pipelines also participating in the search). See [221] and Sec. **??** for details of the associated CPU costs.

CWB2G

The CWB2G pipeline is described in detail in the short-duration burst search plan [204]. The extension of CWB2G to the long duration region of the burst parameter space is achieved by running the baseline all-sky pipeline with the additional time-frequency resolutions and Wilson-Daubechies-Meyer (WDM) time-frequency packet optimized for long-duration transients. The WDM packets allows us better integration of energy over the time-frequency and expect to significantly improve the pipeline detection efficiency for signals longer than few seconds. The extended CWB2G pipeline will efficiently detect signals with the durations up to several hundred seconds. Work should be done to test the CWB2G pipeline sensitivity for longer signals. Due to algorithmic changes likely a separate run will be required to cover the long-duration parameter space. However, the overall computing performance is better than for the O1 version of the pipeline and no significant increase in the overall cwb computational cost is expected.

For all three pipelines, all science data with two or more detectors operating at reasonable sensitivity will be searched, to maximise chances of a detection. Each search will identify and rank candidate events, using GW correlation tests and data quality checks to reduce the noise background. The traditional time-slide method will be used to assess the background and thus the significance of candidate events, as well as quicker alternative methods. Pipeline sensitivities will be evaluated for a number of test waveform morphologies[7]. It is foreseen that the offline analyses will initially be run on a small subset of all available livetime or with a small number of time slides to identify any issues; the results will also feed into data quality studies and data monitoring tasks. The definitive analysis will be performed offline using the best calibration, data quality, and other relevant information available. The O1 analysis is near completion.

3.15.4 Result Validation Plan

The long duration transient search will probe a regime where some types of signals are predicted, but much uncertainty remains. In the case that a pipeline sees a long duration transient the best confirmation strategy will be to examine how the signal appears in the searches by the two other pipelines. We note that each pipeline is tuned and run independently, and rely on a radically different algorithmic implementation, so each provides an independent confirmation of the results of the others. Given the event properties and the known relative sensitivities of the pipelines, we expect to be able to understand why the event is or is

---

[7] See https://wiki.ligo.org/Main/STAMPAllSkyWaveforms for the waveforms used in the 2005-10 STAMP-AS all-sky search.

not seen by each pipeline with a given significance. This will require more comprehensive comparisons to understand the consistency and relative sensitivities of the three pipelines. These comparisons are a high priority activity in preparation for the first science runs.

3.15.5 Publication plan

In the event of a detection, we plan to publish as soon as possible, and ideally within six months of the event. A detection paper would focus on the attributes of the observed signal: the reconstructed time-frequency evolution, the time and sky location of the event, etc. The discovery of even one long-lived gravitational-wave transient that does not conform to a compact binary coalescence model would be of enormous interest to the broad astronomical community. Thus, we would recommend submitting a detection paper to a high-visibility journal. We will also investigate the utility of burst parameter estimation pipelines [204, 222, 223] for reconstructing long-duration signals.

In the event that no candidate event is observed, we will set limits on the distance and/or rate to long-lived sources given different signal models. Waveforms for protoneutron star models and accretion disk instability models are available and the latter have been successfully used in an initial LIGO analysis [201]. Other ad-hoc waveforms will be also considered. We recommend publishing a paper with updated limits if/when the constraints on the distance to a long-transient source with a fixed energy budget improve by a factor of at least two (corresponding to a factor of eight improvement on the rate) *and* there is a convenient break in data-taking (the end of a run). Papers reporting on improved limits can be submitted to journals such as PRD or CQG. It may also be suitable to include these results in a broader paper (e.g., jointly with the short-duration burst searches).

3.15.6 Technical requirements and development plan

STAMP-AS

The baseline plan is to carry out the analysis with the current stable version of STAMP-AS. Most of the STAMP-AS code has been reviewed for the published initial LIGO targeted analysis [201] and the S5-S6 all-sky search [209]. A handful of improvements are currently under test. Among them is the use of the new STOCKTRACK seedless clustering algorithm [195, 196], an alternative SNR pixel calculation to improve the sensitivity to monochromatic signals. The seedless clustering code has been tested and benchmarked with both Monte Carlo and recolored noise [195, 196]. Furthermore we also plan to continue to work on the optimisation of the code in order to speed up the computational time for the background estimation. STAMP-AS is a fully coherent search that is costly when doing time slides. We are investigating pipeline modification to reduce the cost and study alternative methods to time slides [212]. Besides, the current implementation of STAMP-AS allows us to search for signal as long as $\sim 1000\,\mathrm{s}$. Beyond, STAMP-AS is facing memory and computational issues and changes are mandatory. In coordination with similar developments carried out by the Stochastic group we plan to increase the signal duration coverage for signals longer than 1000 s after 01.

Significant coding effort has been made to take advantage of highly-parallel architecture. For instance, the seedless clustering algorithm stochtrack runs most efficiently on GPUs and multi-core CPUs. Note that we plan to adapt the STAMP-AS pipeline to run on Virgo clusters (Lyon and Bologna). This development should not happen before O3.

In order to catch problems early and facilitate a smooth analysis, we analyzed O1 data immediately as it became available with the goal of estimating the background and sensitivity on an approximately biweekly basis. This strategy will continue with the data from O2 and future observing runs. We will coordinate with potentially overlapping efforts to maintain a mock dataset with long-lived injections in order to compare the domain of utility of different searches/algorithms.

X-PIPELINE

The baseline plan is to carry out the analysis with the spherical radiometer version of X-PIPELINE. Most of the matlab and python wrapper codes have already been reviewed as part of the GRB and supernova searches, so review effort will focus on the fast cross-correlator codes [219]. This search has been approved for review and a review team is being assembled.

Current effort is focused on tuning the analysis to optimise the sensitivity to signals with durations in the 10 s-1000 s range. This study is being done through a comprehensive analysis of the S6/VSR2,3 data set [8]. In principle, the current implementation of X-PIPELINE can detect signals of arbitrarily long duration provided they are non-monochromatic. However, the longest signals tested to date are $\sim 250\,\mathrm{s}$; characterisation of the sensitivity to longer signals is an outstanding priority. Longer-term development will also include testing multi-variate analysis methods for signal/background discrimination in X-PIPELINE triggers, and further code optimisation to improve speed and memory usage.

CWB2G

The O1 version of the CWB2G pipeline is available for the long duration search. Current effort is focused on improvements of the pipeline sensitivity and the waveform reconstruction. Long-term development plans include further improvements of the pipeline computational performance.

3.15.7 Resources

Detector Characterization

We do not anticipate that the long-transient searches will require significant detector characterization work beyond what is already planned for other searches. During initial LIGO, STAMP-AS searches were shown to produce well-behaved noise distributions (similar to stationary Gaussian noise) through the application of notches for instrumental lines, basic data quality flags, and a glitch identification flag [207, 201]. This is probably attributable to the long time scales probed by the search as well as the fact that STAMP-AS uses cross-correlation [207]. However, the loudest background events of each search will be scrutinized to understand the main non-Gaussian sources of background events and provide feedback to the detector characterisation group. This continued with the O1 data.

Calibration

There are no special requirements for calibration beyond what has already been requested by the four data-analysis group [224]. Quoting the short duration all-sky burst search plan: "To meet our publication schedule, the offline search will require "final" calibrated $h(t)$ from three months after the beginning of each run (within two months for the 2015 run). All tests to date have shown that the calibration uncertainties will not have a significant impact on the analysis provided they are of the level already achieved in the S5-6, VSR1-3, and O1 runs.

There were some long-duration transient injections at the very end of O1. A few long-duration hardware injections are requested in the engineering run before O2.

Review

The STAMP-AS review for the S5/S6 search [209] was completed in later 2015. The seedless clustering method is just commencing with its review in the summer of 2016. The X-PIPELINE review has just started. The O1 version of the CWB2G pipeline has been reviewed and can be used for the O2 analysis. Limited algorithmic changes in cwb will be reviewed before or shortly after the beginning of the O2 run.

---

[8] https://wiki.ligo.org/Bursts/AllSkySecondPipeline?rev=4

3.16 Searches For Transient Gravitational Waves From Isolated Neutron Stars

3.16.1 Abstract

Violent phenomena associated with neutron stars (NSs), such as flaring activity in magnetars and binary coalescence, may result in the excitation of various oscillatory modes which leads to transient gravitational wave emission. Although the strength and likelihood of any putative signal across a variety of sources ranges from being completely unknown to likely weak and only detectable for galactic or very local galaxies, it is thought that these signals convey unique information on the neutron star equation of state. The detection and characterization of gravitational waves (GWs) associated with NS oscillations holds the potential for GW neutron astereoseismology, whereby NS oscillation mode identification and characterization leads to constraints on the equation of state (EOS). Here, we provide details for a plan of readiness for opportunistic searches for transient GWs from neutron star oscillations for *extraordinary* events, such as a hyperflare from a galactic magnetar or the detection of a binary neutron star inspiral GW signal.

3.16.2 Scientific Justification

Galactic Magnetar Hyperflares

Isolated NSs exhibit a variety of violently energetic and unpredictable phenomena. For example, isolated NSs with powerful magnetic fields ($B \sim 10^{15}$ G) known as *magnetars*, undergo episodic X- and gamma-ray burst activity which manifest as anomalous X-ray pulsars (AXPs) and soft-gamma repeaters (SGRs). Typical isotropic burst energies are usually lower than 10^{42} erg, although three SGR "hyperflares", with energies 10^{44}-10^{46} erg have been observed in the past 30 years [225, 226, 227]. Indeed, it is likely that a fraction ($\sim 15\%$) of short gamma-ray bursts are, in fact, extragalactic magnetar hyperflares.

While these phenomena are not well understood, it is reasonable to expect that such a sudden and localized energy release could excite non-radial oscillation modes in the star, leading to GW emission. The most efficient GW-emission mode is the f-mode, since this is damped almost entirely via GW emission with no competing damping time-scales. The signal thus emitted would be expected to resemble a damped sinusoid lasting O(100) ms and oscillating principally around 1–3 kHz, depending on the NS EOS [228]. However, if the mechanism for a violent event like a magnetar flare is confined to the surface of the star, it may be that, rather than global f-modes, torsional oscillation modes are excited, potentially leading to GW emission at ∼10–2000 Hz. The quasi-periodic oscillations (QPOs) observed in the pulsating tail of giant flares from soft-gamma repeaters such as the 2004 event in SGR 1806-20 are believed to be associated with these modes [229, 230]. While torsional modes themselves are not likely to be particularly efficient GW emitters, if they couple to modes in the NS core, one may expect some form of damped GW signal at similar frequencies to the observed electromagnetic QPOs. Finally, and more speculatively, dynamical or secular instabilities (see e.g., [231]) in the NS may become active following some violent event, leading to transient, but long-lived GW emission.

Previous LIGO/Virgo analyses have generally searched for generic short-duration bursts associated with violent events such as magnetar flaring activity [232, 233, 234], pulsar glitches [235] and potentially nearby ($\sim$ 1 Mpc) short γ-ray bursts where the burst may be an extragalactic magnetar hyperflare [236, 216]. To date, there has only been one galactic hyperflare, the 2004 event in SGR 1806-20, which coincided with a science run and an analysis was performed to search for GWs associated with quasi-periodic oscillations observed in the X-ray light curve for that extraordinary event [237]. The magnetar analyses in particular were met with interest in the astrophysical community and, given the proximity and energetics of the potential source, the science potential of identifying and characterizing NS mode frequencies, as well as the ability to perform an externally-triggered search with a relatively well-defined event time and most likely, sky-location, we propose to continue this legacy in O1 and beyond. However, the uncertainties in the GW detectability and even in the likelihood of mode excitation suggest that we should focus attention only on the most extraordinary events in isolated neutron stars.

Detection prospects for GW signals from magnetars range from unknown to unlikely, depending on which oscillation modes are excited (i.e., the frequency of the GW emission) and the dominant damping mechanism (i.e., the stability and duration of the GW emission). *We therefore propose only to analyze extraordinary events from magnetars, where there is evidence of a hyper-flare and the source can be confirmed as being within our own Galaxy, such as the 2004 flare in SGR 1806-20.* For a known galactic magnetar, the null-result would, as in past analyses, take the form of GW energy upper limits at fiducial frequencies using ad hoc signal injections. The astrophysical significance of the result would depend on the EM energy of the hyperflare and the uncertainty in the source distance: we only consider a null-result to be astrophysically interesting if the GW energy upper limit is within a factor of unity of the measured electromagnetic energy emission.

Post-merger Signals From Binary Neutron Star Coalescence

The inspiral and coalescence of binary neutron star systems is an extremely rich source of astrophysical phenomena, ranging from strong GW emission to short gamma-ray bursts and kilonovae. It is also another potential source of GWs from NS oscillations. It has become apparent in the past few years that the likely outcome of a binary neutron star merger is the formation of a stable, or quasi-stable, neutron star remnant, hereafter referred to as a post-merger neutron star (PMNS) (e.g., [238, 239, 240, 241]. The stability of the PMNS depends both on the NS EOS and the mass of the system: soft EOSs and/or high-masses will result in either prompt or delayed collapse to a black hole (where the delay arises as the object is temporarily supported by centrifugal forces which eventually diminish as it spins down). Transient non-axisymmetric deformations in the surviving postmerger remnant lead to a short duration ($\sim 10-100\,\mathrm{ms}$) burst of GWs with rich high frequency content, dominated by emission from f-mode oscillations at $\sim 2-4\,\mathrm{kHz}$ and generally lower-frequency sub-dominant peaks from nonlinear couplings between certain oscillation modes [242]. A number of studies [241, 243, 244], have identified and confirmed a correlation between the dominant postmerger oscillation frequency (i.e., half the peak GW emission frequency) and the radius of a fiducial cold, non-rotating neutron star. Due to the short-duration and high-frequency nature of the merger/post-merger burst this source is likely to be detectable in aLIGO only for nearby events (10–50 Mpc; see [245] for a comprehensive detectability study of the short burst following the merger) even at design sensitivity.

The significance of the detection, however, would be profound as EOS constraints may be made by the mere detection of the signal and measurement of the dominant oscillation frequency (a relatively easily measured parameter).

If the PMNS remains stable, additional higher-amplitude, longer-duration signals may also be emitted. If, for example, the merger results in a stable magnetar due to magnetic field amplification, the star may be distorted into a prolate spheroid leading to a slowly down-chirping GW signal which sweeps down from $\sim$ kHz, lasting $\mathcal{O}(10^3-10^4)$s [246]. Such a signal may be detectable to $\sim 100\,\mathrm{Mpc}$ (assuming aLIGO design sensitivity). Given the high rotational energies involved, it may also be possible that the dynamical bar-mode instability may activate and survive for a substantial length of time in a stable post-merger remnant, again leading to strong GW emission.

Given the potential for high-impact astrophysics in the event of detecting any post-merger signal, we propose targeted follow-ups of detections of binary neutron star coalescence signals for both the short, merger/post-merger burst, as well as the longer duration transient from a stable PMNS

We note, however, that a null-result would be insignificant: the strength of the post-merger emission is uncertain but likely to be weak and high-frequency, it is not clear that the distance to the source would be well known (introducing an associated uncertainty into an energy upper limit) and there is the potential scenario that the merger results in prompt-collapse to a stellar mass black hole, whose ring-down is far less likely to be detectable than the post-merger oscillations of a surviving NS. This distance uncertainty, together with the degeneracy between a weak/distant source and the prompt-collapse scenario would likely render upper limits somewhat uninteresting.

3.16.3 Search Description

This search proposal discusses searches for GWs triggered by two distinct events: hyperflares in Galactic magnetars and post-merger oscillations in NS remnants which survive binary neutron star coalescence. Many aspects of the proposed search methods and potential GW signals, however, are commmon to both. In particular, both events have the potential to result in:

1. A short (10's of ms), high-frequency burst of GWs associated with f-mode oscillations.
2. Longer-duration (100-1000 s) transients associated with phenomena such as torsional oscillations, instabilities or magnetic-field induced quadrupole moments.

As a preliminary minimal effort and low-latency search, triggers arising from the online burst all-sky search should immediately be examined to look for any temporal and spacial correlation with either class of trigger. A galactic hyperflare would likely manifest as an extraordinarily bright and unusually soft-spectrum short gamma-ray burst and would generate mass interest in the astronomy community. We will manually monitor (e.g.,) the GCN notices and other notification systems such as Atel for indications of Galactic hyperflares. A binary neutron star coalescence which is near enough to stand a hope of observing an associated burst signal will, of course, be detected by the low-latency GSTLAL/MBTA BNS search (see **??**). A nearby merger would likely also be detected by the online burst analysis. In both cases, there will be a well defined event time and, potentially, a sky localisation with which to correlate online search triggers.

Galactic Magnetar Hyperflares

Following this low-latency check, and in the case of a confirmed galactic magnetar hyperflare, a targeted analysis will be performed using X-PIPELINE [5, 69], a pipeline designed for GW follow-up of astrophysical triggers with known sky-location and a specified time window in which a GW signal may be expected (the "on-source"). X-PIPELINE has been used in a number of LSC-Virgo observational results papers in GRB and neutrino-triggered searches [213, 214, 216, 215, 217, **?**]. In its standard configuration, X-PIPELINE is designed to target short-duration, low frequency bursts in the most sensitive regime of LIGO and Virgo. For magnetar analyses, however, we require sensitivity up to f-mode frequencies (i.e., $\sim 1-4$ Kz) and long-duration ($\sim 100-1000$ s) transients. We will, therefore, aim to extend the X-PIPELINE analysis to at least 4 kHz. Studies are currently underway to optimize the selection of time-frequency resolutions used in the X-PIPELINE analysis in order to provide some overlap in sensitivity to long-duration signals with a separate analysis targeting long-duration bursts. The main tool for targeting these long-duration signals will be the STAMP-GRB pipeline [191] which has previously been used to search for long-lived GW signals associated with GRBs [201]. No significant modification to the STAMP analysis is expected to be required.

Detection candidates for short-duration signals associated with extraordinary magnetar events will be followed up with parameter estimation tools currently under development such as BAYESWAVE and LALINFERENCE BURST; see Sect. 3.1. This will allow reconstruction of the impinging waveform and basic spectral analysis, which will be important for mode identification and astrophysical interpretation. Basic spectral analysis and reconstruction of the frequency evolution of long duration transients can and will be addressed by the STAMP analysis.

In summary, we propose the following in the event of a hyperflare from a galactic magnetar:

- **Low-latency analysis (∼minutes–hours):** Initial check for temporal and spatial coincidence of triggers arising from the online burst analysis with the electromagnetic or GW trigger.

- **Higher latency analysis (∼week–month):** Upon confirmation of the galactic and extraordinary nature of a magnetar event, dedicated X-PIPELINE and STAMP analyses will be performed *manually*[9]. X-PIPELINE will be used to target short-duration bursts from 10's of Hz up to $\sim 4\,\mathrm{kHz}$ and will be tuned to maintain sensitivity to longer duration bursts and provide some degree of overlap in sensitivity with the STAMP-based tools which will be used to target exclusively long-duration bursts. Short-duration candidates to be followed-up and characterized with burst parameter estimation (PE) tools.

Post-merger Signals From Binary Neutron Star Coalescence

In the event that the *offline* weekly ahope CBC analysis confirms a BNS inspiral detection initially made by the online GSTLAL/MBTA CBC analysis, we will initiate a burst-led follow-up to characterize the post-merger scenario and detect signals from a surviving NS remnant.

The procedure to target post-merger signals following a BNS inspiral detection is very similar to the proposed magnetar analysis. The notable difference in this case is that we will already have a GW detection (the inspiral) and we wish to infer the late-time behaviour of the same system (prompt vs delayed collapse, measurement of post-merger oscillation frequencies) from the evolution of the coalescence signal. In the case of a BNS inspiral, therefore, the burst parameter estimation tools will be deployed as a follow-up to the inspiral detection and *not* as a follow-up to a short-duration burst detection via e.g., X-PIPELINE. Long-duration bursts arising from instabilities or quadrupole deformations in stable post-merger remnants are somewhat separate from the initial coalescence, have a less certain start time and are not easily targeted by the parameter estimation tools currently in development. As with the magnetar event then, long-duration bursts from stable remnants will be targeted by the STAMP-GRB pipeline.

In summary, we propose the following in the event of a hyperflare from a galactic magnetar and/or a BNS inspiral detection:

- **Low-latency analysis (∼minutes–hours):** Initial check for temporal and spatial coincidence of triggers arising from the online burst analysis with the electromagnetic trigger in the case of a Galactic magnetar hyperflare, or coincidence with a low-latency GSTLAL/MBTA GW trigger in the case of binary neutron star coalescence.

- **Higher latency analysis (∼week–month):** Burst PE tools will be used to characterise the short-duration, high-frequency merger/post-merger signal. The STAMP-pipeline will be used to target any later long-duration bursts from stable remnants.

3.16.4 Result Validation Plan

Galactic Magnetar Hyperflare Search

The first stage in the search for GWs associated with an extraordinary Galactic magnetar event, prior even to launching the offline STAMP (targeting longer duration signals) and X-PIPELINE (targeting shorter duration signals) analyses, will be examination of any available all-sky burst triggers from around the time of the event. If the all-sky analysis provides a detection candidate, we certainly expect the *targeted* analyses to see the same event; we therefore expect consistency between the basic parameters of the signal (e.g., characteristic times and frequencies), insofar as the time-frequency resolution and basis functions permit.

In the event the targeted analyses provide a candidate, but all-sky analyses with sensitivity in overlapping parameter space (as determined from the characteristics of the targeted search trigger) do not,

---

[9] Given the rare nature of the targeted events, we do not feel that investing in automated infrastructure is necessiated

the significance of the candidate will be assesed to determine whether the lack of a matching all-sky trigger is consistent with the plausible amplitude of the signal and the thresholds and tuning choices applied in each pipeline.

Finally, in the event that a trigger arises from a targeted analysis with no possible overlap with existing all-sky analysis (for example, the high-frequency all-sky analysis may run at higher latency than the targeted high-frequency magnetar analysis), cross-validation will take place via studying the results of following up the targeted analysis trigger with parameter estimation tools in the form of a dedicated BayesWave follow-up and/or the production of a CWB coherent event display[10].

In all cases, a coherent event display will be used to more thoroughly study the trigger and reconstructed signal.

Post-merger Signals From Binary Neutron Star Coalescence

The validation procedure for any long-duration burst counterpart to a BNS merger will be identical to that proposed above; checking for consistency with the significance and time-frequency content of candidate events between all-sky triggers and coherent event display follow-ups.

The results of the parameter estimation follow-up study targeting the immediate short-duration burst at and after the merger will be compared with a) available high-frequency all-sky triggers and b) the output of a CWB coherent event display. There should be consistency in the bulk features (e.g., root-sum-squared amplitudes in each detector, characteristic times & frequencies) between the parameter estimation output and CWB results.

3.16.5 Publication Plan

Galactic Magnetar Hyperflare Search: The analysis of GW data near to the time of a galactic hyperflare will be of high interest even in the event of a null result. Our goal, therefore, will be to have a complete paper draft within 3 months of the event. We provide specific plans for the cases of confident, marginal and no detections below.

Evidence for detection Evidence for detection would be comprised of a temporally and spatially coincident (with the hyperflare) trigger with significance estimated at $> 3\sigma$, accompanied by a robust waveform reconstruction (i.e., narrow posterior measurements, free of artefacts) and spectral analysis. The target significance for a confident detection will be the usual 5σ and efforts will be made to estimate to this level for triggers at $> 3\sigma$.

Marginal evidence for detection Marginal detection would be comprised of a detection candidate with significance at 2–3σ. Reconstructed waveform polarizations (and frequency content) would be presented but with less emphasis than for a confident detection.

No detections. In the event of no detection, the publication plan would be contingent on an GW energy upper limit:

- For GW energy upper limits comparable (i.e., within a factor $\sim$unity) to the isotropic equivalent electromagnetic energy, the result would be considered a significant non-detection, given the extraordinary nature of the event and the precendent for interesting magnetar analyses.
- If the GW energy upper limit does not compare favorably to the electromagnetic emission, the result would not necessitate its own publication and a simpler non-detection statement in either an end-of-run all-sky or GRB-specific publication would suffice.

---

[10] the web page produced by CWB detailing reconstructed parameters, time–frequency maps, reconstructed detector responses, likelihood time–frequency maps and reconstructed parameter skymaps

Post-BNS Follow-up: Any detection of high-frequency power associated with a BNS inspiral signal would be a major discovery. Papers reporting confident or marginal detections must be made on the same timescale as the deep CBC parameter estimation studies. The following criteria refer to the short-duration, high-frequency burst associated with the immediate post-merger regime of the coalescence signal:

Confident detection. Confident detection of a BNS post-merger signal would be comprised of clear evidence for a high-frequency oscillation component to the BNS merger in the 1–4 kHz band. 'Evidence' here would be comprised of a combination of Bayesian model selection statistics (i.e., an odds ratio, whose significance threshold is TBD from on-going parameter estimation studies), signal amplitude posteriors inconsistent with zero amplitude *and* a clear dominant mode in the signal frequency posterior probability density function. This scenario would consitute extremely high profile science and would allow accurate spectral analysis of the post-merger oscillation with potentially important implications for the neutron star EOS.

Marginal detections. Significance measures for marginal detection here are comprised of smaller values for Bayesian model selection statistics, amplitude posteriors peaked away from, but not inconsistent with, zero and some indication of at least one distinct mode in the signal frequency posterior PDF.

Even a marginal detection of high-frequency GW power in close temporal coincidence with a BNS inspiral signal would be an extremely significant discovery, confirming that the NS EOS is sufficiently stiff to, at least temporarily, survive gravitational collapse. In addition, it it is possible that estimation of the *dominant* post-merger oscillation frequency (also the most robust, Universal characteristic of these signals) will still be made with reasonable accuracy at low SNR. We do, therefore, plan for publication in the event of marginal detection.

No detections. With regards to the immediate short burst following a BNS signal, the significance of a null detection of a post-merger signal is marginal. We do not, therefore, envisage a dedicated publication in the event that this signal is not observed. GW amplitude or energy upper limits, however, may be of more interest in light of the potential for stable magnetar formation. If one assumes that a stable magnetar is formed, it may be possible to constrain some models for the magnetic field-induced quadrupole moment of a nascent magnetar. This would be particularly interesting in the event of an accurate distance measurement from e.g., host galaxy identification[11]. A dedicated publication reporting the non-detection of a short duration post-merger burst and the GW energy upper limit for the long-duration signal is envisioned. We do, however, expect that a remark would be made in a dedicated inspiral parameter estimation publication reporting that this analysis was conducted but found no evidence of a post-merger signal.

The publication plans and criteria associated with the search for a long-duration transient following a BNS inspiral detection are almost identical to those for long-duration transients in magnetar hyperflares. The exception is that the publication plan for the null detection scenario is identical to that for the short-duration burst: a remark in an inspiral-specific publication that the search was conducted but no evidence for a signal was found.

3.16.6 Technical Requirements and Development Plan

These searches will use X-PIPELINE in a similar configuration as for SNEWS-alert analyses, with an extended frequency range and some additional choice of time-frequency resolution; a modest amount of testing and validation is required to sanity check the performance of the algorithm at higher frequencies

---

[11] This would allow for a reasonable constraint on the GW energy emitted by the source and not simply the GW fluence at the Earth

and additional time-frequency resolutions (expected to be one additional resolution). The STAMP-based analyses are not expected to require further development.

The burst parameter estimation tools currently under development and described in section 3.1 will be used to follow up candidate detections for short-duration bursts. In addition to the on-going development and performance characterization[12] of these parameter estimation pipelines, some additional tuning will be desirable to target the high-frequency and late-time evolution of the BNS signal and, potentially, restrict the sky area searched to that which is consistent with the inspiral detection.

The bulk of development work is expected to be the development and use of appropriate waveform simulation infrastructure. For the short-duration post-merger bursts (where the detector antenna patter does not change significantly over the duration of the signal), the codes and infrastructure developed for the NINJA analyses should prove sufficient for assessing the performance of the analysis. The set of short-duration merger/post-merger waveform simulations used in the study in [245] is available for use in these studies and further simulations from other groups and collaborators may become available in the coming months. Longer duration signals where the antenna pattern changes significantly over the course of the signal will require some additional development and validation. Simulations of these longer duration signals will be based on astrophysically motivated analytic models such as those described in [246] and [247], as well as more ad hoc simulations to explore and characterize the sensitivity to non-stationary frequency content and signals whose frequency content tracks observed QPOs.

3.16.7 Resources

The expected number of events of direct interest to the NS group (Galactic hyperflares and BNS inspirals) during O1 is likely to be < 1. As stated, the analyses for both events is very similar: targeted short-duration burst analysis with X-PIPELINE and a long-duration burst analysis with STAMP with some overlap in sensitivity. Targeted burst parameter estimation analyses will be performed for both sources where appropriate.

Review Review requirements are minimal. The proposed pipelines (X-PIPELINE, STAMP) are reviewed and mature. Only configuration changes to the default used in X-PIPELINE will be required.

Similarly, the parameter estimation follow-up tools, BAYESWAVE and/or LIB are already to be reviewed for various other analyses; again, the only difference between those analyses and this would be in the configuration since it is possible that there may be a high frequency detection candidate.

Development No significant technical development should be necessary. The only changes from other, mature analyses will be in the time window and frequency range analysed. Table **??** details the development milestones and timelines involved.

Detector characterization: Neither of these proposed searches has any specific detector characterization / quality requirements above those of other triggered burst searches.

Calibration: It should be noted, however, that we do expect to analyze frequencies up to at least 4 kHz; *we therefore make the explicit request for calibrated data up to at least 4096 Hz with uncertainties matching those achieved for previous magnetar analyses in S5 onwards*. These searches are not expected to run at low-latency so this calibration requirement does not seem likely to pose additional overhead to the planned second pipeline all-sky analysis (which extends up to 4 kHz).

EM alerts: There is no immediate plan or obvious requirement that the results of these low-latency need to be communicated to electromagnetic partner observatories: both Galactic magnetar hyperflares and GW detections from binary neutron star coalescence are rare and will be of sufficient intrin-

---

[12] See https://wiki.ligo.org/Bursts/AllSkyPE

sic astrophysical importance that the results of the analyses proposed here will not contribute strongly to a decision to study the source further.

Finally, it is worth emphasising that we do not perceive any conflict or overlap with other externally triggered analyses. While it is likely that a Galactic hyperflare will initially trigger the online GRB burst analysis, such an event is unlikely to be included in a final GRB-specific publication. Furthermore, the analyses proposed here cover a wider and more appropriate signal space for magnetar triggers. Similarly, in the case of other related triggers arising from e.g., neutrino detectors or radio observatories, we do not propose any modifications to the search plans in order to maximise the signal space coverage.

3.17 Gravitational-Waves from Galactic and Near-Extragalactic Core-Collapse Supernovae

3.17.1 Abstract

The next supernova to explode in the Milky Way will be the most important astronomical event of the century. With their advanced-generation detectors, the LIGO Scientific Collaboration and the Virgo collaboration will for the first time have a good chance of picking up the gravitational waves (GWs) emitted if the supernova involved the collapse of a massive star and is a so-called *core-collapse supernova*.

Once a massive star (about 10 × the mass of the Sun or more) exhausts its fuel, its core collapses to a hot proto-neutron star. The proto-neutron star cools by emitting neutrinos, a kind of very weakly interacting elementary particle. A shock wave is launched from the proto-neutron star and plows through the stellar mantle. When it breaks out of the star's surface, it lights up the star in a supernova explosion. It is theorized that the shock wave is powered by the absorption of a small fraction ($\sim$10%) of the emitted neutrinos within the first second of the proto-neutron star's life. The neutrinos heat up the material above the proto-neutron star. This drives convection (think: hot buoyant bubbles rise, cold bubbles sink). This convection – a bulk motion of large amounts of material – leads to the emission of GWs. If the star's core was spinning, then also a burst of GWs that lasts for a few milliseconds is emitted when the proto-neutron star is first formed.

Neutrinos were detected from supernova SN 1987A, which exploded in the Large Magellanic Cloud, a neighbor galaxy of the Milky Way. Back then, no detector with sufficient sensitivity to detect GWs from a supernova was operational. Theoretical predictions of the GW emission suggest that the Advanced LIGO detectors have a chance of detecting the GWs from a core-collapse supernova in the Milky Way. The projected improved sensitivities in the 2016-17 (O2) and 2017-18 (O3) runs will possibly allow detection out to the Magellanic Clouds and the establishment of more stringent upper limits on the strength of GW mission for supernovae occurring in the Andromeda galaxy and even more distant galaxies in the Virgo cluster of galaxies. The chance of detection for a supernova in the Milky Way will be particularly high, because the neutrinos from the supernova will be caught in neutrino detectors. They will provide a very clear "timestamp" for when to look in the Advanced LIGO data.

Observing and characterizing GWs from the next nearby core-collapse supernova will open up a completely new observational window. It will allow us to measure, for example, how rapidly the progenitor star's core was spinning and how strong convection was right before the explosion. GW detection will thus help elucidate much of the still unknown physics that is going on as a star transitions from collapse to explosion.

In the search we propose here, we plan to rapidly follow up supernova neutrino event candidates sent by the SuperNova Early Warning System (SNEWS, `http://snews.bnl.gov/`) with model-independent GW searches that use constraints on GW emission time and sky location. Within days of a possible detection, we will characterize the GW signal and extract astrophysical information.

3.17.2 Scientific Justification

The next galactic (core-collapse) supernova ([CC]SN) will be the most important astronomical event of the century and the world will look to the LIGO Scientific Collaboration and the Virgo Collaboration for statements about its GW emission. Multimessenger observations in photons, neutrinos, and gravitational waves of the next nearby CCSN will revolutionize our understanding of massive star structure and angular momentum distribution, of core collapse dynamics, of the still uncertain CCSN explosion mechanism, of explosive nucleosynthesis and mixing of synthesized elements in the explosion, and of fundamental physics such as the equation of state of nuclear matter and neutrino interactions.

GWs are produced by bulk aspherical accelerated motion of mass-energy and in the CCSN context are thus a direct probe of the uncertain degree of asymmetry of the supernova engine. GWs are expected to be emitted by a broad range of processes (e.g., [248, 249]) many of which can be directly associated with particular explosion mechanisms. For example, the GW signal from neutrino-driven convection can be connected to the neutrino mechanism or the strong signal from rotating core collapse can be linked to magnetorotational explosions (e.g., [250, 251]). GWs from rotating core collapse can be used to measure the angular momentum of the collapsing core [252, 253]. GWs from neutrino-driven convection and the standing accretion shock instability can be used (1) to infer the moment of the onset of explosion and (2) to constrain the structure of the nascent neutron star and in this way put constraints on the nuclear equation of state (in combination with neutrino information; e.g., [254, 255, 256]). An abrupt end of GW and neutrino emission would unambiguously herald the formation of a black hole (e.g., [257, 258]).

Much work has been directed toward understanding GW emission from CCSNe and the detectability of the waves at various levels of sophistication: theoretical estimates of optimal or angle-averaged signal to noise ratios (SNRs; e.g., [249]), sensitivity estimates based on real re-colored noise with projected O1 sensitivity and a two-detector network [259], and detection upper limits from the ongoing search for GWs from distant CCSNe in S5/A5/S6 data [260]. These studies show that a galactic CCSN at a distance of $1 - \mathrm{few\,kpc}$ may be detectable by an L1–H1 O1 detector configuration. In the planned O2 and O3 science runs, improved detector sensitivity may allow detection throughout the Milky Way even if pessimistic emission scenarios are considered. A non-detection of a confirmed core collapse event, even during O1, would put highly significant constraints on the degree of asymmetry of the supernova engine. Detection of a CCSN at Small/Large Magellanic Cloud (SMC/LMC) distance will likely require projected the sensitivity projected for later science runs and optimistic emission scenarios such as rotating core collapse, but will still yield astrophysically highly interesting upper limits in the case of a non-detection.

MeV-energy neutrino and GW emission in a CCSN will set in within a few milliseconds of each other (e.g., [261]). A galactic (extragalactic) CCSN at $10\,\mathrm{kpc}$ $(100\,\mathrm{kpc})$ will result in $\mathcal{O}(10,000)$ $(\mathcal{O}(100))$ neutrino events in worldwide detectors. Limited directional information, at an error level of $5^\circ - 20^\circ$, will be available from neutrino observations [262]. Information about these neutrino detections will be disseminated with low latency by the SuperNova Early Warning System (SNEWS, `http://snews.bnl.gov/`, [263]) and can be used to set a tight ($\sim 4\,\mathrm{min}$, [259]) on-source window for a rapid-follow-up GW search. Such a short on-source window dramatically reduces the background of all-sky/all-time search and searches relying on information from electromagnetic detection of the CCSN.

We propose an online SNEWS-triggered low-latency, rapid-follow-up search for GWs from nearby CCSNe with X-PIPELINE [5]. The motiviation for the online search is to provide alerts to the scientific community containing the GW-estimated sky position, ahead of the light emission of SN that is expected up to a day later. Subsequent to a SNEWS trigger with or without GW detection candidate from the online search, we will carry out deeper offline analyses with X-PIPELINE and Coherent WaveBurst 2G (CWB2G, [264]). Upon detection, effort will be directed toward waveform reconstruction and parameter estimation to determine baseline signal properties such as central frequency, time-frequency evolution, and to extract astrophysical parameters such as the most likely explosion mechanism and the amount of angular momentum present in the collapsing core.

This search is motivated and informed by the S5/A5/S6 optically-triggered search for GWs from distant CCSNe [260] and by the sensitivity study of [259]. CCSNe are prime galactic science for Advanced LIGO and Advanced Virgo. CCSNe occuring at distances beyond the Milky Way are unlikely to be detectable with projected two-detector O1 sensitivity on the basis of current GW signal predictions from detailed multi-dimensional simulations (e.g., [255, 265, 249]). However, extreme emission scenarios associated with longer-lasting ($\sim$ one to two seconds) barmode instabilities (e.g., [266]) or fragmenting accretion disks [200] could be constrained for more distant CCSNe [259].

In addition to the SNEWS-triggered search in O2 science runs, we are also working on two additional searches:

(**1**) the development of a search for setting upper limits for GW emission from extragalactic CCSNe exploding within $20\,\mathrm{Mpc}$ of Earth, using optical triggers. This search will be carried out on data from O1, O2. Its motivation is to exclude the most extreme GW emission scenarios for CCSNe at much higher sensitivity

than possible with S5/A5/S6 data [260].
(**2**) the development of a deep search for coincident sub-threshold GW and neutrino events from potential (dark) local-group CCSNe. This search will first be carried out on archival data/triggers from S5/A5/S6 LIGO/Virgo data and triggers from the IceCube [267, 268], LVD [269, 270], and Borexino [271, 272] neutrino detector collaborations.

3.17.3 Search Description

SNEWS-triggered search: The goal of the SNEWS-triggered analysis is to provide a directed online search for a GW burst associated with a galactic or SMC/LMC CCSN. The directed online search will be carried out with X-PIPELINE [5] and will complement the all-sky online analysis with Coherent WaveBurst 2G (described in the all-sky burst search proposal, [204]). After a SNEWS trigger, we will carry out deeper offline analyses with CWB2G, which will complete within a few days. An important issue for this search is that there is a significant probability that at the time of a SNEWS trigger only one detector will be online. Extreme care will be required to vet detection candidates and to take full statistical advantage of the information provided by SNEWS. It is understood that poor data quality around the SNEWS trigger may prevent a strong detection statement. Single-detector searches with and without external triggers have been carried out before by Virgo [273, 274] and we will build upon the experience gained by this previous work.

A nearby CCSN will produce a prominent signal in the global array of neutrino detectors such as Super-Kamiokande [275, 276], Borexino [271, 272], and LVD [269, 270]. In preparation for such an event, the neutrino community has an established alert system known as SNEWS [263]. SNEWS will provide an automated email alert of “GOLD” events to registered users with an estimated latency of five minutes or less.[13] The best pointing accuracy will be approximately $5^\circ - 20^\circ$ from Super-Kamiokande [262], but this information may not be immediately available at the time of the alert. We therefore envision an all-sky scan for GWs at the rapid-follow-up stage and incorporate directional information in a subsequent offline search.

In the case of a SNEWS alert, the cWB analysis will be rerun offline as needed after any significant changes to calibrations, data quality, or as further information on the supernova is received. In particular, we forsee re-running the analysis as improved sky position information becomes available and a more sensitive search (perhaps by up to a factor of two, e.g., [71]) becomes possible.

For the directed CWB2G offline search, we will use the 60s of data to perform the search and 3 hours of data around the SNEWS trigger to estimate the background. We will present a detection statement with 5-sigma confidence within two days of the SNEWS trigger. The actual duration of individual analysis jobs will be less than 15 minutes (estimated from the online speed of CWB2G, [264]) , but preparation and checking will require human input and intervention. The CWB2G offline search will be run in multiple configurations using parameter settings optimized to best resolve the different expected GW emission mechanisms. The base CWB2G code will be run with a sky mask that will take advantage of the almost exact knowledge of the sky location of the CCSN at the time of the offline analysis. In the unlikely case no or only poor direction information is available at the time of the CWB2G offline analysis, the sky mask will be dropped or tuned accordingly. if the ER10 SN calibration studies show that the impact of calibration errors is a concern, in case of a nearby CCSN the supernova hardware injections will be immediately requested. Several developments are planned for the O1/O2 optically triggered SN search (see section 3.1.9). In case of a Galactic or near-Galactic SN, only the pipelines and features that are reviewed at the time of the SNEWS alert will be included in the first pubblication, unless under-review pipelines/features are necessary for a detection statement.

Parameter Estimation Follow-Up: Upon an identification of a detection candidate by X-PIPELINE (or in the offline-only CWB2G analysis), we intend to carry out an array of rapid follow-up analyses to infer

---

[13] The false alarm rate for SNEWS alerts is estimated to be less than one per century [263].

general signal properties and physics/astrophysics from the detection candidate.

- We will characterize the detection candidate waveform's central frequency and time-frequency content and reconstruct the waveform using tuned configurations of the BAYESWAVE [222], and CWB2G [264] algorithms. We will also utilize the LALInference_Burst (LIB, [223]) pipeline for parameter estimation, using the sine-Gaussian signal model.
- We will employ the Supernova Model Evidence Extractor (SMEE, [251], [277]) to find the CCSN explosion mechanism that is best fit by the detection candidate. Should there be a detection candidate, the burst group will carry out an ad-hoc review of SMEE and expedite a more detailed review for subsequent follow-up papers. We expect a formal review of the SMEE pipeline to start early 2017.
- We will use a multivariate regression model for waveform prediction by Engels *et al.* [253] in combination with MCMC sampling to estimate the total angular momentum and the degree of differential rotation in the progenitor star's inner core. We will use the GW signal catalog of Abdikamalov *et al.* [252] as the bases for our waveform model. This method has not been reviewed and a review until O1 is unlikely. Should there be a detection candidate that is identified as rotating core collapse, the burst group will conduct an ad-hoc review of this approach and expedited a more detailed review for subsequent follow-up papers.
- We will employ a novel time-frequency (spectrogram-based) analysis to infer physical parameters such as the postbounce accretion rate, the structure of the proto-neutron star, and the strength of neutrino-driven turbulence. This analysis is presently under development and is unlikely to be mature by the start of O2.

EM-triggered search to establish upper limits for extragalactic CCSNe: This search will be along the lines of the current S5/A6/S6 search [260], but will be carried out with CWB2G We will select CCSNe that have well established on-source windows from late optical non-detections / early optical detections by supernova surveys. Main goals of this search are to put constrains or exclude some of the extreme emission models and present updated upper limits for GW energy. Additionally several new techniques that are under development will be incorporated into the search. List of these techniques can be found in section 3.1.6. We do not plan a parameter estimation component for this search.

Neutrino-triggered search for (dark) local-group sub-threshold GW bursts from CCSNe: A new effort aiming to perform a joint search for GWs and low-energy neutrinos from CCSNe is under development. This search intends to use neutrino data from individual neutrino detectors (and thus not available as SNEWS alerts) in order to improve the search sensitivity (in terms of distance reach and overall model parameters). This is achieved by lowering thresholds of individual detectors. The effort looks forward in establishing a working relation with the low-energy neutrino detector community, preparing us for the next nearby CCSN and developing joint analysis strategies that will maximize the science output of such astrophysical events. A proposal –and a corresponding Memorandum of Understanding– for such a joint search was approved in 2014 by the LIGO-Virgo collaborations and the Borexino [271, 272], LVD [269, 270], and IceCube [267, 268] neutrino detector collaborations. The effort so far has been focusing on developing common simulation engines for the three neutrino detectors in order to establish their joint sensitivities. Adding GW simulations into this framework as well as analyzing archival data from the 2005-2010 science as a prototypical search are the next steps in this. We expect this effort to ultimately lead during later observing runs of Advanced LIGO-Virgo to a low-latency search for CCSNe that will involve both the neutrino and GW data.

3.17.4 Results Validation Plan

In the event a galactic CCSN occurs and the X-PIPELINE search is triggered by a SNEWS alert, we will immediately follow up the low-latency analysis to validate its results:

- We will carry out offline analyses with X-PIPELINE and CWB2G that take information about the location of the CCSN into account. This offline follow-up is integral part of our search plan (see §3.17.3).
- We will compare the results of our search with the untriggered all-sky CWB2G and omicron+LIB.
- We already plan to employ multiple parameter estimation approaches (see Search Description, §3.17.3). These generally complement each other, but also have some overlap (e.g., in signal reconstruction). We will use overlapping capabilities for cross-validation. The SMEE pipeline exists in multiple implementations and we will cross-validate results of each independent implementation.

A Galactic CCSN will be an exciting event and the scientific community will want to know as soon as possible if we have a detection. Though pipelines that are not reviewed at the time of SNEWS trigger will not enter the search unless they can provide an important scientific merit that cannot be provided by any other pipeline. S5/A5/S6 SN search paper provides instructions of how to combine results of two or more pipelines.

3.17.5 Publication Plan

A galactic/near extragalactic CCSN will be an extremely important astrophysical event. A GW analysis will be of very high interest even if no signal was detected. Our goal will be to have a complete paper draft within 3 months of the event. The target journal would be a high-profile journals such as *Physical Review Letters* or *The Astrophysical Journal Letters*. We envision a more extendend report within 6 months of the event in a subsequent paper with more details on parameter estimation and constraints on astrophysical parameters and fundamental physics. The target journal for this will be *The Astrophysical Journal* or *Physical Review D*.

For O1/O2 optically triggered search we estimate start of the review in the fall 2016. The paper draft is planned to be ready 3 months after O2 (October 2017) and the submission to the journal is planned 6 months after O2 (Janaury 2018). The target journal is *Physical Review D*.

3.17.6 Technical Requirements and Development Plan

SNEWS-triggered online search: X-PIPELINE will be used. The core pipeline and the online triggering system were used to do fully autonomous GRB-triggered searches in S6/VSR2,3. Only small modifications are expected to be needed for the SNEWS triggered search, with minimal review burden. The major milestones for the search already accomplished:

- We have enabled GraceDB to receive and parse SNEWS alerts.
- We have implemented code which appropriately calculates the H1-L1 time delays that will cover all potential source locations at the initial alert with no sky-position information.
- We have investigated what X-PIPELINE parameters are optimal to use in the case of single detector data. The achievable significance with a loud event in the single interferometer case has not been estimated yet.

SNEWS-triggered offline follow-up: CWB2G will be used. The version of CWB2G to be run will be very similar to the reviewed all-sky version The main difference on the CWB2G side compared to the S5/A5/S6 optical search will be a shorter on-source window and the use of data around the on-source window for background estimation. Several developments are planned for the O1/O2 optically triggered SN search (see same section). Galactic or near-Galactic SN might happen any time and some of the developments will be included if mature and reviewed while the SNEWS alert.

Parameter Estimation Follow-Up: At the time of writing, the LIB, BAYESWAVE, SMEE parameter estimation / model selection, and waveform reconstruction with BAYESWAVE and CWB2G have reached partial maturity. Some additional development and simulation work is needed to ready these parameter estimation pipelines for follow-up of a potential SN trigger.

The BAYESWAVE pipeline currently makes assumptions about the polarization of the detected signals and the SMEE pipeline still requires further development (inclusion of multiple detectors, different kinds of principle components and signal models etc.).

Significant work will be required to ready multivariate/MCMC angular momentum estimation [252, 253], signal reconstructions/characterization, and advanced parameter estimation using GW spectrograms that will go after progenitor parameters such as the postbounce accretion rate or the compactness parameter [278]. The goal is (1) to run preliminary versions of these algorithms and ad-hoc review them if there is detection in O2 and (2) bring these algorithms to full maturity and review them by O2.

The major milestones for parameter estimation are:

- Further test, bring to full maturity, and review basic signal characteristic extraction and signal reconstruction with the optimal set of the LIB, BAYESWAVE, and CWB2G codes.
- Deploy a multi-detector SMEE pipeline that can be run on X-PIPELINE and CWB2G detection candidates. Multi-detector SMEE is mature but not reviewed by the start of O2. It will be run only on detection candidates in O2 and will then receive an ad-hoc review if a detection is confirmed. A full review of SMEE is expected to completed before the end of O2.
- Ready a multivariate regression / MCMC pipeline for angular momentum estimation [253, 252] that can be run on X-PIPELINE and CWB2G detection candidates. We expect a preliminary version of this pipeline to be ready to be run in case of a detection in O1 (and to be reviewed in an ad-hoc review) and a reviewed mature version to be available by O2.
- Develop and test an advanced parameter estimation pipeline based on GW spectrograms to infer progenitor physics such as postbounce accretion rate and compactness from neutrino-driven CCSNe. We plan for an initial version of this pipeline to be ready by O2 and a fully mature and reviewed one to be completed by O3.

Mock Data Challenge: SN MDCs for the tests and developments in O2 will be created using Minke software and the review is planned in the fall 2016. cWB team will use either MDCs created with Minke or MDC On-The-Fly that is already reviewed.

cWB planned developments: In O2 cWB team will perform extensive development studies that are carried to benefit O1/O2 SN search. A list of developments include the following:

- *The Rate of Core-Collapse Supernovae within the Local Universe yielding Astrophysically based SNe populations for All Sky Searches.* This study is divided into two parts: an estimate of intristic SN rate within Local Universe versus the observed rate and application of counting methods. The results are planned to be published in the fall 2016 and the assigned dcc number for the paper is P1500232.
- *Harmonic Regeneration Noise Reduction (HRNR)* HRNR is a plug-in to CWB2G for the noise reduction procedure developed by the University of Texas at Brownsville group [279]. This method

involves a two step noise reduction approach based on accurate spectral estimation. The Matlab/C++ codes are fully modular and can be integrated with the pipeline with minimal intervention. The goal of this analysis is to enhance the efficiency of the CWB2G search for GWs from CCSNe. We have derived several receiver operating curves for large variety of waveforms with combinations of the iLIGO/Virgo and O1 data showing systematic improvement. The algorithm is finalized and it is ready for the review that will start in the fall 2016. Along with the methodology paper [279] a companion paper focusing on results including different SN morphologies is in the writing phase.

- *Distributional Tests* Realistic GW signals from CCSNe are predicted to be rather weak unless Galactic SN. We expect order of 4 CCSNe a year in the Local Universe. The goal of this study is to create a statistical framework for detection statements using multiple supernovae.
- *Using BW as follow up to cWB events* It was demonstrated that BayesWave as a follow-up of cWB gives better noise reduction than cWB alone for binary system searches. We are testing robustness of this approach for SN waveforms especially for rapidly rotating waveforms.
- *Pairing SMEE with the search* It was demonstrated that SMEE pipeline can distinguish explosion mechanisms of the GW triggers as well as it can be used for glitch removal. We want to test its potential for SN search to distinguish SN signal from the noise.
- *SN Detector Characterization* The study has the goal to establish if the nature of the glitches originating from cWB with SN specific tunings are different from those originating with all-sky tunings.
- *Single Detector Case* The cWB team is planning to expand and continue the studies on the single IFO case that were performed by the X pipeline until March 2016 to achieve significance with a loud event in the single interferometer case that has not been estimated yet.
- *Hardware injections* Harware injections in engineering runs are planned to quantify the impact of calibration errors on the correlation of the GW signal between different interferometers. In turn this allows to quantify the impact on detection statistics and parameter estimation/waveform reconstruction measures.

3.17.7 Resources

A galactic core collapse supernova would be an event so rare and so important that it would be imperative for the LSC and Virgo to make available all necessary resources for a complete and rigorous analysis; the scientific world would be watching. In particular, we would expect that the requested computing resources would be made available *even if this requires temporarily pre-empting non-SNEWS analyses*. However, time-critical low-latency searches should be allowed to continue. Also, computational requirements for additional supernova analyses not already discussed in this search plan will need to be justified and will require an ad-hoc review. This is to ensure that other searches are not unreasonably pre-empted by unplanned supernova work.

The various parameter estimation and waveform reconstruction pipelines that would be used in a follow-up analysis of a SN trigger are still under development and require computing resources for testing and simulation work in the 2015-2016 time frame.

The O1/O2 search, the neutrino-triggered search and parameter estimation studies are under development. The computational estimates for O2 and O3 of the searches and developments with optimization plans can be found in: https://wiki.ligo.org/Bursts/SNO1Computing. In summary, O2 computional cost is estimated to be $930,000$ SU and for O3 it is $2,025,000$ SU.

3.18 Search for transients in coincidence with Fast Radio Bursts

3.18.1 Abstract

Since the publication in summer 2013 of four Fast Radio Bursts (FRBs) identified in Parkes Telescope data [280] there has been considerable scientific interest in these millisecond-scale radio transients which, based on their observed dispersion measures, appear to occur at cosmological distance scales. A total of 17 FRBs have been published so far [281]. Currently, while numerous papers have suggested plausible sources for these radio transients, their origin is unclear. While not all plausible mechanisms for emission of FRBs are likely to result in simultaneous gravitational wave (GW) emission at detectable frequencies, there are several mechanisms which may result in coincident signals. Searches in initial detector data in coincidence with known FRBs have already been conducted [282], and plans are underway to continue these analyses using Advanced detector data.

3.18.2 Scientific Justification

Little has been definitively determined about the source of fast radio bursts, so we have elected to perform a “burst” search to look for gravitational waves as broadly as possible, in hopes of providing insight into the mechanism causing FRB emission. Current results suggest that FRBs are of astrophysical origin rather than being “perytons” from terrestrial sources [283, 284]. Nevertheless, if FRBs result from stellar collapse scenarios [285] then we would not expect a GW signal. There are, however, a number of astrophysical phenomena that may plausibly produce gravitational waves in close coincidence with radio frequency emission matching the characteristics of FRBs. The discussion presented here is not an exhaustive list of source candidates, rather we focus on three general classes of sources which may produce both GWs and FRBs with frequency and duration suitable to the instruments being used in these analyses. Further discussion of these mechanisms can be found in [286].

Cosmic strings - Cosmic strings, formed during symmetry breaking in the early universe, are topological defects thought to be capable of emitting large amounts of energy from their cusps or kinks [287] and have been suggested as a possible emission mechanism for FRBs [288, 289]. A cosmic string cusp may emit gravitational waves with a $f^{-4/3}$ frequency dependence up to a cutoff frequency [290], potentially at frequencies and amplitudes detectable by ground-based interferometers [185, 10].

This class of sources is particularly promising for purposes of an FRB related search since the distance scales on which GW signals may be observable for cosmic strings are consistent with the cosmological scales suggested by current FRB observations.

Binary neutron star coalescence - There are several models for radio emission in coincidence with a compact binary coalescence GW signal. This may be pulsar-like radio emission, either from the reactivation of the dormant pulsar emission in one of the neutron stars through interactions prior to merger [291] or by a hypermassive neutron star, which may sometimes result as an intermediate result of a merger before collapsing to a black hole, emitting at radio frequencies through a pulsar mechansism [292]. A third possible mechanism is the radiation at radio frequencies as a result of magnetospheric interactions [293].

Given an appropriate density in the surrounding environment, the gravitational waves emitted by a compact binary coalescence may induce electromagnetic radiation through magnetohydrodynamic interactions. While this interaction would directly produce radiation at the same relatively low frequencies as the GWs themselves, upconversion through inverse compton radiation may result in emission at radio frequencies [294]. This particular magnetohydrodynamic mechanism does not necessarily require neutron star coalescence as the mechanism for production of the GWs, but this class of source is likely to be able to produce GWs of suitable amplitude and may be surrounded by an environment suitable to this mechanism [295].

Single neutron stars - Most models of gravitational-wave emission resulting from single neutron stars would most likely produce signals too weak to detect at the distance scales suggested by the dispersion measures under consideration. However, if FRBs result from extreme SGR events as has been suggested [285], if future observations result in a lower dispersion measure event, or if some subset of FRBs is much closer than estimates due to the bulk of the dispersion happening close to the source rather than in the intergalactic medium, this class of models is still worth considering.

Transient gravitational wave emission can occur when a temporary deformation of a rapidly rotating neutron star creates a quadrupolar moment. Typically, this is believed to happen as a result of crust cracking from magnetic, gravitational or superfluid forces, dubbed a starquake [296], or from other asteroseismic phenomena resulting in shifting of the neutron star's crust [297]. While asteroseismology may result in several distinct types of quasinormal oscillatory modes of the neutron star, the f-mode is the most promising for the purpose of gravitational wave detection. Gravitational emission resulting from f-mode oscillation typically peaks around 2 kHz, although the exact emission depends on several factors, including the neutron star equation of state and the mass of the emitting neutron star [228]. The amplitude of the GW emission even in optimistic cases, however, is small enough that sensitivity to this type of source will be limited to our own Galaxy even in the advanced detector era.

Radio pulsars result from beamed emission from the poles of a rapidly rotating, highly magnetized neutron star sweeping past the Earth, producing reliably periodic radio signals. The asteroseismic events described above may result in a distinct increase in the rotation rates of these neutron stars, typically followed by a gradual return to their original period. This phenomenon, called a pulsar glitch, has been observed across a large number of pulsars, especially younger ones (see e.g. [298] and references therein). A search for gravitational wave emission from quasinormal modes in coincidence with the observed glitching of pulsar was the subject of a previous LIGO publication [235]. Models for neutron star asteroseismic phenomena similar to those under discussion have also motivated previous gravitational wave searches in coincidence with SGR flares [299].

The standard indication of an asteroseismic event in an isolated neutron star is a pulsar glitch, but there are are plausible mechanisms that could result in the observation of a transient radio pulse. This could simply be through the pulsar radio emission coming into view from the Earth as the pulsar's orbit shifts slightly, but there is also some evidence that pulsar-like radio emission can be "switched on" in coincidence with with a glitching mechanism [300, 301, 302]. We therefore consider single neutron stars as a possible source of coincident GW and radio transient events.

As the FRB121102 has been observed by Arecibo to be a repeating signal [284], some additional credence has been lent to these single neutron star scenarios as possible sources of FRB emission in recent months.

3.18.3 Search Description

Currently, MoUs are being negotiated to facilitate rapid communication of known FRBs from the SUPERB survey utilizing the Parkes telescope or the Realfast project utilizing the VLA. The GW/FRB coincidence search will be conducted as a "target of opportunity" search when the timing and spatial information of known FRBs are either provided by partner collaborations or made available from other sources via publication. Based on previous observation rates, the rate of observation is expected to be less than 1 FRB per month, with a rate increased by an order of magnitude if VLA's "Realfast" program is successfully run overlapping with O2.

Since the search for transient GWs of unknown morphology in coincidence with a known electromagnetic signal suggests an approach similar to established burst GRB searches, the first FRB-coincident analysis described in this search plan uses a "GRB-type" X-Pipeline analysis. The analysis uses existing X-Pipeline code and does not require separate code review, however the parameters of the analysis have been adjusted to reflect the astrophysical models under consideration for this particular search. Relative to the standard X-Pipeline based burst GRB search, the FRB coincident search utilizes a shorter duration on-source window. This reflects our expectation that joint radio and GW emission should generally occur within seconds of each other for the set of viable models we consider, based on a case-by-case analysis of the sources considered in the “scientific justification” section. We also use tighter spatial localization given Parkes’ relatively narrow field of view, as well as a different set of simulated waveform software injections used to tune background rejection cuts that are consistent with the sources described in the “scientific justification" section above. Specifically, two compact binary coalescence, two cosmic string cusp, two sine gaussian, two chirplet sine gaussian and two damped sinusoids of different frequencies are used to represent a broad distribution of plausible emission mechanisms. A subset of these waveforms overlaps the set used for standard GRB X-Pipeline searches, including the NS-NS (1.4 solar mass) and NS-BH (1.4 and 10 solar mass, respectively) waveform types. Since single neutron star emission mechanisms are under consideration as a plausible source of joint emission, we also truncate the analysis at 3 kHz rather than 2 kHz where higher frequency analysis is permitted by the calibration of the interferometers.

As with similar externally triggered searches, a single trial false alarm probability of 0.01 or lower would trigger some follow-up activities as outlined in the X-Pipeline wiki pages. If the candidate survives initial scrutiny, further follow-up procedures as laid out on the burst “detection checklist” would be initiated. In the event of a viable detection candidate, parameter estimation may be a useful means of distinguishing between various emission scenarios, especially as a diverse group of possible sources are considered in this analysis.

A second FRB/GW search will be conducted by using spatio-temporal coincidence of known FRBs identified by the SUPERB survey and sub-threshold triggers from existing gravitational wave all-sky searches. The exact analysis method and statistical framework for this search will be fine-tuned during the coming year, with details of the analysis depending on the number of observed FRBs in coincidence with LIGO/Virgo data.

3.18.4 Publication Plan

In the absence of a detection, but given a sufficient number of analyzable FRBs (to be determined, but on the order of a dozen or more triggers) a combined O1 and O2 upper limit paper will be written. If too few analyzable FRBs are identified over this period, a combined O1, O2 and O3 upper limit paper will be written. Any collaboration with which signed MoUs have resulted in analyzed FRBs will be included as authors on this upper limit paper.

“Evidence” or “detection” of a GW, according to standards agreed to by LIGO and Virgo, would merit its own publication. Members of partner collaboration would be included as authors in this paper as per MoU agreements. If detections were made in both an FRB triggered search and another analysis over the same data, a single “detection” paper would be written in collaboration with the other searches. The collaborations involved would reach a decision about dedicated follow-up papers focused on implications of a specific analysis.

It should be noted that since the source of FRBs is still an ongoing debate the burden of proof to establish “evidence” or “detection” may be higher than in externally triggered searches where the joint emission mechanism is more clearly established (such as GRB searches). Plans to follow-up FRBs as external triggers for gravitational waves in later observation runs may be affected by the evolving science around FRBs. In particular, if the broader astrophysics community is able to come to a consensus regarding the origin of these bursts then the motivation for pursuing FRB-GW analyses will need to be revisited.

3.18.5 Results validation plan

In addition to the published radio transient search paper [282], X-Pipeline has been used in numerous previous externally triggered searches [303, 214, 304], and is therefore considered a dependable search method. While there is no plan to run a second targeted pipeline on radio transients, all-sky analyses over the same stretch of data will serve as a useful cross-check in order to validate the results. As the primary burst all-sky [305] pipeline, coherent WaveBurst [264] is expected to be the main tool used for this, although in the event of an interesting trigger, omicron+LIB and possibly CBC pipelines [306, 307] would be utilized as well.

Like the X-Pipeline-based search, the FRB search using existing sub-threshold GW triggers utilizes well-established search algorithms and so requires minimal work for reviewing the validity of results. The statistical methods used to establish correlations between GW and FRB triggers will be subject to the usual internal LSC review procedures prior to publication or presentation.

3.18.6 Resources

Computing needs - Since the analysis correlating sub-threshold GW triggers with FRBs utilizes data from existing searches, required computing resources will be small with respect to other GW analyses.

For the X-Pipeline-based analysis, requirements on a per-trigger basis are similar to the burst analysis of a Swift GRB. We estimate that 9500 SUs would be required for each FRB event based on previous events occuring in initial LIGO/Virgo data. Since these FRBs are identified by Parkes infrequently (less than one event per month based on identified FRBs [281] and data sets with known non-detections) the overall use of computing resources is negligible relative to the most computationally intensive all-sky all-time searches. This may increase substantially if VLA's Realfast project performs as hoped and has substantial overlap with O2, but will most likely remain at least an order of magnitude below the GRB detection rate for the next couple years.

Detector Characterization and Calibration - As the FRB search primarily utilizes X-Pipeline and other existing low-latency infrastructure, no additional effort should be required for purposes of detector characterization or calibration. (The possible exception to this statement would be a statistically significant event, which would require exercising the full detection checklist.)

Review - Most of the code utilized was already reviewed in the context of previous searches, e.g. [308]. Supplemental review for minor code adjustments and analysis procedures specific to radio-coincident analyses was performed as part of the Green Bank analysis [282] . Therefore no additional code review is required for ongoing FRB searches.

3.19 All-sky Searches for Isolated Spinning Neutron Stars

3.19.1 Abstract

Gravitational waves (GWs) are small ripples in the geometry of space-time, predicted to exist by Einstein's Theory of General Relativity, and propagating at the speed of light. Rapidly spinning neutron stars in our galaxy may emit such waves if they are not perfectly symmetric around their spin axis. Their deviation from such axisymmetry is usually characterized by a parameter called *ellipticity* which, for example, might be as large as 10^{-6} for a broad, 1-cm-high *bulge* across the surface of the 20-km-diameter star. A comprehensive search has been carried out in data from the LIGO and Virgo gravitational wave interferometers for signals from such spinning stars. No such signal was detected, allowing scientists to rule out rapidly spinning neutron stars with ellipticities greater than 10^{-6} anywhere within 2000 light years of the Earth. Those limits are more stringent (10^{-7}) for neutron stars within 200 light years. We describe here the plans to extend the all-sky search for isolated spinning neutron stars to the next generation of ground based gravitational wave detectors. New data to be taken in the coming year after improvements to the LIGO and Virgo detectors is expected to be still more sensitive, allowing scientists to probe deeper into the galaxy and down to smaller ellipticities, in the hope of detecting these expected continuous waves for the first time.

3.19.2 Scientific Justification

Rapidly rotating neutron stars (NS) are the most promising sources of continuous-wave (CW) gravitational signals in the LIGO and Virgo frequency band. These stars are expected to emit gravitational radiation through a variety of mechanisms, including elastic deformations [309, 310, 311], magnetic deformations [312, 313], unstable r-mode oscillations [309, 314, 315], and free precession [316]. A review of these emission mechanisms can be found in [317]. Here, we focus on the all-sky search for unknown, isolated neutron stars. The number of undiscovered, electromagnetically quiet neutron stars within 5 kpc can be estimated to be $O(10^6 - 10^7)$ from the neutron star birth rate [318], although it is likely that only a tiny fraction would both be rotating fast enough to be accessible to LIGO [319] and remain bound to the galaxy over the age of the galaxy [320]. Only ∼2500 radio or x-ray galactic pulsars have been discovered so far [321]. It has been argued, based on the observed supernova rate and inferred population of neutron stars in the galaxy, that the indirect limit on the strongest signal from this population is no higher than

$$h_{\rm IL} = 4 \times 10^{-24} \left(\frac{30\,\rm yr}{\tau} \right)^{1/2}, \qquad (1)$$

where τ is the mean time between supernovae in the Galaxy. The latest and most detailed derivation of this upper limit is given in [317]. Note, however, that a later simulation analysis found significantly lower expectations that depend on the assumed source frequency and ellipticity [322]. Moreover, these calculations make the optimistic assumption that a sizable fraction of neutron stars are gravitars, *i.e.*, their spindown is dominated by gravitational wave energy loss. In the end, the first detection of a previously unknown source may come down to a statistical fluctuation of a star's being especially near the Earth.

The absence of a signal detection does not place strong limits on neutron star physics, unfortunately. While exotic equations of state (EOS) *permit* relatively large ellipticities, accessible to the initial and advanced detectors, those EOS *do not require* that such ellipticities be realized in stars. The actual ellipticity of a star will presumably depend on its initial conditions and perhaps on its environment via post-birth accretion. Hence we simply do not know how close we might be to a first detection. On the other hand, observation of a CW signal would potentially reveal a great deal about NS EOS, especially once a corresponding electromagnetic counterpart were identified, ideally, in multiple bands.

3.19.3 Search Description

Given our ignorance of the physics of neutron stars (which may well be quark stars or hybrid stars) and given the tiny fraction observed to date ($<10^{-5}$ most likely), it seems prudent to cast a wide net in searches for these exotic yet pervasive objects, wide both spatially and in assumed phase evolution.

Below we describe five search pipelines, all of which are computationally bound, that make different tradeoffs in intrinsic strain sensitivity *vs.* robustness against deviations from assumed phase modeling. Four are "quick-look" pipelines, and one (Einstein@Home) aims at deeper searches, exploiting the substantial resources available via distributed computing with O(100K) users. With these pipelines we intend to search a GW frequency band from as low as 10 Hz (detector sensitivity permitting) to as high as 2000 Hz. The fastest known pulsar rotates at 716 Hz, implying GW radiation at 1432 Hz for a rotating-ellipsoid model; to be conservative, we plan to search well above this observational limit. The spindown range over which to search is affected by available computing resources, by the assumed minimum age of the stars, by the assumed ellipticity distribution of the stars and by the assumed maximum distance to the stars. As a minimum, we will search the spindown range -10^{-8} Hz s^{-1} $< \dot{f}_{\rm GW} < 10^{-9}$ Hz s^{-1}, where a slightly positive frequency derivative upper bound is chosen in the spirit of keeping one's eyes wide open and mindful that a star in a long-period binary system could appear to have a spin-up instead of a spin-down. Choosing rectangular coverage in the f–$\dot{f}$ plane is somewhat arbitrary in its simplicity, but has the virtue of automatically searching younger stellar ages at low frequencies, where young pulsars are predominant. We will likely also search for still higher spindown magnitudes and perhaps higher frequencies in lengthier searches, as discussed below. For now we plan to search these nominal frequency and spindown ranges with no special preference given to any subset (e.g., via longer coherence or observation times), but we may refine our search strategy if future detailed studies based on galactic neutron star modeling suggest that doing so can substantially improve detection probability.

An all-sky search faces formidable computing challenges. The parameter space over which one must search includes source right ascension and declination, source frequency and at least one frequency derivative, along with source inclination and polarization angles. For coherent integrations, the computational cost scales as the sixth power of the coherence time (if a single frequency derivative suffices) and as the cube of the upper limit on search band frequency. To exploit the power of long observation times requires semi-coherent search methods with detection statistics created from multiple coherent observation times.

Quick-Look Searches

The quick-look search pipelines will be run on LVC clusters and may be in contention for limited resources in the months immediately following the conclusion of a data run. To assist in allocating those resources, if needed, each pipeline team will be asked at the conclusion of each run to carry out searches in relatively narrow, representative bands of that run's data (50–100 Hz, 150–200 Hz, 1050-1100 Hz in O1) and report preliminary results promptly, as part of a "Real Data Challenge" (RDC). The sensitivity, robustness and timeliness of those results may play a role in resource allocation, depending upon demand and supply.

PowerFlux [323, 324] applies a stack-slide approach [325] to compute from many thousands of 30-minute Short Fourier Transforms (SFTs) an average strain power corrected for antenna pattern and with weighting based on detector noise and antenna pattern. Its signal estimator is direct excess strain power for an assumed source direction and polarization, using one circular polarization projection and four linear polarization projections. PowerFlux corrects explicitly for Doppler modulations of apparent source frequency due to the Earth's rotation and its orbital motion around the Solar System Barycenter. Source frequencies are searched with $\sim$0.56 mHz spacing and limits presented separately for 0.25 Hz bands. Interesting outliers are followed up with the loose-coherence zooming technique [326, 327].

The Sky Hough method [328, 329, 330] uses short coherence times (30 minutes) to compute spectral powers. These values are compared against a threshold, with noise weights summed together over the course of a run, to create a semi-coherent detection statistic. These statistics are histogrammed in bins of sky location, corresponding to different assumed f and $\dot{f}$ templates, with outliers indicated by high final counts. A recent improvement was the addition of a χ^2-statistic computed over subsets of the data run, which has proven useful in vetoing certain detector artifacts [331].

The hierarchical Frequency Hough method [332, 333, 334, 335] uses relatively short coherence times (8000 s up to 128 Hz and 1000 s at higher frequency). Significant peaks in the equalized spectra are selected and used as input to the frequency Hough transform, which, for each direction in the sky, connects the data time/frequency plane to the source frequency/spin-down plane. Candidates are selected using coarse and refined grids in the parameter space and are then subject to coincidences, validation and follow-up.

The time-domain $\mathcal{F}$-statistic method [336, 337] computes the $\mathcal{F}$-statistic over coherence times of $\sim$2 days and then searches for coincidences among candidates over the course of a data run with consistent source parameters. Extensive line and transient cleaning is used in data preparation. Work is under way to parallelize the code using the Message Passing Interface (MPI) to run on very large computing facilities. There are plans to implement a follow-up procedure based on global correlations, as in the Einstein@Home search and to exploit GPUs.

Deep and Broad Search:

The **Einstein@Home** [338, 339] distributed computing resources enable the use of longer coherence times ($\sim$day in recent searches) in an all-sky search with smaller mismatch than can presently be supported by the LIGO and Virgo computing clusters for those coherence times. The detection statistic for each coherence time is the well known $\mathcal{F}$-statistic for a particular choice of sky location, frequency, frequency derivative, marginalized over unknown source inclination and polarization. Individual $\mathcal{F}$-statistic values are used in a power-summing algorithm [339] to derive a semi-coherent detection statistic over a full data run. Recent improvements in the Einstein@Home infrastructure include (1) lower effective thresholds by moving more computing to remote hosts, (2) global correlations in search parameters to make semi-coherent combination more efficient, and (3) Bayesian line-veto inference to suppress single-detector artifacts.

All pipelines, with the exception of Einstein@Home, share comparable sensitivity and computational cost, as confirmed by a recent mock data challenge §3.19.6 and detailed in [340].

Two additional search methods are under development aiming at sensitivity improvement while maintaining robustness against uncertainty in the source model: 1) a "loosely coherent" method [326], which builds on top of the PowerFlux infrastructure; and 2) a cross-correlation method [341] which bridges between semi-coherent and coherent methods, with the possibility of parameter tuning. The computational viability of these two methods for all-sky searches remains uncertain and will not be discussed further here. Note, however, that loose coherence already allows a small patch of sky to be probed more deeply ("spotlight search"), a technique applied in a recently completed S6 search of two spurs of the Orion galactic spiral arms [342].

Despite our wish to field a broad suite of approaches, the present proliferation of pipelines is a luxury. If computational resources become too limited to support running each pipeline over the full parameter space, experience from RDCs should aid in setting priorities. The goal is not to converge on a single pipeline, but we do want to understand clearly the justification for each one that uses substantial computing resources. The justifications can include:

- Best sensitivity
- Ability to cover (with astrophysically interesting – if not best – sensitivity) the largest region of parameter space
- Best robustness against signal deviations from assumed phase model
- Fastest pipeline for quick looks at data
- Deliberate redundancy (using an independent software base) for safety in this critical search

This search will also benefit from two follow-up pipelines for "zooming in" on interesting sources, including the "loose coherence" approach [326, 327] used in the full-S5 PowerFlux paper [343] and the "Nomad" approach [344] used in the full-S5 Einstein@Home paper [345]. In the case of an isolated neutron star detection, this will allow us to focus promptly on pinning down the source parameters via zooming. There are several important considerations to bear in mind with respect to such follow-ups. First, the SNR increase from zooming can be an order of magnitude or more, allowing relatively precise parameter estimation compared to what is found upon first detection. Second, one can then go back to older, less sensitive data and still find a source with very good SNR that had been missed previously; moreover, that expanded time baseline itself offers improved parameter precision, at the cost of requiring an expanded search range to account for extrapolation errors due to uncertainties in the initial (discovery) parameters. Finally, although the semi-coherent methods used in all-sky searches have sensitivities that improve only as the fourth root of observation time, once a true signal has been pinpointed, then the SNR and parameter estimation from coherent followups improve as the square root of observation time (assuming stable detector noise during the data run).

Electromagnetic follow-ups play a critical role in assessing the scientific impact of a detection in this search. Before publishing a CW discovery, we wish to consult electromagnetic partners with access to radio, X-ray and γ-ray telescopes on what they can see in the direction of the source. With a year's observation time and good SNR, we expect to achieve an angular resolution of O(arcsec), which should suffice for excellent electromagnetic follow-up. We already have partnerships in the radio, X-ray and γ-ray communities for obtaining ephemerides for our targeted pulsar searches. A discovery publication might include co-authors from those communities who carry out follow-ups at our request (whether or not they confirm the source), a blanket request we envision going out through our existing liaisons in those communities[14]. Inclusion of these authors in the discovery paper (as opposed to later papers or companion papers), would depend on the timeliness and astrophysical importance of their results. We fully expect results from some observers that would be rapid and enhance the astrophysical impact of the discovery paper.

Assuming that pulsations are indeed observed in one or more electromagnetic bands in follow-up, there is immediate astrophysical payoff. If the gravitational wave frequency is twice that of the rotation frequency, with no GW emission observed at the rotation frequency, then a rotating triaxial ellipsoid model is favored. On the other hand, if the two frequencies agree, then precession probably plays an important role. If the GW frequency is approximately 4/3 the rotation frequency, then r-modes are strongly favored, yielding direct information on the interior fluid motion of a neutron star. In the conventional scenario of $f_{\rm GW} = 2f_{\rm Rot}$, the phase of the GW emission relative to the phase of the electromagnetic pulse(s) gives insight into relation of the stellar quadrupole asymmetry to the magnetic poles. Similarly, the inclination angle and transverse polarization angle of the star's spin axis can be inferred from the GW emission, and if deep electromagnetic observations detect a pulsar wind nebula around the star, it may be possible to compare the GW- and EM-inferred angles. More generally, one can envision a sequence of beyond-discovery collaboration publications, as we and electromagnetic astronomers continue studying a source that (we hope) remains

---

[14] We envision a very lightweight MOU arrangement with electromagnetic observers. In the event of a GW discovery, observers would be offered the opportunity to sign an MOU setting out publications ground rules, in order to obtain the GW source coordinates and ephemeris. While leaks of such parameters to MOU non-signers are likely, the pulsar community has established an etiquette for protecting priority on discoveries that makes such leaks benign, we believe.

detectable throughout the ADE.

Another interesting follow-up possibility after a discovery is to exploit advanced interferometer narrow-banding to improve parameter estimation. Whether the potentially improved SNR from narrow-banding is worth the cost in sensitivity in other bands and in interferometer downtime is difficult to judge in advance, however. Unless all interferometers are narrow-banded together, the SNR gain from narrow-banding over broadband operation may be modest, and given current astrophysical knowledge, there is no compelling reason to choose narrow-banding in an all-sky isolated-star search. We can't even say with confidence that detection of an unknown high-frequency millisecond star is more or less likely than detection of a young, low-frequency star. (Even for low-mass X-ray binaries, such as Scorpius X-1, which were often cited in the past as targets for narrow-banding, it is not at all clear that narrow-banding is truly sensible.)

3.19.4 Result Validation Plan

As discussed in section 3.19.3, "zooming" in on all-sky candidates offers the potential for an order of magnitude increase in signal-to-noise ratio for a source that follows the signal model of an isolated star with constant spindown over the observation span. With SNRs of 50-100 or more, confirmed by the three independent targeted-search pipelines described elsewhere, there will be no uncertainty as to whether a detection has been made. If there is no detection, the fact that there are up to five independent all-sky pipelines of comparable sensitivity will give us confidence we have not missed an easily detectable signal.

3.19.5 Publication Plan

Following the observing scenarios document [346], we assume a 6-month O2 run in 2016-2017, and a 9-month O3 run in 2017-2018. In each run we assume an intrinsic strain sensitivity significantly improved over previous runs. Hence we envision at least one all-sky publication from each run and perhaps more if deeper or broader searches require more computational time. Roughly speaking, all-sky upper limits on strain amplitude scale with the noise floor of the most sensitive instrument operating and with the fourth root of observation time. Steadily improving detector sensitivity will argue for expedited analysis of each data set, including a pragmatic approach to detector artifacts and unpromising outliers[15] For each of the first three runs, we plan the following all-sky publications:

1. A quick-look analysis, based on one or more pipelines that report final results promptly. Ideally, the publication for each run will be completed within $\sim$6 months of the end of data collection, before the next run begins.

2. A deeper and broader analysis, based on one or more pipelines that use longer coherence times [O(day)]. Based on past experience, these results are likely to be delayed by as much as an extra year even though a streamlined method to mime the Einstein@Home results on S6 promises a much faster turn-around than seen in the past. Sub-threshold follow-ups of marginal candidates could lead to further gains in sensitivity. That said, large delays in producing results, combined with availability of newer, more sensitive data, could make publication contingent upon broad parameter space coverage. Hence we envision increasing spindown range by an order of magnitude (with perhaps an increase in frequency range) while maintaining or improving upon the strain sensitivity of the quick-look searches.

---

[15] This approach contrasts with that used for the S6 run, where a long hiatus of new data argued for digging aggressively into the noise to try teasing out signals, which necessitated following up millions of outliers. This development of systematic follow-up procedures should be helpful in advanced detector searches. The substantial non-Gaussianity of the S6 data also required developing new techniques to avoid excluding large swaths of the search band.

Although we implicitly assume here that published results from the first three runs will be upper limits on CW sources, we may well detect a signal from the all-sky searches. In that event we would, of course, publish one or more papers on the detected source and would collaborate with radio, optical, X-ray and γ-ray astronomers on deriving astrophysical insight from joint observations, as discussed in §3.19.3.

If detector sensitivity does not improve significantly from one year to the next, *e.g.*, 2016 running is comparable to that in 2015, then the searches will nonetheless be carried out, but the journal (or perhaps conference proceedings) to which results are submitted for publication may be adjusted accordingly.

Pipeline	**Published (submitted) observational results to date**	**Search & review status**
PowerFlux	*PRD* 77 (2008) 022001 (S4) *PRL* 102 (2009) 111102 (S5) *PRD* 85 (2012) 022001 (S5) (arXiv:1605:03233 - May 2016) (S6)	S6 search review completed completed
Einstein@home	*PRD* 79 (2009) 022001 (S4) *PRD* 80 (2009) 042003 (S5) *PRD* 87 (2013) 042001 (S5)	S6 search review completed
Sky Hough	*PRD* 72 (2005) 102004 (S2) *PRD* 77 (2008) 022001 (S4) *CQG* 31 (2014) 085014 (S5)	S5 search review completed
Frequency Hough	*PRD* 93 (2016) 042007 (VSR2/4)	VSR2/4 search review completed
Time Domain $\mathcal{F}$-statistic	*CQG* 31 (2014) 165014 (VSR1)	VSR1 search review completed

Table 4: Summary of CW all-sky pipelines, including published observational results from previous data runs and the current search and review status.

3.19.6 Technical requirements and development plan

Pipelines status and review

PowerFlux has been used in published searches on LIGO S4 data [323], S5 data [347, 343] and S6 data [348](submitted), with significant improvements from one publication to the next. The multitude of spectral artifacts in S6 data (far higher than in earlier LIGO runs) led to a longer-than-expected follow-up analysis and to the development of a novel method of setting upper limits in non-Gaussian data [349], based on a "universal statistic." The tagged pipeline from this search serves as a baseline for the ADE.

The **Sky Hough** pipeline has been used in published searches in LIGO S2, S4 and S5 data [350, 323, 330]. This reviewed pipeline serves as a baseline for the ADE.

The **Frequency Hough** pipeline has been used in a published search in Virgo VSR2/4 data of sources with frequencies below 128 Hz [351]. This reviewed pipeline serves as a baseline for the ADE.

The **time-domain $\mathcal{F}$-statistic** pipeline has been used in a published search in Virgo VSR1 data [337]. This reviewed pipeline serves as a baseline for the ADE.

Einstein@Home has been used in published searches on LIGO S4 data [329] and S5 data [338, 345], with significant improvements from one publication to the next and an S6 publication imminent [339]. This reviewed pipeline serves as one E@H baseline for the ADE.

Einstein@Home pipeline: manpower needs

It is likely that necessary ADE manpower will be comparable to previously needed manpower.

Investigators: Bruce Allen, Carsten Aulbert, Christian Beer, Oliver Bock, Heinz-Bernd Eggenstein, Henning Fehrmann, David Hammer, David Keitel, Badri Krishnan, Bernd Machenschalk, Jing Ming, Maria Alessandra Papa, Reinhard Prix, Xavier Siemens, Avneet Singh, Sinead Walsh, Karl Wette, Sylvia Zhu, UWM System

Admins

The planned ADE publications described in §3.19.5 will rely on additional resources from both inside and outside the CW group, to address data preparation, detector characterization, calibration uncertainty and reviewing of analysis results.

Data Preparation:
Because many of the CW searches are carried out in the frequency domain, using long coherence times, data quality flags are applied sparingly in selecting data to analyze, to avoid needless fragmentation. Typically, only flags considered by transient search groups to be "category 1" are applied, flags that indicate severe interferometer malfunction or unreliable calibration.

Many, but not all, searches use 30-minute SFTs. A "standard" set of Tukey-windowed SFTs is created for each interferometer for each data run for general CW use, including detector characterization. It should be noted, however, that additional SFTs are created by some search teams with different windowing and/or optimized start/stop times for their particular pipelines.

For the Rome and Polgraw all-sky searches a short data base of 50%-overlap FFTs, using a flat cosine window, is built, after a time domain data cleaning to remove glitches.

Detector Characterization:
Detector characterization for all-sky CW searches focuses on spectral line artifacts. We will continue to use and improve upon the software tools applied in aLIGO subsystem commissioning, NoEMi [352], FScans and auxiliary channel coherences, in addition to on-site investigations of lines found to create trouble for searches. We have applied and will continue applying these tools to Advanced LIGO and Advanced Virgo installation and commissioning of subsystems. Several members of the CW group have contributed to line investigations and reporting throughout the Advanced LIGO commissioning period and engineering runs.

The manpower needs are non-trivial. We expect to need O(2-3 FTEs) summed over O(10 persons), including graduate students, in the ADE steady state, to identify frequencies where artifacts reside and to make tentative correlations with potential sources. Based on past experience, definitively identifying (or merely confirming) instrumental sources of spectral lines can require additional intensive and sometimes invasive investigation at the observatories. Ideally, there should be one or more collaborators stationed at each observatory whose primary duty while in residence would be line investigations. As in past runs, priority should be given to very loud and/or broad lines and to weak lines lying in near spectral coincidence among one or more interferometers. Based on past experience, it is unlikely to be feasible to track down every single-interferometer line that appears, since such work is manpower-intensive, and in some cases, intrusive during data taking.

Calibration:
Calibration requirements for the all-sky searches are driven by maintaining phase consistency among 2-3 interferometers at the highest frequencies likely to be searched. For the purposes of setting upper limits, the requirements of targeted searches are more stringent (amplitude uncertainty of 10%, phase uncertainty of 25 deg, timing uncertainty of 50 μs), but in the event of a detection from the all-sky search at 2000 Hz, we would want smaller phase and timing uncertainties of 18 deg and 25 μs. We leave it to the Calibration Committee to assess the manpower needed to reach these precisions.

Review of analysis results:
The baseline ADE pipelines to be used in all-sky searches will have been reviewed and tagged. There will still remain the task of reviewing the results produced by the pipelines, including the handling of outliers. For spectrally relatively clean data, such as we had in S5 above ~120 Hz, two experienced reviewers per

pipeline working for ∼2-3 months should suffice. For aggressive searching in highly contaminated data, this estimated time could well double, as reviewers sign off on vetoing strategies. The low-frequency combs in both the H1 and L1 interferometer data in the O1 run have been especially troublesome. A pragmatic approach of simply giving up on searches in certain, well defined bands might be wise in any given year of interferometer development. The choice of which pipeline results to review for a paper from each data run will depend on the demonstrated sensitivities of those pipelines in that run's data and on the timeliness of the results obtained.

3.20 Targeted Searches for Gravitational Waves from Known Pulsars

3.20.1 Abstract

Gravitational waves (GWs) are small ripples in the geometry of space-time, propagating at the speed of light, predicted to exist by Einstein's General Theory of Relativity. Rapidly spinning neutron stars in our galaxy may emit such waves if they are not perfectly symmetric around their spin axis. Their deviation from such axisymmetry is usually characterized by a parameter called the *ellipticity* of the neutron star which, for example, might be as large as 10^{-6} for a broad, 1-cm-high *bulge* across the surface of the 20-km-diameter star.

Searches have been carried out in data from the LIGO and Virgo gravitational wave detectors for signals from known radio and X-ray pulsars. No GW signals have been detected from these stars, leading to upper limits on their ellipticities reaching as low as 10^{-8}. These limits provide tests of neutron star structure and of fundamental nuclear physics in a realm inaccessible to terrestrial experiments. We describe here the plans to extend targeted searches for gravitational waves from known pulsars to the next generation of ground based detectors: Advanced LIGO and Advanced Virgo.

3.20.2 Scientific Justification

Rapidly rotating neutron stars are the most promising sources of continuous-wave (CW) gravitational signals in the LIGO and Virgo frequency band. These stars are expected to emit gravitational radiation through a variety of mechanisms, including elastic deformations [309, 310, 311], magnetic deformations [312, 313], unstable r-mode oscillations [314, 309, 315], and free precession [316]. A review of these emission mechanisms can be found in [317].

Here, we focus on the targeted search for gravitational waves from known neutron stars that are also radio, X-ray or gamma ray pulsars with expected gravitational-wave signal frequencies in the LIGO/Virgo band. Given our ignorance of the physics of neutron stars (which may well be quark stars or hybrid stars), and the relatively small fraction of their full population that are currently known, it is prudent to target these known stars with deep search techniques that are tailored to exploit the knowledge of their rotation and spindown rates to maximise our sensitivity to gravitational waves.

Our pipelines target a subset of sources for which pulsations are observed in radio, X-ray, or other electromagnetic radiation, giving timing with sufficient precision to merit a deep, usually single-template, search. Electromagnetic (EM) astronomy can tell us precisely the sky positions, frequencies, and frequency evolution of these objects, so that targeted analyses need search only a small parameter space and are not computationally limited. EM astronomy also sets an upper limit on the gravitational wave strain we could see from a known pulsar, assuming that all of the observed spindown is due to gravitational wave emission. In terms of the distance D, gravitational wave frequency $f_{\rm gw}$ and its time derivative $\dot{f}_{\rm gw}$, this indirect limit is [317]

$$h_{\rm IL} = 8.1 \times 10^{-25} \left(\frac{1\,{\rm kpc}}{D}\right) \left(\frac{-\dot{f}_{\rm gw}}{10^{-10}\,{\rm Hz/s}} \frac{100\,{\rm Hz}}{f_{\rm gw}}\right)^{1/2} \left(\frac{I}{10^{38}{\rm kg\,m}^2}\right)^{1/2}. \qquad (2)$$

Here I is the star's moment of inertia (as estimated by theory as these are yet to be directly observed) and could be higher than the fiducial value by a factor of up to three. For most pulsars the distance D is determined by combining their observed radio dispersion measure with a model of the galactic HII distribution and is uncertain to at least 20%. Analysis of the LIGO full S5/S6 data and the Virgo VSR2/VSR4 data has improved on this indirect "spindown limit" by a factor of 10 for the Crab pulsar (at 59.45 Hz) and by a factor of 3 for the Vela pulsar (22.38 Hz) [353]. Other pulsars for which the spindown limit was approached in S6/VSR2/VSR4 include PSRs J0205+6449 (30.45 Hz), J1833−1034 (32.33 Hz), J1813−1749

(44.74 Hz), J1913+1011 (50.59 Hz), J1952+3252 (55.69 Hz), J0737−3039A (88.11 Hz) and J0537−6910 (123.95 Hz) [354].

The discussion above assumes gravitational wave emission from a triaxial neutron star, with the electromagnetic and gravitational wave components rotating as one unit. Detecting such emission would represent the first ever measurement of the difference between the two (equatorial) components of the inertia tensor. This would provide important information on the strength and strain profile of the solid phase of the star (the crust, or possibly a solid core) and/or information on the nature of the internal magnetic field.

While this form of gravitational wave emission is the simplest and most plausible, it is by no means the only possible wave generation mechanism. Alternatives include free precession, excited modes of oscillation of the fluid, and the spindown of a multi-component star. The identification of such mechanisms would provide information on asymmetries in the inertia tensor, the viscosity of the fluid, and the internal structure of the star. However, the observational challenge is correspondingly greater, as the gravitational wave emission no longer occurs at twice the spin frequency, and special care should be given to the choice of search range in parameter space (i.e., the wave frequency and its time derivatives) that is both astrophysically reasonable and computationally feasible. Such a search has already been carried out for the Crab and Vela pulsars, concentrating on a small patch of parameter space centred on (twice) the observed spin frequency [355]. A more comprehensive search over an enlarged parameter space and for more pulsars is needed to fully exploit the science potential of targeted searches.

Targeted searches look for gravitational wave emission from pulsars of known position, rotation frequency, spindown rate, and binary orbital parameters where necessary. This information greatly reduces the size of the search space, and allows us to perform a fully coherent search over the full dataset for many pulsars. Timing accuracy is sufficient to maintain coherence both during and between science runs, and the relative phasing of the interferometers is also sufficiently well determined for us to be able to combine data from all runs and all detectors coherently, resulting in the best signal sensitivities achievable by LIGO and Virgo.

3.20.3 Search Description

Targeted searches require extreme precision and are not as resilient to ephemerides and coding mistakes as multi-template searches. Our strategy is to use multiple pipelines for these searches, cross-validated on hardware and software injections; for a more robust result, these pipelines use complementary techniques to reject out-of-band signals and for statistical interpretation. In principle we can use *all* the data we have available, both historical and current, and data from detectors with any sensitivity. However, in practice the more up-to-date data from a single IFO usually dominates the overall sensitivity. The derived parameters define the orientation of the neutron star and the strain amplitude at Earth.

Time domain Bayesian Pipeline. The time-domain Bayesian method has been applied successfully to data from the first six LSC science runs [356, 357, 358, 359, 360, 353] and to the Virgo VSR2/VSR4 runs [361, 353]. The method is described in detail in [362]; the inclusion of binary system parameters is described in [363]. This pipeline is designed to carry out robust signal extraction and optimal parameter estimation, rather than search over a large parameter space. Its primary purposes are therefore (1) to perform searches for signals from known pulsars and, (2) to determine the astrophysical parameters of candidate sources.

The method comprises a heterodyne and filtering stage to extract interferometer data in a tracked 1/60 Hz band centered on the expected gravitational wave signal, followed by a Bayesian parameter estimation stage. This second stage delivers an upper limit to the strain amplitude of any signal and an estimation of the signal's parameters, should one be detected, in the form of marginal posterior probability distributions for the signal parameters. The method has successfully determined the parameters of the injected signals in all our science runs. The most computationally intensive part of the search is the heterodyning and down-sampling of the raw data. Currently this takes about 25 min per pulsar per detector per day of data. We have developed a new method of computing the tracked 1/60th Hz band by interpolating between frequency bins in one-minute short Fourier transforms (SFTs) of the data rather than by heterodyning the timeseries. This gives a very significant speed-up when processing multiple targets and is suitable for all isolated and some binary targets. For these targets, the computational load for this preprocessing step becomes trivial.

The parameter estimation stage uses a Markov-chain Monte-Carlo (MCMC) algorithm to explore the unknown parameter space, combining the data with priors on pulsar parameters (including spin axis orientation) to return a joint posterior distribution for the parameters of each pulsar. From this posterior distribution we form marginalised posteriors on each parameter and can infer an upper limit on the gravitational wave amplitude. In addition to this, a new parameter estimation code has been developed, based on the `lalinference` functions within `lalsuite` (these are also being used as the main parameter estimation tools in the CBC searches), which uses nested sampling to explore the parameter space. As well as the posterior distribution this algorithm also returns the “evidence” for the signal model. This evidence, when compared to the evidence that the data consists of noise alone (or contains a different signal model), can be used as a detection statistic. The code has also been designed to be more flexible at including different pulsar emission models and allowing searches over expanded parameter spaces. In the advanced detector era (ADE) we also plan a fully automated version of the pipeline, producing preliminary data products and results a few days after data has been collected.

Time domain matched-filter method using the $\mathcal{F}$ and G statistics. Here, as above, we assume we know the pulsar’s position, frequency and frequency derivatives so that the standard $\mathcal{F}$-statistic [336], used in all-sky searches, can be applied to a single template corresponding to the target in question. If, in addition, the orientation of the spin axis of the pulsar is known, the signal can be detected using the $\mathcal{G}$-statistic [364]. Once the signal is detected, a calculation of the $\mathcal{F}$-statistic enables estimation of the amplitude, phase, polarization and inclination angles, whereas application of the $\mathcal{G}$-statistic results in estimation of the amplitude and phase. If the computed value of the $\mathcal{F}$-statistic or $\mathcal{G}$-statistic is not significant, we can derive an upper limit on the gravitational wave signal using a standard frequentist approach, that is, by injecting signals into the data with random parameters. The input data for the calculation of the $\mathcal{F}$ and G statistics are the coarse- or fine-heterodyned data generated for the time domain Bayesian method described above. This method was first applied to search for the Vela pulsar in VSR2 data [361] and was recently applied to search for several known pulsars in VSR2/VSR4/S6 data sets: J0534+2200 (the Crab), J0537-6910, J0835-4510 (Vela), J1813-1246, J1833-1034, J1952+3252 and J2022+3842 [353].

Signal Fourier 5 components method. This independent targeted search method consists of three steps:

- extract a small (say 0.1 Hz) band from a Short FFT Database (built from 1024 s data segments, after a time-domain cleaning);
- transform to the time domain and apply Doppler, spin-down and Einstein delay corrections through a re-sampling procedure;
- down-sample the corrected data to a much smaller rate (e.g., 1 Hz).

After an additional cleaning step to remove outliers present in the small analyzed band, data- and signal-template 5-vectors are computed and used to calculate a detection statistic, as described in [365, 361]. The corresponding p-value is then computed in order to establish how compatible the data are with pure noise. If no significant evidence of a signal is obtained, an upper limit on the signal amplitude is determined. This method has been applied, together with the other two coherent pipelines, for the search of CW signals from the Vela pulsar in the VSR2 data [361] beating the spin-down limit by a factor of about 1.6. It was recently applied to the analysis of VSR4/S6 data, obtaining upper limits for Vela (VSR4), Crab (VSR2/VSR4/S6) and a few other low-frequency pulsars [353].

3.20.4 Result Validation Plan

- Results will be validated via our standardized set of software signal injections into a parallel stream of real data from the LIGO and Virgo interferometers. Cross-validation between pipelines and injections has produced robust results in initial targeted pulsar results from LIGO and Virgo and the same successful policy will be employed for advanced detector data.

3.20.5 Publication Plan

Following the observing scenarios document [346], we assume here a 6-month O2 run in 2016-2017, and a 9-month O3 run in 2017-2018. In each run we assume an intrinsic strain sensitivity significantly improved over previous runs. Hence we envision at least one targeted publication from each run and perhaps more if specific sources pass the spin-down sensitivity point. We expect the publication rate for targeted searches to be more rapid in the ADE than for the S5–S6/VSR1–4 era. We have established reviewed, tagged pipelines, based on those used for the final S6/VSR2–4 searches. Although refinements will likely be explored in the ADE, there will be default pipelines for which the reviews can focus on analysis results, not source code. The expected pace of the data runs and the sensitivity improvements make it attractive to put a premium on rapid analysis and review.

Targeted searches are constrained by the availability of radio and X-ray pulsar ephemerides. It is good-practice to get timing solutions for our targets that cover the entire science run to ensure that there are observations at the end that confirm the pulsar has not undergone a glitch over the period. As a result, we must wait for our EM partners to deliver final ephemerides before the analysis is completed, and past experience has shown this to be the rate-limiting step in our multi-target publications (note that the Crab Pulsar ephemeris is kept up-to-date online, and there are no plans by the University of Manchester Jodrell Bank to stop this service).

Specifically, for each of the first three runs, we plan the following targeted publications:

1. A synoptic publication, updating upper limits on the entire target list.
2. When appropriate, one or possibly two publications highlighting a milestone passed on particular sources.

Although we assume here that published results from the first three runs will be upper limits on CW sources, we may well detect a signal. In that event we would, of course, publish one or more papers on the detected source and would collaborate with radio, optical, X-ray and γ-ray astronomers on deriving astrophysical insight from joint observations. The relationships we have developed already to use detailed unpublished ephemeris data from these communities in targeted searches should assist in joint follow-up observations.

If detector sensitivity does not improve significantly from one year to the next, *e.g.*, the 2016 run is comparable to that in 2015, then the searches will nonetheless be carried out, but the journal (or perhaps conference proceedings) to which results are submitted for publication may be adjusted accordingly.

3.20.6 Technical requirements and development plan

Pipeline	Published observational results to date	Search& review status	
Time Domain Bayesian	*PRD* 69 (2004) 082004 (S1) *PRL* 94 (2005) 181103 (S2) *PRD* 76 (2007) 042001 (S3/S4) *ApJL* 683 (2008) 45 (S5) *ApJ* 713 (2010) 671 (S5) *ApJ* 737 (2011) 93 (VSR2) *ApJ* 785 (2014) 119 (S6/VSR2/VSR4)	Review complete	
Time Domain Matched Filter	*ApJ* 737 (2011) 93 (VSR2) *ApJ* 785 (2014) 119 (S6/VSR2/VSR4)	Review complete	
Signal Fourier 5-component	*ApJ* 737 (2011) 93 (VSR2) *PRD* 91 (2015) 022004 (S6/VSR2/VSR4) *ApJ* 785 (2014) 119 (S6/VSR2/VSR4)	Review complete	

Time domain Bayesian Pipeline
This pipeline has been intensively reviewed and used for every science run of LIGO and Virgo. Additions and refinements to the pipeline are reviewed as they come into use, but are generally improvements in efficiency, and a fully-reviewed pipeline is always available for production runs. Most recently the pipeline was used for S6/VSR2/VSR4 analyses and the majority of the pipeline is identical to the one used and reviewed for S5. The only changes were to increase automation of the post-processing scripts and to incorporate priors from searches in older data. These changes have now been reviewed. A new method that uses spectral interpolation of Short Fourier Transforms (SFTs) to create a downsampled timeseries was recently completed and reviewed.

The new parameter estimation code has already been validated against the current code using both fake data and simulated signals [366, 367]. The central algorithms for posterior sampling have also been reviewed as part of the CBC parameter estimation code review. However, the code calling these sampler functions and providing the specific pulsar model, prior initialisation and data reading functions, requires review, which has begun. This code refinement is in place and being used for O1 searches.

Time domain matched-filter method using the $\mathcal{F}$ and G statistics
The pipeline has been extensively tested and reviewed during its application to the search of the VSR2 data for the Vela pulsar. The current version of the pipeline is a simple extension that is able to read any coarse and fine heterodynes produced by the time domain Bayesian method and can use any pulsar ephemeris file. Also the Monte Carlo simulations to establish the upper limits are automated.

Signal Fourier 5 components method
The single-detector pipeline has been extensively reviewed and tested in the past. Recently the method was extended to allow a coherent analysis of different datasets, coming from the same or different detectors [368]. Moreover, a new method for computing upper limits in the frequentist framework has been developed, which overcomes some problems of the standard frequentist methods [369], and a methodological paper is in preparation. The review of these method and software updates was completed in summer 2013. We have also extended the method to narrow-band searches, allowing a small mismatch between the EM and GW frequency and frequency derivatives.

3.21 Directed Searches for Gravitational Waves from Isolated Neutron Stars

3.21.1 Abstract

Gravitational waves (GWs) are small ripples in the geometry of space-time, propagating at the speed of light, predicted to exist by Einstein's General Theory of Relativity. Rapidly spinning neutron stars in our galaxy may emit such waves if they are not perfectly symmetric around their spin axis. Their deviation from such axisymmetry is usually characterized by a parameter called the *ellipticity* of the neutron star which, for example, might be as large as 10^{-6} for a broad, 1-cm-high *bulge* across the surface of the 20-km-diameter star.

Searches have been carried out in data from the LIGO and Virgo gravitational wave detectors for signals from the centers of supernova remnants, where isolated neutron stars are thought to reside. No GW signals have been detected from these stars, leading to upper limits on the strengths of possible gravitational radiation emitted by these stars. These limits improve substantially upon searches carried out in data from the initial LIGO detector. We describe here the plans to extend directed searches for gravitational waves from isolated neutron stars to the next generation of ground based detectors: Advanced LIGO and Advanced Virgo.

3.21.2 Scientific Justification

Rapidly rotating neutron stars are the most promising sources of continuous-wave (CW) gravitational signals in the LIGO and Virgo frequency band. These stars are expected to emit gravitational radiation through a variety of mechanisms, including elastic deformations [309, 310, 311], magnetic deformations [312, 313], unstable r-mode oscillations [314, 309, 315], and free precession [316]. A review of these emission mechanisms can be found in [317].

Here, we focus on the directed search for gravitational waves from isolated neutron stars, where we know a potential source location to high accuracy, but have little prior information on the rotational frequency of the star. The most promising such source is perhaps the compact central object at the center of the Cassiopeia A (Cas A) supernova remnant (SNR). There is excellent reason to believe a neutron star was formed there just over 300 years ago in a supernova event, a star that is rapidly cooling and may have significant residual quadrupole asymmetry. In addition, there are of O(10) other SNRs in the galaxy young enough and near enough to warrant a search. A list of SNRs for which we have searched in S6 data is given in Table 5. Aside from Cas A, perhaps the most interesting source in the table is Vela Jr. for which two entries appear, corresponding to two distinct possible interpretations of astrophysical observations to date, one of which places the star quite close and quite young (so much so that it's hard to understand how it could have been missed by medieval astronomers). The weight of evidence, however, argues for the more distant and older interpretation, which is nonetheless comparable in its age-based strain limit to Cas A. Because of the large uncertainties in this source's properties and its likely greater age than the very young Cas A, it has been given a lower priority in prior search planning, but a recent study indicates a greater potential than originally thought [370]. Another intrinsically interesting direction is the galactic center, where enhanced star formation could create young neutron stars, but where dust could obscure the present-day SNR and could have obscured the optical signal of a supernova from earlier astronomical observers. Other interesting directions where undiscovered isolated neutron stars might reside are at the cores of globular clusters. Since globular clusters host very old stars, detected milli-second pulsars dominate over young pulars. In addition, it is possible that a neutron star was created in Supernova 1987A, making the center of that supernova remnant an intriguing direction in which to search, despite the large distance (51 kpc) to it.

Our pipelines exploit the known sky location of the source to search more deeply and for younger objects than is possible for all-sky searches. The increased depth comes from increasing the coherence time of each

SNR (G name)	Other name	RA+dec (J2000)	D (kpc)	a (kyr)	h_0^{age}
1.9+0.3		174846.9−271016	8.5	0.1	8.4×10^{-25}
18.9−1.1		182913.1−125113	2	4.4	5.4×10^{-25}
93.3+6.9	DA 530	205214.0+551722	1.7	5	6.0×10^{-25}
111.7−2.1	Cas A	232327.9+584842	3.4	0.3	1.3×10^{-24}
189.1+3.0	IC 443	061705.3+222127	1.5	3	8.7×10^{-25}
266.2−1.2	Vela Jr.	085201.4−461753	0.2	0.69	1.4×10^{-23}
266.2−1.2	Vela Jr.	085201.4−461753	0.75	4.3	1.5×10^{-24}
291.0−0.1	MSH 11−62	111148.6−603926	3.5	1.2	5.9×10^{-25}
347.3−0.5		171328.3−394953	0.9	1.6	2.0×10^{-24}
350.1−0.3		172054.5−372652	4.5	0.6	6.5×10^{-25}

Table 5: List of supernova remnant objects for which an S6 directed search has been carried out. Values of distance D and age a are at the optimistic (nearby and young) end of ranges given in the literature, except for the second search for Vela Jr.

segment searched, and the probing of young ages comes from searching over higher frequency derivatives, normally neglected beyond the first spin-down parameter in all-sky searches.

The conventional spindown limit for known pulsars, based on measured spin and spindown, does not directly apply to a source with an unknown frequency, but if the source's approximate distance D and age τ are known, as is the case for many SNRs, one can derive a frequency-independent age-based limit under the assumption that the star has been a gravitar since birth (spindown dominated by gravitational wave emission)[371]

$$h_0^{age} = \frac{1}{D}\sqrt{\frac{5GI_{zz}}{8c^3\tau}} \tag{3}$$

Here I_{zz} is the star's moment of inertia (as estimated by theory, as these are yet to be directly observed) and could be higher than the fiducial value by a factor of up to three. For nominal Cas A parameters, this can be conveniently rewritten:

$$h_0^{age} = 1.2 \times 10^{-24}\left(\frac{3.4kpc}{D}\right)\sqrt{\left(\frac{I_{zz}}{10^{45}\mathrm{gcm}^2}\right)\left(\frac{300\mathrm{years}}{\tau}\right)} \tag{4}$$

In designing a search, it is customary [371] to determine the band over which a search of fixed computational cost can beat this age-based limit. For the S5 Cas A search, this band was 100-300 Hz, while for the nearly complete S6 coherent search the band widened to 91-573 Hz, and among other supernova remnants coherently searched in S6 data, band widths varied from ~150 Hz to ~2000 Hz. The ongoing Einstein@Home semi-coherent search for Cas A is searching up to 1000 Hz. The boundaries of the band to be searched are defined by the intersections of the age-based strain limit above and the expected strain sensitivity of the search. All of the nominal values of h_0^{age} in Table 5 can be beaten with advanced detector data over at least some frequency band.

Assuming that pulsations are indeed observed in one or more electromagnetic bands in follow-up, there is immediate astrophysical payoff. If the gravitational wave frequency is twice that of the rotation frequency, with no GW emission observed at the rotation frequency, then a rotating triaxial ellipsoid model is favored. On the other hand, if the two frequencies agree, then precession probably plays an important role. If the GW frequency is approximately 4/3 the rotation frequency, then r-modes are strongly favored, yielding direct information on the interior fluid motion of a neutron star. In the conventional scenario of $f_{\mathrm{GW}} = 2f_{\mathrm{Rot}}$, the phase of the GW emission relative to the phase of the electromagnetic pulse(s) gives insight into the relationship between the stellar quadrupole asymmetry and the magnetic poles. Similarly, the inclination angle and transverse polarization angle of the star's spin axis can be inferred from the GW emission, and if deep electromagnetic observations detect a pulsar wind nebula around the star, it may be possible to compare the GW- and EM-inferred angles. More generally, one can envision a sequence of beyond-discovery collaboration publications, as we and electromagnetic astronomers continue studying a source that (we hope) remains detectable throughout the ADE.

Another interesting follow-up possibility after a discovery is to exploit advanced interferometer narrow-banding to improve parameter estimation. Whether the potentially improved signal-to-noise ratio from narrow-banding is worth the cost in sensitivity in other bands and in interferometer downtime is difficult to judge in advance, however. Unless all interferometers are narrow-banded together, the signal-to-noise ratio gain from narrow-banding over broadband operation may be modest, and given current astrophysical knowledge, there is no compelling reason to choose narrow-banding in a directed isolated-star search. We can't even say with confidence that detection of an unknown high-frequency millisecond star is more or less likely than detection of a young, low-frequency star. (Even for low-mass X-ray binaries, such as Scorpius X-1, which were often cited in the past as targets for narrow-banding, it is not at all clear that narrow-banding is truly sensible.)

3.21.3 Search Description

At present two mature approaches are available for directed searches. The first, used for the S5 Cas A search [372] and for the S6 SNR search, is based on computing the $\mathcal{F}$-Statistic[336] for a single coherence time of O(10 days) and includes an explicit search over the 2nd derivative of the GW frequency. A variation of this first pipeline, based on a more efficient, barycenter-resampled $\mathcal{F}$-Statistic [373] has also been used in a pilot search for a source in globular cluster NGC 6544 [374]. Henceforth this approach based on a single coherent measurement (with or without barycenter-resampling) will be called the *coherent* method.

The second mature approach is based on stacking $\mathcal{F}$-Statistic values semi-coherently from many separate segments of data. This approach (henceforth called *semi-coherent*) was pioneered in the S5 galactic center search [375] but without an explicit search over $\ddot{f}$, and has been used in an Einstein@Home S6 Cas A search over a range of $\ddot{f}$ values consistent with SNR age.

In general, one expects the semi-coherent search to yield better strain sensitivity than the coherent search, even for fixed computation cost, for a long data run and uniform sensitivity throughout the run. Increasing computational resources through the use of Einstein@Home adds further to the potential gain in sensitivity. Figure 5 shows a comparison of directed-search efficiencies for coherent and semi-coherent methods from a recent mock data challenge. In the long term it is likely that future directed searches will rely on the semi-coherent method, but for the 4-month O1 run, the intrinsic benefit of the semi-coherent approach is reduced from what it would be for a yearlong run, and if there is substantial improvement in detector performance during a run (as has often been the case), then a coherent search of the most sensitive data subset may give the best sensitivity. For these reasons, and given the long experience of the CW group in coherent directed searches, we expect to continue supporting this approach for the time being.

In the event of an interesting candidate detection, either search can benefit from "zooming in" on interesting sources, using the "Nomad" approach [344] used in the full-S5 Einstein@Home paper [345]. In the case of an isolated neutron star detection, this would allow us to focus promptly on pinning down the source parameters via zooming. There are several important considerations to bear in mind with respect to such follow-ups. First, the signal-to-noise ratio increase from zooming can be an order of magnitude, allowing relatively precise parameter estimation compared to what is found upon first detection. Second, one can then go back to older, less sensitive data and still find a source with very good signal-to-noise ratio that had been missed previously; moreover, that expanded time baseline itself offers improved parameter precision,

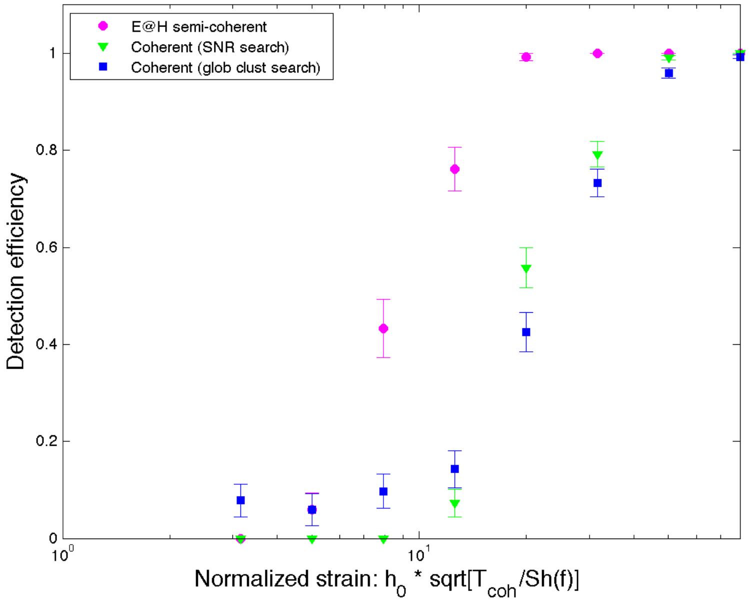

Figure 5: Approximate detection efficiencies of coherent pipelines with (glob cluster) and without (supernova remnant) resampling; and of a semicoherent directed search pipeline, based on mock data challenge studies. The semi-coherent results are taken from a cluster emulation of what can be achieved with Einstein@Home, using a 20 mHz search band and ignoring $\ddot{f}$.

at the cost of requiring an expanded search range to account for extrapolation errors due to uncertainties in the initial (discovery) parameters. Finally, although the semi-coherent search in all-sky searches has a sensitivity that improves only as the fourth root of observation time, once a true signal has been pinpointed, then the signal-to-noise ratio and parameter estimation from coherent followups improve as the square root of observation time (assuming stable detector noise during the data run).

Electromagnetic follow-ups play a critical role in assessing the scientific impact of a detection in this search. Before publishing a CW discovery, we wish to consult electromagnetic partners with access to radio, X-ray and γ-ray telescopes on what they can see in the direction of the source. With a year's observation time and good signal-to-noise ratio, we expect to achieve an angular resolution of O(arcsec), which should suffice for excellent electromagnetic follow-up. With an ephemeris provided by GW measurements, these follow-ups can be more sensitive in detecting pulsations for an already-known star or in confirming a new source. We already have partnerships in the radio, X-ray and γ-ray communities for obtaining ephemerides for our targeted pulsar searches.

Neither the coherent nor the semi-coherent pipeline is thought to be well suited to a search for Supernova 1987A because such a young object, if emitting detectable gravitational radiation, is highly likely to be spinning down at such a rate that explicit searching over higher-order spindowns would be necessary. A more robust approach based on cross correlation techniques [376] is under development, but is not expected to be ready for O1 use.

The criteria for prioritizing targets is likely to follow past practice, with highest priority given to Cas A and other young, close SNRs, to the galactic center and to close globular clusters (pending new electromagnetic observations). One concern in searches for young pulsars is glitching that leads to small changes in frequency and its derivatives. These happen infrequently and would be unlikely to affect a short-coherence-time search, but become more of a concern for a semi-coherent search over many months.

3.21.4 Result Validation Plan

As discussed in section 3.21.3, "zooming" in directed-search candidates offers the potential for a large increase in signal-to-noise ratio for a source that follows the signal model of an isolated star with constant spindown over the observation span. With high SNRs confirmed by the three independent targeted-search pipelines described elsewhere, there will be no uncertainty as to whether a detection has been made.

Given the significant differences in achievable sensitivities between coherent and semi-coherent searches, validating upper limits from the semi-coherent search in the absence of detection will rely mainly on careful review.

3.21.5 Publication Plan

Following the observing scenarios document [346], we assume a 6-month O2 run in 2016-2017, and a 9-month O3 run in 2017-2018. In each run we assume an intrinsic strain sensitivity significantly improved over previous runs. Hence we envision at least one directed publication from each run and perhaps more, separated by source type (SNR, galactic center, other) and with a possible quick-look publication based on coherent searches (within $\sim$3-6 months of run completion), followed later by a deep-search paper using the semi-coherent pipeline. Whether or not to publish the latter paper will depend on the improvement in depth and breadth of the search, and on the timeliness of the results with respect to new data sets. We expect the publication rate for directed searches to be more rapid in the ADE than for the S5–S6/VSR1–4 era. We will have established reviewed, tagged pipelines, based on those used for the final S6/VSR2–4 searches. Although refinements will likely be explored in the ADE, there will be default pipelines for which the reviews can focus on analysis results, not source code. The expected pace of the data runs and the sensitivity improvements make it attractive to put a premium on rapid analysis and review.

If detector sensitivity does not improve significantly from one year to the next, *e.g.*,the 2016 run is comparable to that in 2015, then the searches will nonetheless be carried out, but the journal (or perhaps conference proceedings) to which results are submitted for publication may be adjusted accordingly.

A discovery publication might include co-authors from those communities who carry out follow-ups at our request (whether or not they confirm the source), a blanket request we envision going out through our existing liaisons in those communities[16]. Inclusion of these authors in the discovery paper (as opposed to later papers or companion papers), would depend on the timeliness and astrophysical importance of their results. We fully expect results from some observers that would be rapid and enhance the astrophysical impact of the discovery paper.

---

[16] We envision a very lightweight MOU arrangement with electromagnetic observers. In the event of a GW discovery, observers would be offered the opportunity to sign an *ad hoc* MOU setting out publications ground rules, in order to obtain the GW source coordinates and ephemeris. While leaks of such parameters to MOU non-signers are likely, the pulsar community has established an etiquette for protecting priority on discoveries that makes such leaks benign, we believe.

3.21.6 Technical requirements and development plan

Pipeline	**Published observational results to date**	**Search& review status**
Coherent	*APJ* 722 (2010) 1504 (S5)	Review complete in Q4 2014 Review of resampling enhancement complete in Q1 2015
Semi-coherent	*PRD* 88 (2013) 102022 (S5)	Review completed 2013 Review of $\ddot{f}$ incorporation complete in Q3 2015

Coherent Pipeline

The first iteration of this pipeline was originally reviewed for the S5 Cas A search [372]. An updated version of the pipeline, better suited to multiple sources, was extensively reviewed for the S6 supernova remnant search. A barycentered-resampled version of the pipeline was used for the S6 globular cluster search and recently reviewed.

Semi-Coherent Pipeline

The first iteration of this pipeline was originally reviewed for the S5 galactic center search [375]. An updated version of the pipeline, including a search over non-zero $\ddot{f}$ began review in Q2 2015 in the context of the Einstein@Home S6 all-sky "bucket search" which shares a code base with this one. This review was recently completed. part of the code is expected in Q4 2015.

3.22 Directed Searches for Scorpius X-1 and Other Known Binary Stars

3.22.1 Abstract

Gravitational waves (GWs) are small ripples in the geometry of space-time, predicted to exist by Einstein's Theory of General Relativity, and propagating at the speed of light. Rapidly spinning neutron stars in our galaxy may emit such waves if they are not perfectly symmetric around their spin axis. Scorpius X-1 is a binary system believed to include a neutron star experiencing a high accretion rate from its lighter companion star. This accretion of material could lead to a sustained deviation from pure axisymmetry of the star's mass distribution or lead to excitations of oscillatory vibrations, either of which can cause gravitational wave emission. A comprehensive search has been carried out in data from the LIGO and Virgo gravitational wave interferometers for such radiation from Scorpius X-1. No gravitational-wave signal was detected over a broad frequency range, allowing scientists to constrain the degree to which accretion distorts the shape of the Sco X-1 neutron star or excites oscillations. New data to be taken in the coming year after improvements to the LIGO and Virgo detectors is expected to be still more sensitive, allowing scientists to probe Scorpius X-1 more deeply, in the hope of detecting continuous gravitational waves for the first time.

3.22.2 Scientific Justification

Scorpius X-1 (Sco X-1) offers one of our most intriguing potential sources of continuous gravitational waves. A low mass X-ray binary (LMXB) system, it emits X-rays copiously, indicating a high accretion rate from its companion star. Such accretion could lead to a sustained non-axisymmetry large enough to produce detectable gravitational radiation, or it could lead to excitation of r-modes [377, 378, 379, 380, 315, 309, 314, 381]. The X-ray luminosity from the accretion is a measure of mass accumulation at the surface. As the mass rains down on the surface it can add angular momentum to the star, which in may be radiated away in gravitational waves. Hence one can derive in equilibrium a torque-balance limit [377, 378, 309]:

$$h_{\mathrm{torque}} \quad \sim \quad (5\times10^{-27})\sqrt{\left(\frac{600\ \mathrm{Hz}}{f_{\mathrm{GW}}}\right)\left(\frac{\mathcal{F}_{\mathrm{x}}}{10^{-8}\ \mathrm{erg/cm^2/s}}\right)} \tag{5}$$

where $\mathcal{F}_{\mathrm{x}}$ is the observed energy flux at the Earth of X-rays from accretion. Note that this limit is independent of the distance to the star. Sco X-1 is the brightest steady-state X-ray source in the sky (outside of the Sun) with $\mathcal{F} \approx 4\times10^{-7}$ erg/cm^2/s, yielding the nominal torque-balance strain relation:

$$h_{\mathrm{torque}}^{\mathrm{ScoX1}} \quad \sim \quad (3\times10^{-26})\sqrt{\left(\frac{600\ \mathrm{Hz}}{f_{\mathrm{GW}}}\right)} \tag{6}$$

The notion of gravitational wave torque equilibrium is potentially important, given that the maximum observed rotation frequency of neutron stars in LMXBs is substantially lower than one might expect from calculations of neutron star breakup rotation speeds (∼1400 Hz) [382]. It has been suggested [383] that there is a "speed limit" governed by gravitational wave emission that governs the maximum rotation rate of an accreting star. In principle, the distribution of frequencies could have a quite sharp upper frequency cutoff, since the angular momentum emission is proportional to the 5th power of the frequency. For example, for an equilibrium frequency corresponding to a particular accretion rate, doubling the accretion rate would increase the equilibrium frequency by only about 15%.

A number of mechanisms have been proposed by which the accretion leads to gravitational wave emission. The simplest is localized accumulation of matter, *e.g.*, at the magnetic poles (assumed offset from the rotation axis), leading to a non-axisymmetry [309]. One must remember, however, that matter can and will diffuse into the crust under the star's enormous gravitational field. This diffusion of charged matter can be slowed by the also-enormous magnetic fields in the crust, but detailed calculations [384] indicate the slowing is not dramatic. Another proposed mechanism is excitation of r-modes in the fluid interior of the star [379, 309, 380, 314], with both steady-state emission and cyclic spinup-spindown possible [381, 385].

While Sco X-1 is probably the most promising source of its type, given its bright X-ray emission, large uncertainties in neutron star physics and in the accretion process argue for searching other X-ray binary systems for continuous gravitational waves [386]. We envision a program in which the search for Sco X-1 is given highest priority (CW group commitment to deliver publishable results for each observing run), but in which attention is also given to other X-ray binary systems, including accreting millisecond pulsars, burst oscillation sources and stars with detected quasi-periodic oscillations, as time and computational resources permit. Any X-ray binary system observed to burst during an ADE observing run would be considered for a directed search. Other potential sources are Fermi satellite gamma-ray sources at high galactic latitudes (suggesting nearness), sources with spectral and temporal properties consistent with pulsars, but for which no pulsations have been detected. For such sources, with neither source frequency nor orbital parameters known, not all search pipelines described below can be sensibly applied.

Three other binary systems are especially intriguing. Two (XTE J1751-305 and 4U 1636-536) are thought to be LMXBs with neutron stars accreting matter and for which a sharp spectral line has been observed in X-rays after demodulating for the known spin frequency of the star. These lines suggest a non-radial mode of oscillation which, in principle, could indicate gravitationally detectable r-modes. The inconsistency of the observed spindowns for these sources with ordinary r-mode emission, however, suggests that a different type of oscillation is being observed [387] or that the r-modes are restricted to the neutron star crust and hence gravitationally much weaker than core r-modes [388]. Were the X-ray oscillation observed in J1751 in 2002 to occur again during a full-sensitivity ADE run and to correspond to a core r-mode, it would very likely be detectable. How much weaker in gravitational waves the signal would be if due to a crustal r-mode is hard to know. For these two sources, the absence of precise ephemerides make truly targeted searches difficult, but searching only a handful of discrete, extremely narrow frequency bands makes these searches computationally cheap.

The third additional binary system of special interest, perhaps surprisingly, is Cygnus X-1 which is an HMXB thought to host a black hole of 14.8 solar masses. An interesting scenario receiving some attention in the theoretical community is the formation of a Bose-Einstein condensate (BEC) of string axions in the vicinity of a black hole [389, 390, 391]. In this scenario the axion BEC undergoes a continual emission of gravitational waves at a frequency (in the BH rest frame) determined by the axion mass and couplings. Detecting such emission in a binary system would require the same corrections for orbital Doppler modulations as for emission from a neutron star.

While it may be difficult to place much confidence in detectable gravitational-wave emission from any of these three intriguing sources, it is desirable to carry out searches for them, using our best available pipelines. The narrowband searches for J1751 and 4U 1636 are computationally quite cheap and should simply be carried out. The search strategy for Cygnus X-1, on the other hand, is not yet well understood. A recent meeting between the CW search group and the proponents [391] of the Cygnus X-1 signal indicated considerable uncertainty concerning signal frequency modulations (potentially a few percent in modulation depth) due to BEC self-interactions. Even the relatively coarse resolution of the Radiometer pipeline may be too fine for such a source. The Cygnus X-1 proponents have been encouraged to examine this issue more quantitatively.

If precise ephemeris information for Sco X-1 or other binary sources were available, *targeted* searches exploiting that information could use optimal detection statistics to exploit the full intrinsic sensitivity of the interferometers, as has been done for binary millisecond pulsars [392]. Here we consider instead sources for which there is little, if any, prior knowledge of the GW source frequency. In addition, frequency evolution is presumably governed by accretion processes subject to fluctuations; hence at least some searches must be robust against phase wandering.

In the event of GW detection with electromagnetic follow-up, successful EM detection would bring an immediate astrophysical payoff. If the gravitational wave frequency is twice that of the rotation frequency, with no GW emission observed at the rotation frequency, then a rotating triaxial ellipsoid model is favored. On the other hand, if the two frequencies agree, then precession probably plays an important role. If the GW frequency is approximately 4/3 the rotation frequency, then r-modes are strongly favored, yielding direct information on the interior fluid motion of a neutron star. In the conventional scenario of $f_{\rm GW} = 2f_{\rm Rot}$, the phase of the GW emission relative to the phase of the electromagnetic pulse(s) gives insight into the relation of the stellar quadrupole asymmetry to the magnetic poles. Similarly, there is some *a priori* information available for the inclination angle and transverse polarization angle of Sco X-1's spin axis, based on Sco X-1 jet observations, allowing comparison with the corresponding inferred GW values.

3.22.3 Search Description

CW Pipelines used in targeted searches for known pulsars and in directed searches for isolated neutron stars of unknown frequency cannot be used without substantial modification in a search for a neutron star in a binary system because of the frequency modulations due to the star's orbital motion. Searches must allow for those modulations, in addition to allowing for likely phase wandering over long time scales of GW signals from accreting systems. Given the large uncertainties of the astrophysics that govern the signal's time evolution, it seems prudent to apply a diverse suite of pipelines in this search. Potential considerations include broadband coverage, sensitivity for short data stretches, e.g., during detected X-ray outbursts, sensitivity for long data stretches (steady sources), robustness against phase wandering, ability to exploit orbital parameter knowledge, ability to exploit approximate phase evolution for accreting millisecond X-ray pulsars (AMXPs) and computational cost. Highest priority will be given to deploying several pipelines to target Sco X-1 in a search up to 2 kHz, with lower priority given to deploying one or more pipelines to target other promising X-ray binaries, including J1751-305, 4U1636 and Cygnus X-1 (BEC axion scenario). An upper limit on the search band of 2 kHz provides some safety margin above the 1.4 kHz defined by twice the rotation frequency of the fastest known pulsar. There is good reason to expect the accreting systems of most interest to GW searches to sit near the upper range of pulsar spin frequencies, and neutron stars should, in principle, be able to spin as fast as 1 kHz, for a variety of assumed equations of state [382].

Seven existing or potential pipelines in all are under consideration for these searches (one of which is a Stochastic Search Group pipeline). Five of these pipelines are mature enough to have participated fully in the first Sco X-1 mock data challenge [393]: CrossCorr, Sideband, TwoSpect, Polynomial and Radiometer (Stochastic Search Group pipeline). CrossCorr has the best strain sensitivity in this year-long search for which orbital period and phase are known well, while TwoSpect and Radiometer have strain sensitivities several times worse and Sideband has still worse sensitivity when restricted to a 10-day observation span, a limit motivated for a fully coherent search by expected source phase wandering from accretion fluctuations [394]. Based on these MDC results, Polynomial appears to offer no significant advantage for a directed binary search (but is being pursued for all-sky binary searches). All of the pipelines described here are expected to be robust against plausible fluctuations. they also have modest computational cost and seem appropriate to include in the suite described below.

Two other pipelines were not mature enough to participate fully in the first MDC stage, but are undergoing development and are expected to participate fully in later stages: PowerFlux (developed for isolated-star searches, but adaptable to binary searches) and an Einstein@Home-based F-Statistic search. Further development of PowerFlux for this search is manpower-limited, with prospects uncertain. An Einstein@Home-based $\mathcal{F}$-Statistic search is unlikely to be ready before the O2 run begins.

Below we describe the four search pipelines that are currently mature and likely to be run on upcoming O2 data: CrossCorr, Sideband, Radiometer and TwoSpect.

The Cross-Correlation (CrossCorr) pipeline[341, 395] was developed as an improvement to the radiometer search method, tailored to periodic gravitational-wave sources rather than unmodelled stochastic backgrounds. By using the periodic signal model, it is able to look for correlations not just between data from different detectors at the same times, but also between data taken at different times, from the same or different detectors. By restricting the terms in the cross-correlation to include only SFTs (Short Fourier Transforms) separated in time by less than some maximum lag time T_{lag}, the pipeline can be tuned to trade off sensitivity versus computing cost by adjusting the time lag parameter, as discussed in section 3.22.3.

The expected cross-correlation between two SFTs, which is used to coherently combine all of the included SFT pairs, depends on the signal parameters, which means the method needs to search over a grid of parameter-space points in the phase-modulation parameters. For Sco X-1, where the period is well enough known that it need not be searched over, the parameter space consists of spin frequency, projected semimajor axis, and time of ascension. When T_{lag} is small compared to the orbital period of 19 hours, the density of points needed in each dimension is proportional to T_{lag}. Since the number of SFT pairs for a fixed observation time also scales with T_{lag}, the computing cost should scale like T_{lag}^4. On the other hand, the h_0 to which the search is sensitive scales like $(T_{\text{lag}}T_{\text{obs}})^{-1/4}$. Note that the sensitivity of the search is not affected by the choice of SFT duration T_{sft} (shorter SFTs means more SFT pairs, each of which contributes less to the overall sensitivity). However, the number of SFT pairs for fixed T_{lag} and T_{obs} will scale like T_{sft}^{-2}, so we expect the computing cost to depend similarly on the choice of T_{sft}, which makes it advisable to use the longest SFTs we can get away with. The SFT duration is limited by the validity of the linear phase model, which assumes that the signal can be characterized by a single frequency during each SFT. An empirical Monte Carlo measurement has shown that for $f \lesssim 400\,\text{Hz}$, the sensitivity degrades when T_{sft} exceeds 600 seconds. The computing cost will also increase with frequency because the density of templates (at a given mismatch) in the two orbital parameter directions is proportional to frequency. A promising approach to reducing CrossCorr's computational cost and thereby allow deeper searching is use of barycentric resampling, analogous to that now used in isolated-star searches. Development is under way to test this approach on O2 data and deploy it on O3 data [396].

The Sideband pipeline [397, 394] is based on the venerable $\mathcal{F}$-Statistic [336] applied over coherence times long compared to the orbital period of the source (18.9 hr for Sco X-1), where Doppler demodulation is carried out to correct for the Earth's motion relative to the Solar System Barycenter, but no demodulation is carried out for the source's orbital motion. The remaining time-dependent frequency modulation in the detector frame allows decomposing the signal into an infinite sum of frequency modulated sidebands. Under the conditions that the observation time is $\gtrsim$ 3 orbital periods and that there is negligible drift in the intrinsic spin frequency of the source (i.e $\dot{\nu} \lesssim T^{-2}$ where T is the observation time) this sum is truncated leaving $M \sim 4\pi f_{\text{gw}} a \sin i/c$ frequency resolvable sidebands where f_{gw} is the intrinsic GW frequency and $a \sin i/c$ is the orbital semi-major axis projected along the line of sight and normalised by the speed of light. Each of the sidebands is uniformly separated from the next by $1/P$ where P is the orbital period, and any orbital eccentricity acts only to redistribute power amongst existing sidebands.

By computing the $\mathcal{F}$-statistic for a given sky position and for a long enough observation time, a signal of adequate amplitude can be extracted by incoherently summing together the $\mathcal{F}$-statistic at each sideband frequency [398, 399]. This is equivalent to convolving the detection statistic frequency series with a "comb" of unit amplitude spikes separated in frequency by the inverse of the orbital period. The incoherent summing to create a "C-Statistic" makes this a non-optimal strategy, but one that can have greater sensitivity to GW signals than a matched–filter approach because its observation length is not computationally limited. When using this approach, the parameter space resolution (and hence the number of search templates) is significantly reduced. It should also be noted that the sensitivity of this search to GWs scales with $T^{-1/2}$, as with a coherent search (and unlike other incoherent searches); the sensitivity, however, also scales as $M^{-1/4}$ (M is the number of sidebands) and hence high frequency, large orbit sources will be harder to detect with this method.

Of the LMXBs it is those of unknown spin frequency, but known sky location and orbital period, to which this search is most suited. The remaining orbital parameters, semi-major axis, time of passage through the ascending node ("time of ascension"), eccentricity, *etc.*, are generally quite poorly known. This scenario suits this search, as the sensitivity is relatively insensitive to all orbital parameters except for the orbital period.

The search code and associated pipeline are complete, and a methods paper detailing the search was published in early 2014 [397]. Search results obtained from a ten-day stretch of S5 data have been reviewed and published [394]. A possible future enhancement to this pipeline is double-demodulation, in which an approximate orbital demodulation is performed in computing the $\mathcal{F}$-Statistic, thereby reducing the number of peaks over which to sum in the creation of the C-Statistic. Combining C-Statistic values from multiple observing times during a data run is another enhancement, using the Viterbi method [400]. This method was recently demonstrated on the MDC data set, yielding a substantial gain in detection efficiency. This method will be explored using O1 data with likely production deployment on O2 data.

The Radiometer pipeline[401] is one of two pipelines used in the Stochastic Group's directed search for an anisotropic gravitational-wave background, described in detail in the corresponding search plan. Briefly, the method computes cross-correlations among pairs of detectors after correcting for the expected GW time delay for the source direction and time of observation. The full observation span of a data set is parsed into 60-s, Hann-windowed, 50%-overlapping segments, which are coarse-grained to achieve 0.25-Hz resolution. No Doppler correction is applied to the source frequency, given the relatively coarse frequency resolution of the search, although at higher frequencies there can be substantial signal leakage [393] across frequency bins.

The present search program is quite mature, having been used previously for S4 and S5 searches [401, 402], and will be used for a forthcoming paper describing a search in S6/VSR2-4 data. A modest pipeline refinement to reduce sensitivity loss from leakage across bins at high frequencies is under development and will require additional review.

The TwoSpect pipeline[403, 404] was originally developed for an all-sky search for continuous waves from unknown binary systems, but has been more recently adapted for directed searches. The TwoSpect method [403] relies on computing two successive power spectra of the calibrated strain data channel, hence the name TwoSpect. First, the program computes a power spectrum of the time series data, where the coherence time for the first power spectrum depends on the region of parameter space to be covered. For shorter-period binary systems, a shorter coherence time for each SFT is used. These choices ensure the signal remains in one bin during most of each SFT interval. The SFTs are then demodulated based on the sky location, correcting for the Earth's daily and annual motions. The SFTs are noise- and antenna-pattern-weighted in the same manner as for the PowerFlux algorithm. The initial power spectra are mean-subtracted within search bands to ensure that the powers computed in the second-stage spectra are distributed as a χ^2 distribution with two degrees of freedom. The second spectra are taken over a long observation time, e.g., 1 year, for each bin in the first set of spectra. The resulting frequency-by-frequency plot is matched against templates based on the expectation for a nominal CW signal from a binary system. The current pipeline has no explicit search over polarization and uses a polarization weighting for a circularly polarized source.

An all-sky binary search (in S6 and VSR2-3 data) over a $\sim$500-Hz band was recently published [404], which included a low-frequency search for Sco X-1. A dedicated S6 search for Sco X-1 up to $\sim$2 kHz using the directed pipeline was recently completed and is under review. Some additional, modest review of the pipeline refinements for directed searches will be needed. In addition, a more ambitious effort to enhance TwoSpect's sensitivity in both the all-sky and directed modes is under way. Specific improvements recently completed or planned include 1) coherent summing of SFTs from multiple interferometers prior to taking the second Fourier transforms; 2) weighting for arbitrary elliptical polarization; 3) orbital phase determination from matched filtering (or exploitation for directed searches); and a more sensitive first hierachical stage, using sparsely sampled templates ("X Statistic") [405]. It is not yet clear how many of these enhancements will be ready and reviewed by the start of production O2 searches in winter 2017.

Comparison of pipelines

As described below (section 3.22.6), the first stage of a **mock data challenge** has evaluated the pipeline performances (detection and upper limits strain sensitivity, parameter estimation), with a methods paper recently published [393]. Figure 6 shows the detection efficiency of the five pipelines that participated in the MDC, which included performance measurement on a year-long simulated sample of Gaussian white-noise data for H1, L1 and V1, with data segmentations taken from prior LIGO science running. (The Sideband search used only a 10-day subset of the data, under the assumption that a longer search would require Sco X-1's frequency evolution to be more stable than is astrophysically plausible.) Based on this efficiency comparison, it is likely that published upper limits (assuming no detection) from the O1 run will come from the CrossCorr pipeline, with backup validation provided by TwoSpect and Radiometer, albeit with significantly worse sensitivity. It is not clear that results from the Sideband pipeline, in its current form and with a continued reliance on a coherence time no greater than 10 days, can contribute usefully, but the new Viterbi enhancement to allow multiple 10-day segments to contribute offers a more promising approach. Polynomial (which has been optimized for all-sky binary searches) will likely not contribute.

It should be noted that the pipelines have different tolerances for astrophysical uncertainties. Specifically, Sideband assumes frequency stability of O(μHz) for O(10 days); CrossCorr's tolerance for frequency wandering depends on the coherence time, but O(10^5 s) lag times are compatible with frequency wandering of O(mHz) or less for the observation time span, which is also the bound on frequency wandering tolerated by TwoSpect; and Radiometer can tolerate O(500 mHz) frequency wandering. The next stage of the ongoing MDC will address this issue, along with the sensitivities of the pipelines in non-Gaussian (recolored S6) data.

Search strategy

There is little chance of observing Sco X-1 in O1 data, given the run's expected sensitivity and observation span of three months. The longer-term prospects, however, are brighter, albeit not at all assured. The mock data challenge results to date indicate that at least one existing pipeline (CrossCorr) will be able to reach h_0 sensitivities of O(5×10^{-26}) in the bucket at full aLIGO design sensitivity with one year of joint H1-L1-V1 data. Barycentric resampling may extend the band over which that reach extends. From equation 5, this reaches the torque-balance limit for GW signal frequencies below 200 Hz. As discussed above, however, signals may well lie at much higher frequencies. On the other hand, the derivation of the torque-balance limit assumes the relevant radius for accretion is that of the neutron star. Given the poorly understood magneto-hydrodynamics of neutron star-accretion disk interactions, the Alfven radius may be more relevant, which could lead to higher angular momentum transfer to the star and hence a greater GW emission in equilibrium. That said, the astrophysical uncertainty can go in the other direction too, with accretion disk models that maintain torque balance without significant GW radiation[406]. Hence we have reason for tempered optimism in a Sco X-1 search at full ADE sensitivity.

Although the large number of pipelines we have in mind to use in searching for Sco X-1 may seem excessive, there are good reasons to field a broad suite of approaches, even more than is the case for other CW searches. In the case of directed searches for binary systems, considerations for running pipelines include

- Best sensitivity for long observation times
- Best sensitivity for short observation times or long observation times of highly varying sensitivity
- Best sensitivity in the case of disparate detector performances
- Best robustness against signal deviations from assumed phase model, *e.g.,* due to accretion fluctuations
- Fastest pipeline for quick looks at data
- Best robustness against non-Gaussian artifacts

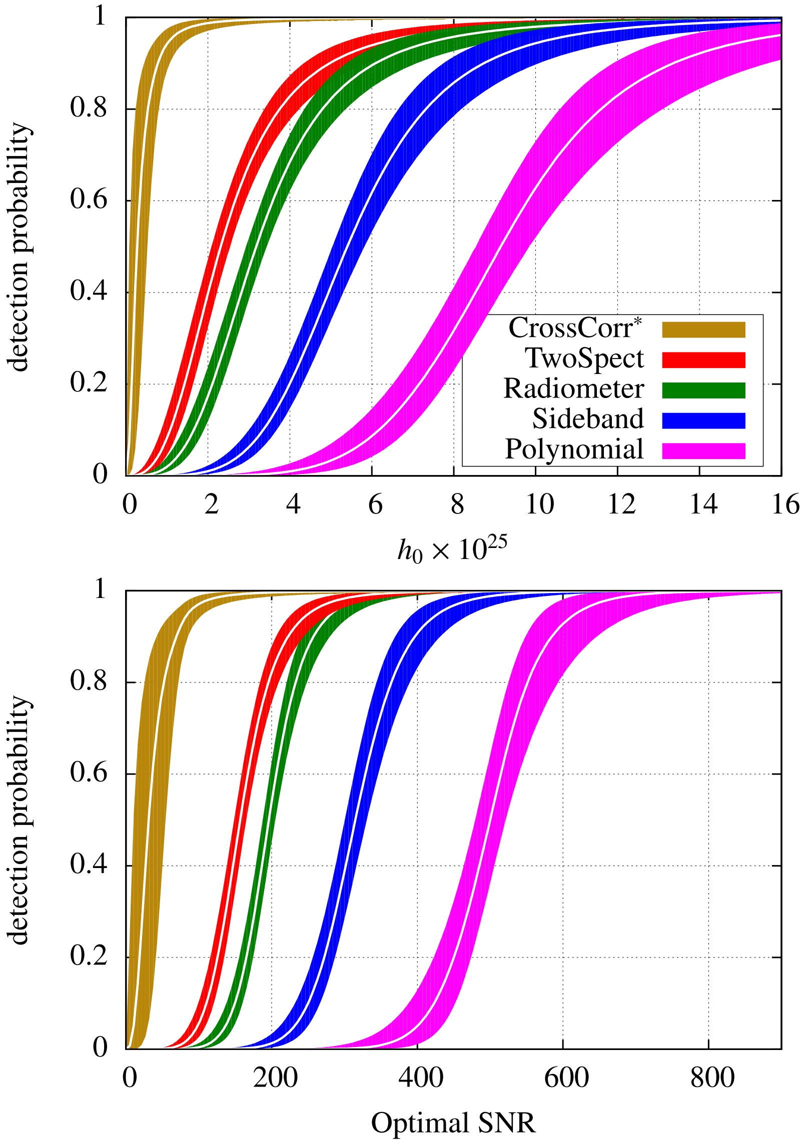

Figure 6: Detection efficiencies *vs* strain amplitude h_0 and *vs* optimal achievable SNR of five participating directed binary search pipelines in the first stage of the Sco X-1 mock data challenge.

- Ability to probe deeply in strain in the event of hierarchical detection ("zooming")

We expect only a few (1-3) pipelines to excel according to these criteria, allowing an eventual winnowing of pipelines, based on realistic MDC studies and based on running competing pipelines on test bands of ADE data, starting with O1. At this point, CrossCorr is likely to prevail on the long-term, most critical criterion, namely best sensitivity for long observation times, and given its structure with a tunable time lag, it is also well positioned to prevail on the important criterion of zooming capability. Pipeline teams will be asked to produce those test results before receiving allocations of substantial computing resources. The two most important criteria are best sensitivity achievable in real data and best robustness against source modeling uncertainty. Note that the use of multiple interferometers differs among the pipelines. Sideband and TwoSpect can be run in single-IFO or multi-IFO modes, allowing for coincidence detection or for single- vs multi-IFO signal-to-noise ratio consistency tests, e.g., joint detection confidence should be higher than any single-IFO confidence. In contrast, the Radiometer pipeline can only be run on an network of at least two detectors. CrossCorr can be operated with data from any number of detectors, including one, but a single-detector analysis will involve considerably fewer possible SFT pairs, and therefore be less sensitive, unless the capability is added to include auto-correlation terms. However, consistency checks for Radiometer and CrossCorr are also possible for analyses involving different detector pairs.

Electromagnetic follow-ups would play an important role in assessing the scientific impact of a detection in this search. Before publishing a CW discovery, we wish to consult X-ray astronomers to determine if a pulsation signal consistent with GW observations can be observed. A discovery publication might include co-authors from the X-ray community who carry out follow-ups at our request (whether or not they confirm the source), a blanket request we envision going out through our existing liaisons in the X-ray community[17]. Inclusion of these authors in the discovery paper (as opposed to later papers or companion papers), would depend on the timeliness and astrophysical importance of their results. We fully expect results from some observers that would be rapid and enhance the astrophysical impact of the discovery paper.

Another interesting follow-up possibility after a discovery is to exploit advanced interferometer narrow-banding to improve parameter estimation. Whether the potentially improved SNR from narrow-banding is worth the cost in sensitivity in other bands and in interferometer downtime is difficult to judge in advance, however. Unless all interferometers are narrow-banded together, the SNR gain from narrow-banding over broadband operation may be modest, and given current astrophysical knowledge, there is no compelling reason to choose narrow-banding in even a directed binary search.

3.22.4 Result Validation Plan

As discussed in section 3.22.3, zooming in on directed-search candidates offers the potential for a significant increase in signal-to-noise ratio. With high SNRs confirmed by the three independent targeted-search pipelines described elsewhere, there will likely be no uncertainty as to whether a detection has been made.

Given the significant differences in achievable sensitivities among the pipelines, however, validating upper limits from the most sensitive pipeline in the absence of detection will rely mainly on careful review.

3.22.5 Publication Plan

Following the observing scenarios document [346], we assume a 6-month O2 run in 2016-2017, and a 9-month O3 run in 2017-2018. In each run we assume an intrinsic strain sensitivity significantly improved over previous runs. Hence we envision at least one directed-binary search publication from each run with

---

[17] We envision a very lightweight MOU arrangement with electromagnetic observers. In the event of a GW discovery, observers would be offered the opportunity to sign an MOU setting out publications ground rules, in order to obtain the GW ephemeris. While leaks of such parameters to MOU non-signers are likely, the pulsar community has established an etiquette for protecting priority on discoveries that makes such leaks benign, we believe.

Pipeline	**Published observationa results to date**	**Search & review status**
CrossCorr	(Only mock data analyzed so far)	Review under way
Sideband	*PRD* 91 (2015) 062008 (S5)	Reviewed
Radiometer	*PRD* 76 (2007) 082003 (S4) *PRL* 107 (2011) 0271102 (S5)	S6 / VSR2-4 search carried out; mods under review
TwoSpect	*PRD* 90 (2014) 062010 (S6/VSR2) (all-sky binary pipeline)	S6 Sco X-1 search carried out; mods under review

Table 6: Summary of directed binary pipelines, including published observational results from previous data runs, and the current search and review status.

the first such publication featuring a Sco X-1 search. Subsequent publications for a given run could include additional X-ray binary targets or perhaps a deeper or broader search for Sco X-1 - if justified by substantially improved sensitivity or parameter space coverage. Steadily improving detector sensitivity will argue for expedited analysis of each data set, including a pragmatic approach to detector artifacts and unpromising outliers.

Although we implicitly assume here that published results from the first three runs will be upper limits on CW sources, we may well detect a signal from the directed binary searches. In that event we would, of course, publish one or more papers on the detected source and would collaborate with radio, optical, X-ray and γ-ray astronomers on deriving astrophysical insight from joint observations, as discussed in §3.22.3.

If detector sensitivity does not improve significantly from one year to the next, *e.g.*, 2016 running is comparable to that in 2015, then the searches will nonetheless be carried out, but the journal (or perhaps conference proceedings) to which results are submitted for publication may be adjusted accordingly.

3.22.6 Technical requirements and development plan

Pipelines status and review

CrossCorr has been implemented as lalapps search code within the last year and is under review for use in O1.

Sideband has been used in a recently published search of LIGO S5 data [394]. Review of the recent post-production Viterbi enhancement is expected to require modest resources.

Radiometer has been used in published searches of LIGO S4 data [401] and S5 data [402], with an S6 / VSR2-4 search carried out prior to O1. Modest enhancements have been recently implemented to correct for signal leakage across bins at high frequencies, which require additional review.

TwoSpect has been used in its original, all-sky implementation in a published search of LIGO S6 and Virgo VSR2 data [404]. Review is under way of recent minor modifications for use in a directed search, tested in the Sco X-1 MDC [393] and used in a LIGO S6 search. More substantial review will be needed for additional ongoing enhancements to support coherent detector combination, explicit polarization searching and orbital phase exploitation that improve sensitivity to known binary systems.

Mock Data Challenge The performances of the various pipelines used in this search are being systematically evaluated via a multi-stage mock data challenge. The first stage was based on injection of 100 Sco X-1 signals of various frequencies ranging up to 1500 Hz into one year of Gaussian white noise of amplitude spectral noise density $4 \times 10^{-24}\,\mathrm{Hz}^{-\frac{1}{2}}$, where realistic data segmentation was simulated using segmentation from past LIGO science running. An open set of 50 of the injections was used for tuning the parameters of the pipeline that determine detection efficiency and upper limit estimation. Then the pipelines were tested on a closed (blind) set of 50 injections. The resulting performances of the pipelines are summarized as detection efficiency curves in figure 6. A methodological paper describing the results of the first stage of the MDC was recently published [393].

The next stage of the MDC, planned for summer 2016, will include evaluation of pipeline performance in the presence of significant phase wandering of the source and in the presence of non-Gaussian noise.

3.23 All-sky Searches for Spinning Neutron Stars in Binary Systems

3.23.1 Abstract

Gravitational waves (GWs) are small ripples in the geometry of space-time, predicted to exist by Einstein's Theory of General Relativity, and propagating at the speed of light. Rapidly spinning neutron stars in our galaxy may emit such waves if they are not perfectly symmetric around their spin axis. Their deviation from such axisymmetry is usually characterized by a parameter called *ellipticity* which, for example, might be as large as 10^{-6} for a broad, 1-cm-high *bulge* across the surface of the 20-km-diameter star. A comprehensive search has been carried out in data from the LIGO and Virgo gravitational wave interferometers for signals from spinning neutron stars in binary systems. No such signal was detected, allowing scientists to rule out rapidly spinning neutron stars with ellipticities greater than 10^{-5} anywhere within 2000 light years of the Earth. Those limits are more stringent (10^{-6}) for neutron stars within 200 light years. We describe here the plans to extend the all-sky search for binary spinning neutron stars to the next generation of ground-based gravitational wave detectors. New data, to be taken in the coming year after improvements to the LIGO and Virgo detectors, is expected to be still more sensitive, allowing scientists to probe deeper into the galaxy and down to smaller ellipticities, in the hope of detecting these expected continuous waves for the first time.

3.23.2 Scientific Justification

Rapidly rotating neutron stars (NS) are the most promising sources of continuous-wave (CW) gravitational signals in the LIGO and Virgo frequency band. These stars are expected to emit gravitational radiation through a variety of mechanisms, including elastic deformations [309, 310, 311], magnetic deformations [312, 313], unstable r-mode oscillations [309, 314, 315], and free precession [316]. A review of these emission mechanisms can be found in [317]. Here, we focus on the all-sky search for unknown neutron stars in binary systems. The number of undiscovered, electromagnetically quiet neutron stars within 5 kpc can be estimated to be $O(10^6 - 10^7)$ from the neutron star birth rate [318], although it is likely that only a tiny fraction would both be rotating fast enough to be accessible to LIGO [319] and remain bound to the galaxy over the age of the galaxy [320]. Only $\sim$ 2000 radio or x-ray galactic pulsars have been discovered so far [321].

Neutron stars in binary systems are of particular interest because of the phenomenon of "recycling" in which a companion star accretes matter onto the neutron star, imparting angular momentum to it and speeding it up. Such accretion is observed, for example, in low mass X-ray binary systems, such as Scorpius X-1, and most observed millisecond pulsars observed in radio, X-rays and gamma rays, reside in or once resided in systems where the accretion has stopped, but where the neutron stars retain a high angular velocity [319]. The fraction of known millisecond pulsars ($f_{\rm rot} > 100$ Hz) that are binary is more than half, and the fraction of pulsars with $f_{\rm rot} > 400$ Hz that are binary is more than 3/4. The fraction of all known binary pulsars that are millisecond pulsars is $\sim$70% [321].

Unfortunately, neutron stars in unknown binary systems also present extreme challenges for continuous waves searches because the unknown orbital characteristics produce unknown modulations of the source frequency in the Solar System Barycenter (SSB), in addition to calculable modulations due to the Earth's motion with respect to the SSB. As is well known, even the calculable modulations for an assumed source frequency make an all-sky search for unknown isolated stars a formidable computational challenge. Adding unknown modulations makes the problem all the more difficult.

The recent publication [404], however, of the first all-sky binary CW upper limits (based on S6 and VSR2-3 data) indicates this challenge can be met, and there is good reason to believe that the strain sensitivity of future searches will improve significantly with further algorithm development.

Assuming that pulsations are indeed observed in one or more electromagnetic bands in follow-up, there is immediate astrophysical payoff. If the gravitational wave frequency is twice that of the rotation frequency, with no GW emission observed at the rotation frequency, then a rotating triaxial ellipsoid model is favored. On the other hand, if the two frequencies agree, then precession probably plays an important role. If the GW frequency is approximately 4/3 the rotation frequency, then r-modes are strongly favored, yielding direct information on the interior fluid motion of a neutron star. In the conventional scenario of $f_{\rm GW} = 2f_{\rm Rot}$, the phase of the GW emission relative to the phase of the electromagnetic pulse(s) gives insight into relation of the stellar quadrupole asymmetry to the magnetic poles. Similarly, the inclination angle and transverse polarization angle of the star's spin axis can be inferred from the GW emission, and if deep electromagnetic observations detect a pulsar wind nebula around the star, it may be possible to compare the GW- and EM-inferred angles. More generally, one can envision a sequence of beyond-discovery collaboration publications, as we and electromagnetic astronomers continue studying a source that (we hope) remains detectable throughout the ADE.

Another interesting follow-up possibility after a discovery is to exploit advanced interferometer narrow-banding to improve parameter estimation. Whether the potentially improved SNR from narrow-banding is worth the cost in sensitivity in other bands and in interferometer downtime is difficult to judge in advance, however. Unless all interferometers are narrow-banded together, the SNR gain from narrow-banding over broadband operation may be modest, and given current astrophysical knowledge, there is no compelling reason to choose narrow-banding in an all-sky binary-star search.

3.23.3 Search Description

As in all-sky searches for isolated neutron stars, it is prudent to establish and maintain more than one search pipeline, preferably with somewhat different approaches, given our relative ignorance of the underlying astrophysics of neutron stars. In this case, the unknown orbital dynamics of the system only increases the uncertainty as to which regions of parameter space are most promising. We aim to search for GW signal frequencies as least as high as 1000 Hz and to cover orbital periods from as short as a few hours to as long as several months.

Below we describe two existing pipelines, one mature (TwoSpect) with published results (but with recent significant enhancements) and the other (Polynomial) now approaching maturity.

The TwoSpect pipeline[404, 403] relies on computing two successive power spectra of the calibrated strain data channel, hence the name TwoSpect. First, the program computes a power spectrum of the time series data, where the coherence time for the first power spectrum depends on the region of parameter space to be covered. For shorter-period binary systems, a shorter coherence time for each SFT (Short Fourier Transform) is used. These choices ensure the signal remains in one bin during most of each SFT interval. The SFTs are then demodulated based on the sky location, correcting for the Earth's daily and annual motions. The SFTs are noise- and antenna-pattern-weighted in the same manner as for the PowerFlux algorithm [323]. The initial power spectra are mean-subtracted within search bands to ensure that the powers computed in the second-stage spectra are distributed as a χ^2 distribution with two degrees of freedom. From these demodulated spectra, a spectrogram is created, and a second spectrum is taken over each of its rows (along the time axis), to create a plane of strain power squared vs modulation frequency (horizontal) and nominal source frequency (vertical). The pixels in this plane are matched against templates based on the expectation for a nominal CW signal from a binary system. The current pipeline has no explicit search over polarization and uses a polarization weighting optimized for a circularly polarized source, a weighting which is also optimized for performance on an average over other signal polarizations.

An all-sky binary search (in S6 and VSR2-3 data) over a 500-Hz band was recently published [404], which also included a low-frequency search for Scorpius X-1. A dedicated S6 search for Sco X-1 up to $\sim$2 kHz using the directed pipeline was recently completed and is under review. In addition, a more ambitious effort to enhance TwoSpect's sensitivity in both the all-sky and directed modes is under way. Specific improvements recently completed or planned include 1) coherent summing of SFTs from multiple interferometers prior to taking the second Fourier transforms; 2) weighting for arbitrary elliptical polarization; 3) orbital phase determination from matched filtering (or exploitation for directed searches); and a more sensitive first hierachical stage, using sparsely sampled templates ("X Statistic") [405].

The present all-sky sensitivity of TwoSpect is severely limited by its first stage of a hierarchical search, which uses a relatively insensitive but computationally efficient incoherent harmonic sum (IHS) in the frequency-frequency plane. This limitation is easily eliminated in the directed search because of the vastly smaller parameter space volume to search. In the all-sky TwoSpect search, one must search over sky location, nominal source frequency, orbital period and orbital modulation depth (circular orbit approximation), while in the search for Sco X-1, there is only the search over frequency and a highly restricted range of orbital modulation depth. A study is under way to assess whether or not shortening the SFT coherence time in combination with use of the X Statistic is sufficient to allow elimination of the IHS stage in the all-sky search, while improving sensitivity on the whole.

The **Polynomial** [407] pipeline is based on searching systematically for quasi-sinusoidal signals with up to 2nd order time derivatives (3rd order in phase) in short stretches of data and then correlating different stretches of data for which consistent signal parameters are detected. The method is best suited to short-period binary systems for which frequency evolution is too rapid for more conventional search methods.

The orbital motion of the neutron star around the center of gravity of the binary system may induce large and rapidly changing frequency modulations of the gravitational wave. The frequency $f_{\rm ssb}$ detected in the solar system barycenter may be modeled as

$$f_{\rm ssb} = f_{\rm gw}\gamma\left(1 - \frac{\vec{v}\cdot\vec{n}}{c}\right) \tag{7}$$

with $f_{\rm gw}$ the frequency of the gravitational wave in the neutron-star rest frame, γ the Lorentz contraction factor, $\vec{v}$ the velocity of the neutron star with respect to the solar system barycenter, and $\vec{n}$ a unit vector in the direction of the source. Similarly, the change in frequency per unit time may be modeled by

$$\frac{df_{\rm ssb}}{dt} = f_{\rm gw}\gamma\left(1 - \frac{d\vec{v}}{dt}\cdot\frac{\vec{n}}{c}\right) + \frac{df_{\rm gw}}{dt}\gamma\left(1 - \frac{\vec{v}\cdot\vec{n}}{c}\right). \tag{8}$$

Assuming that the motion of the neutron star can be described adequately by Keplerian orbits, the phase of the gravitational wave depends on 6 extra parameters (e.g., the phase in the orbit, the orbital period, the mass of the accompanying star, the eccentricity, and the angles of the major and minor axes with respect to $\vec{n}$). For short orbital periods, the derivative of the detected frequency df/dt will be completely dominated by the Doppler shift. As an extreme example, for a neutron star orbiting an object with the same mass in a circular orbit with a period of 5000 s, $df_{\rm ssb}/dt$ may be as large as $0.002 \times f_{\rm gw}/s$.

An extension of coherent search methods to use additional parameters to describe the orbital motion of the neutron star is computationally infeasible for an all-sky binary search (for coherence times in the order of 1 h, the extra number of parameter values needed to cover all likely Keplerian orbits exceed a factor of 10^9). Even a conventional hierarchical search method used for isolated stars, such as the Stack-Slide or Hough transform methods as discussed in Ref. [325] would also incur exorbitant computational costs in an all-sky binary search, to accommodate the possible modulation variations.

As an alternative, a set of filters that describe the phase of the gravitational wave as a third-order polynomial in time (and hence the frequency as a second-order polynomial in time) is used. The presence of the gravitational wave may be detected by looking for the correlation of the data with these filters. The polynomial shape of the filters facilitates the analysis (a large reduction in filter parameters is obtained by relying on the fact that translating the polynomial filter in time or in frequency will give another polynomial filter in the same parameter set) and renders a complete scan over years of data computationally feasible. The filters should be coherent over the time that they are applied, implying that third-order derivatives of the frequency of the gravitational signal should be small. If a correlation between a filter and the data exceeds a threshold and constitutes a hit, then for the hit the frequency is known as a function of time. Therefore, hits between data stretches can be correlated. Development of the algorithm and search strategy are under way; it is believed that the approach offers a means to search a parameter range that is not currently covered by other analysis techniques, i.e., waves with frequency derivatives df/dt up to 2 mHz/s and d^2f/dt^2 up to 10^{-6} Hz/s^2.

The Polynomial pipeline has been implemented and tested on simulated data with white noise (see S. van der Putten's Ph.D. thesis [407]) and has been further tested in the Scorpius X-1 mock data challenge [393]. Review of the pipeline is planned for the calendar year 2016.

Another new method, similar in approach to TwoSpect, but likely to be less computationally intensive, has been proposed [408], in which relatively short-coherence-time SFTs are used, short enough that Doppler effects due to the Earth's motion can be neglected, to construct spectrograms over the course of a data run. Autocorrelations along the time dimension can then pick out turning-point frequencies of orbital modulation, without explicit Earth-motion Doppler demodulation and without use of binary templates. It is not yet clear, however, when a pipeline based on this method will be available for evaluation.

A recent, promising development is the implementation of sidereal folding of data in the Stochastic Group's all-sky Radiometer search. This enhancement has the potential to permit rapid all-sky, frequency-binned searches for background gravitational radiation, including from neutron stars in binary systems. First indications are that the method could be competitive with the pipelines described here and computationally much faster. It is not yet clear if a full pipeline will be ready and reviewed for O1 production searches.

As for all-sky isolated-star CW searches, "zooming in" on interesting signals should be possible via lengthening the relevant coherence time, once a hint of a signal is found, allowing the parameter space volume to shrink by orders of magnitude. If, for example, TwoSpect detected a signal using very short SFTs, lengthening the SFTs would likely improve signal-to-noise ratio and parameter estimation accuracy (except for the shortest-period binaries). Other directed binary searches, such as the Cross-Correlation pipeline [341, 395] could also be put to good use in zooming. Ultimately, one could aim for a fully coherent follow-up for non-accreting systems and perhaps quasi-coherent follow-up for accreting systems. Future stages of the Scorpius X-1 mock data challenge should yield a quantitative understanding of what is feasible, but based on what has been achieved in isolated-star follow-ups, it seems likely that signal-to-noise ratio could improve by more than an order of magnitude via zooming, ensuring a high detection confidence. In isolated-star follow-ups, zooming can lead to signal-to-noise ratios that grow more rapidly with coherence time than the corresponding fixed-false-alarm-rate threshold does from increased trials factors [326, 327, 344].

Electromagnetic follow-ups play a critical role in assessing the scientific impact of a detection in this search. Before publishing a CW discovery, we wish to consult electromagnetic partners with access to radio, X-ray and γ-ray telescopes on what they can see in the direction of the source. With a year's observation time and good SNR, we expect to achieve an angular resolution of O(arcsec), which should suffice for excellent electromagnetic follow-up. We already have partnerships in the radio, X-ray and γ-ray communities for obtaining ephemerides for our targeted pulsar searches. Confirmation in follow-up of a previously unknown source in radio, optical, X-ray or gamma-ray with pulsations consistent with the observed GW signal would add to our own detection confidence and permit the multi-messenger studies discussed in section 3.23.2. The added confidence that would come from confirming a new source not displaying pulsations is harder to assess at this point, and the absence of any EM confirmation would likely increase the effective signal-to-noise threshold at which we would feel confident in declaring a discovery. We would expect partners to be able to acquire telescope time with high priority, *e.g.,* through target of opportunity programs, if following up a credible GW signal; hence results should be timely from at least some EM groups, permitting inclusion in a discovery paper with O(weeks) delay.

Pipeline	**Published observational results to date**	**Search & review status status**
TwoSpect	*PRD* 90 (2014) 062010 (S6/VSR2-3)	S6/VSR2-3 search review completed
Polynomial		Review begins 2016

Table 7: Summary of existing CW all-sky binary pipelines, including published observational results from previous data runs and the current search and review status.

3.23.4 Publication Plan

Following the observing scenarios document [346], we assume a 6-month O2 run in 2016-2017, and a 9-month O3 run in 2017-2018. In each run we assume an intrinsic strain sensitivity significantly improved over previous runs. We envision one all-sky binary publication from each run by default. Subsequent publications using significantly more computing time would be considered if justified by a significant improvement in strain sensitivity or in parameter space coverage. Steadily improving detector sensitivity will argue for expedited analysis of each data set, including a pragmatic approach to detector artifacts and unpromising outliers that can be followed up in more sensitive data.

Although we implicitly assume here that published results from the first three runs will be upper limits on CW sources, we may well detect a signal from the all-sky searches. In that event we would, of course, publish one or more papers on the detected source and would collaborate with radio, optical, X-ray and γ-ray astronomers on deriving astrophysical insight from joint observations, as discussed in §3.23.3. A discovery publication might include co-authors from those communities who carry out follow-ups at our request (whether or not they confirm the source), a blanket request we envision going out through our existing liaisons in those communities[18]. Inclusion of these authors in the discovery paper (as opposed to later papers or companion papers), would depend on the timeliness and astrophysical importance of their results. We fully expect results from some observers that would be rapid and enhance the astrophysical impact of the discovery paper. The target journal for such a discovery paper might depend on whether or not other types of GW detections have been made by that time, and the decision would presumably be made at the executive/steering committee level.

If detector sensitivity does not improve significantly from one year to the next, *e.g.*, 2016 running is comparable to that in 2015, then the searches will nonetheless be carried out, but the journal (or perhaps conference proceedings) to which results are submitted for publication may be adjusted accordingly.

3.23.5 Technical requirements and development plan

Pipelines status and review

TwoSpect has been used in a published search of LIGO S6 and Virgo VSR2-3 data [404]. Hence a reviewed and tagged pipeline is ready for use in O1. Nonetheless, further enhancements are under way, to improve strain sensitivity and parameter estimation. One enhancement (coherent multi-interferometer SFT

---

[18] We envision a very lightweight MOU arrangement with electromagnetic observers. In the event of a GW discovery, observers would be offered the opportunity to sign an MOU setting out publications ground rules, in order to obtain the GW source coordinates and ephemeris. While leaks of such parameters to MOU non-signers are likely, the pulsar community has established an etiquette for protecting priority on discoveries that makes such leaks benign, we believe.

summing) is ready and under review for use in O1 searches, along with minor refinements implemented for the Sco X-1 mock data challenge [393] and Sco X-1 S6 search [409].

Polynomial too has participated in the Sco X-1 mock data challenge and is preparing for a review to begin in 2016.

3.24 Search for an Isotropic Stochastic Gravitational Wave Background

3.24.1 Abstract

Gravitational waves, predicted by Einstein's general theory of relativity, are ripples in the fabric of spacetime, which propagate at the speed of light. A stochastic gravitational-wave signal is formed from the superposition of many events or processes that are too weak and too numerous to be resolved individually, and which therefore combine to produce a stochastic background. A stochastic background can arise from cosmological sources such as inflation, cosmic strings, and pre-Big-Bang models. Alternatively, it can arise from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars. The prime objective of the Stochastic Group is to measure the stochastic background. A comprehensive search has been carried out using data from initial LIGO and Virgo. No signal was detected, but our results constrain the energy density of the stochastic background to be $\Omega_0 < 5.6 \times 10^{-6}$ at 95% confidence [410]. The results from Advanced LIGO's first observing run are forthcoming. The advanced detectors will ultimately have about 10-times better strain sensitivity than the initial detectors, as well as to extend the sensitive band from 40 Hz down to 10 Hz. Furthermore, the number of detectors operating in a worldwide network is expected to increase, eventually including sites at LIGO-Hanford, LIGO-Livingston, Virgo, GEO-HF (at high frequencies), KAGRA (Japan), and potentially LIGO India. The significant strain sensitivity improvements and wider bandwidth will enable real breakthroughs in the searches for the stochastic background, with a potential sensitivity of $\Omega_0 < 6 \times 10^{-10}$. The detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The detection of an astrophysical background is not unlikely and would also be of great interest. The implications from the observation of GW150914 [411] are that the stochastic gravitational-wave background from binary black holes, created from the incoherent superposition of all the merging binaries in the Universe, could be higher than previously expected [412].

3.24.2 Scientific Justification

The stochastic isotropic search targets stochastic gravitational-wave backgrounds. A stochastic background arises from the superposition of an ensemble of gravitational-wave sources each of which is too weak to be detected individually. There are two broad categories of stochastic backgrounds. In cosmological scenarios, gravitational-wave backgrounds can be created in the early universe from a variety of processes such as the amplification of vacuum fluctuations following inflation [413], phase transitions in the early universe [414, 415], cosmic strings [416, 417, 418, 419], and pre-Big Bang models [420, 421]. In astrophysical scenarios, the gravitational-wave signals from more ordinary objects, such as binary neutron stars [422] or binary black holes [412], combine to produce a stochastic signal . Astrophysical backgrounds may arise from core collapses to neutron stars or black holes [423, 424, 425, 426], rotating neutron stars [427, 428] including magnetars [429, 430, 431, 432], phase transition [433, 434] or initial instabilities in young neutron stars [435, 436, 437, 436], compact binary mergers [438, 439, 440, 441, 442, 443] and compact objects around supermassive black holes [444, 445]. In the context of detecting a cosmological background, astrophysical sources are sometimes referred to as "foregrounds", as they may mask the cosmological contribution. One hope is that the astrophysical background has a different statistical signature and can be identified and removed. For instance, astrophysical sources may not be numerous enough to create a Gaussian "stochastic" background in the sense that the sources do not overlap in the time-frequency domain [440]. For our purposes here, we refer to both astrophysical and cosmological signals as stochastic backgrounds. Together, they constitute the target for the isotropic stochastic search.

The detection of a cosmological background would yield arguably the most exciting science possible with gravitational wave astronomy. There would be enormous interest from the wider physics and astronomy community, and the implications of the discovery would likely be far-reaching. By measuring gravitational waves from the early universe, we could infer the existence of previously conjectural objects such as cosmic strings or, even more exciting, probe physics at energy scales inaccessible through other means. LIGO/Virgo will probe energy scales of $\sim 10^9$–10^{10} GeV in the early universe [446]. The detection of an astrophysical background would also be an important discovery, though, not with the revolutionizing implications of cosmological background detection. Differentiating a cosmologically produced background from one that might be astrophysically produced will not be easy, but parameter estimation techniques could provide the ability to do so [447]; the statistical nature of the signal will also provide information [440]. By detecting the stochastic background from binary neutron stars or binary black holes, for example, we can learn about the properties of a large ensemble of binaries. The stochastic measurement would complement results obtained from the detection of individual binaries, and since the stochastic signal is dominated by very distant objects (redshift $z \approx 1$–2), the stochastic search probes a different population of binaries than the nearby ones that can be detected individually. While astrophysical backgrounds are interesting in their own right, it is also important to develop an observationally informed understanding of them in order to facilitate a confident detection of a cosmological background.

The theoretical uncertainties for the amplitude of cosmological backgrounds are significant, and observational measurements by LIGO and other experiments/observatories play a crucial role in guiding theoretical models. The amplification of vacuum fluctuations is the most well-known cosmological model, and it is widely regarded as plausible. Unfortunately for gravitational-wave astronomers, the expected amplitude of this canonical model is $\Omega_{\rm gw}(f) \approx 10^{-15}$, which is significantly below what will be achieved by second-generation detectors. However, the canonical model is merely the simplest one to write down, and we should keep in mind that very little is actually known about inflation and the very early universe in general; reality may very well be different. Cosmologists have proposed models, which can produce inflation-era gravitational waves that are detectable with advanced detectors [448, 449]. Similarly, there are regions of parameter space where we may be able to detect cosmic strings [450, 451]. As for astrophysical backgrounds, it is not, perhaps, widely appreciated, but advanced detectors have a good chance of detecting a stochastic background from unresolvable compact binaries [452, 412]. In the event of a non-detection, the upper limits obtained from a stochastic search will be of astrophysical interest. Another point worth considering is the possibility of looking at contributions to stochastic background coming from gravitational waves with nonstandard polarization [453]. While general relativity allows only for two kind of tensorial polarizations, a generic prediction of extended gravitational theories, such as scalar-tensor ones [454, 455], $f(R)$ gravity [456, 457], bimetric [458] and massive [459] gravity theories, is the presence of other physical degrees of freedom, with polarizations of a scalar or vectorial kind. Advanced detectors will probe previously unexplored parameter space in the plane of frequency vs energy density plane. The constraints on cosmological and astrophysical models will probe new and interesting parts of parameter space that are not constrained by other observations.

The isotropic search is the flagship search of the Stochastic Group, and this search will build on a series of LIGO/Virgo papers [460, 461, 450, 410, 462]. Advanced LIGO operating at design sensitivity is expected to surpass initial LIGO sensitivity by four orders of magnitude in energy density for a low frequency (less than 150 Hz) search; this is due to the increase in detector sensitivity by a factor of 10 and the reduction of the lower limit of the search from 40 Hz to 10 Hz. In addition, a factor of 10 increase in advanced Virgo's sensitivity will results in a reduction of the stochastic background energy density upper limit by at least a factor of 100 in the 1 kHz regime.

The final initial detector isotropic searches [410, 462] have been published. The O1 isotropic search is undergoing review, and the results will be published soon. A search for extended polarizations is also ongoing. With the coming observation runs the isotropic search will benefit from dramatically improved sensitivity.

3.24.3 Search Description

The primary goal of the isotropic search is to estimate the energy density of the stochastic background:

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c} \frac{d\rho_{\rm GW}}{d\ln f} \,, \tag{9}$$

where $\rho_{\rm GW}$ is the energy density of gravitational waves, ρ_c is the critical density of the universe, and f is the frequency. This is accomplished through a well-established cross-correlation procedure, documented in [463, 464], which has served as the basis for all previous LIGO/Virgo stochastic searches, e.g., [460, 461, 450, 410, 462]. The expected signal-to-noise ratio for a stochastic search, using two detectors I and J, is given by

$$\mathrm{SNR} = \frac{3H_0^2}{10\pi^2}\left(2T\int_0^\infty df\,\gamma_{IJ}^2(f)\frac{\Omega_{GW}^2}{f^6 P_I(f)P_J(f)}\right)^{1/2} \tag{10}$$

where H_0 is the present value of the Hubble expansion rate, $\gamma_{IJ}(f)$ is the overlap reduction function (see [464]), and P_I is the strain power spectral density of detector I. Due to the factor of f^6 (and also the $\gamma(f)$), the integral is dominated by the low frequencies $\lesssim 200\,\mathrm{Hz}$.

In order to handle gaps in the data, non-stationarity, and for purposes of computational feasibility, the data for an interferometer pair are divided into many segments of equal duration (60 s for S6; 192 s for O1), and estimators $\hat{\Omega}$ and σ_Ω are calculated for each segment. The loss in duty-cycle due to the finite segment size is small $\lesssim 1\%$. The LIGO data are resampled from $16384\,\mathrm{Hz}$ to $4096\,\mathrm{Hz}$ ($20000\,\mathrm{Hz}$ to $4000\,\mathrm{Hz}$ for Virgo). They are also Hann-windowed to avoid spectral leakage from strong lines present in the data. Since Hann-windowing effectively reduces the interval length by 50%, the data segments are overlapped by 50% to recover the original signal-to-noise ratio.The effects of windowing are discussed in [465].

The power spectral densities for each segment (needed for the calculation of $\hat{\Omega}$ and σ_Ω) are calculated using the two neighboring segments. (This approach avoids a bias that would otherwise exist due to a non-zero covariance between the cross-power and the power spectra estimated from the same data.) Furthermore, by comparing σ_Ω calculated using the neighboring segments with σ'_Ω calculated using each segment by itself (not its neighbors), we identify segments containing large noise transients and reject them from the analysis. In addition to this stationarity cut, we impose some data-quality flags (such as 30 s before lock-loss), a large-σ cut (rejecting particularly noisy time-periods), and we ignore frequency bins which are determined to contain instrumental correlations. The segments that pass all the data-quality cuts are combined using a weighted average to yield final estimators.

The stochastic pipeline estimates $\Omega_{\rm gw}(f)$ given some assumed power law $\Omega_{\rm gw}(f) \propto f^\alpha$. For cosmological sources, we emphasize $\alpha = 0$ limits, while $\alpha = 2/3$ is appropriate for the signal from binaries. We will report results for arbitrary spectral indices [450, 447]. Also, we will use the results to place constraints on specific models such as cosmic strings [450] and astrophysical backgrounds from binary coalescence [447]. In the event of a detection, we will employ consistency checks, spectral fitting, and tests of isotropy in order to speculate about the origin of the signal; see [447].

The search for an isotropic stochastic gravitational-wave background in a single detector is confounded by noise, and it is therefore necessary to cross-correlate the output of pairs of detectors. The detection statistic that maximizes the signal-to-noise ratio depends on the exact shape of the stochastic gravitational-wave background spectral energy density and it is shown to be optimal in the case the signal is stationary, isotropic and Gaussian. Recent mock data challenges have also proven this method is still nearly optimal for non-Gaussian astrophysical backgrounds [466, 467]. The stochastic group has developed a single data analysis pipeline, based on the optimal method, to search for an isotropic stochastic gravitational-wave background. In the event of an observed signal, the stochastic group will employ a detection checklist[19]. In the event of

---

[19] https://dcc.ligo.org/LIGO-T1500251

an observed signal the a spherical-harmonic decomposition analysis will be conducted to see the distribution of the background across the sky [402]. By summing the spherical-harmonics the isotropic signal will be recovered. While the spherical-harmonic decomposition analysis is not a completely independent second pipeline, it will provide important validation of the detection.

The search for nonstandard polarizations uses the same pipeline of the standard isotropic search, with minimal modifications which take into account the different coherence structure of the expected signal, parameterized by the overlap reduction function. Only the postprocessing phase is different in a significant way, as it is designed to disentangle different degrees of freedom in order to obtain detailed upper limits and constraints on extended gravitational theories. It should be noted that the possibility of separating in a model independent way different contributions is greatly improved by using a network with more than one pair of detectors.

3.24.4 Publication Plan

By the end of the Advanced LIGO and Advanced Virgo observations, we expect to improve on our initial low frequency (less than 150 Hz) sensitivity to $\Omega_{\rm gw}$ by four orders of magnitude. In the event of an unambiguous detection, we plan to publish as quickly as we can vet the detection and produce a paper describing the implications of the discovery. If no signal is present, we plan to publish after we have achieved at least a factor of two improvement in $\Omega_{\rm gw}$ sensitivity *and* we have reached a convenient milestone in data collection, e.g., the end of a science run. (One science run with a factor of eight improvement in $\Omega_{\rm gw}$ will yield one paper, not three.) It should be noted that the upper limits to be set on the energy density of the stochastic background should evolve rapidly during the commissioning phase for advanced LIGO. Once advanced LIGO hits its target sensitivity one year of data will allow for an upper limit of $\Omega_{\rm gw} \sim 1 \times 10^{-9}$, while 3 years of data will give a limit of $\Omega_{\rm gw} \sim 6 \times 10^{-10}$. As these numbers show, rapid progress will be made at every commissioning stage, thereby justifying publishing upper limit results at the end of each observational run during the commissioning era –if no signal is detected. At the present time no upper limits for backgrounds with nonstandard polarizations have been published by the collaboration. We expect that a separate observational paper based on the exploratory study in progress will be published within a year from now. Results are expected to improve with Advanced LIGO and Advanced Virgo by a factor analogous to the standard search's one, and we plan to publish a standalone paper based on these also.

A *detection paper* will establish that a stochastic signal is present. It will discuss the statistical significance of the signal and the data-quality and sanity-check steps we have taken to ensure that the signal is real. The paper will include spectral fits and tests of isotropy. We will comment on possible origins of the signal. In the event of a *marginal detection*, we advocate collecting more data since the stochastic signal-to-noise ratio grows like the square root of observation time. If this is not possible, we advocate publishing with the data available and stressing that the apparent signal is marginal. In the event of a *null result*, we will present upper limits on energy density as well as constraints on models such as cosmic string backgrounds and compact binary backgrounds.

The stochastic pipeline is well established. It runs quickly and reliably. The isotropic results are straightforward to interpret. We have many years of experience running this analysis. Thus, we plan to analyze data as it is collected. If no signal is apparent, we plan to produce paper drafts to submit for review within $\approx 2\,\mathrm{months}$ after meeting the requirements for a new paper (see above). The O1 review commenced approximately 2.5 months after the completion of the run. In the event of a detection, we will carry out additional tests to make sure the detection is real. We will also characterize the isotropy and spectral shape of the signal. We expect this extra work to take an additional two to four months. Due to the potentially far-reaching implications, we recommend publishing a detection paper in a high-visibility journal. Upper-limit papers can be submitted to a variety of journals. We leave for future discussion the question of what constitutes an important milestone as this will depend in part on the state of the literature (theoretical and observational) at the time of publication.

There is no overlap with any current search plans.

3.24.5 Technical Requirements and Development Plan

The stochastic pipeline is Matlab-based code that lives in the matapps repository[20]. The main function is stochastic.m.

The stochastic pipeline can be traced back to S1 [465]. While the pipeline has evolved since then, e.g., to carry out the stochastic directional searches, the basic isotropic code has been remarkably stable over many years and publications (see, e.g., [460, 461, 450, 410, 462]). The code is reviewed and ready to be used for advanced-detector analyses. No development is required. We have implemented the filters needed to reduce the low frequency cut off to 10 Hz; the addition of data from more interferometers is trivial

The only real difference with the advanced detector pipeline versus the initial detector pipeline pertains the the low frequency cut off difference, 10 Hz for advanced detectors and 40 Hz for the initial detectors. The group has already successfully designed and tested (in the mock data challenge) a new high pass filter. This new filter was implemented for the O1 search. Involving more detector pairs in the advanced detector era will have a computational cost, as the number of CPU is proportional to the number detector pairs; however, this will not change the fact that the computational cost for the stochastic isotropic search is very low.

A mock science data and science challenge is an on-going exercise of the stochastic group. The purpose of a recently completed mock data and science challenge [467] was to prepare the data analysis and science interpretation for the future generation of gravitational-wave experiments by advanced LIGO - advanced Virgo in the search for a stochastic gravitational wave background signal from an astrophysical origin. The results from this mock data and science challenge have shown that advanced LIGO and advanced Virgo are ready and able to make make a detection of the stochastic background within a few years of operations of the advanced detectors, given a high enough rate of compact binary coalescing events. The continuation of mock science data and science challenges will be an important part of the verification process for LIGO and Virgo when a stochastic gravitational-wave background is eventually observed.

The stochastic pipeline is ready to analyze advanced detector data, and has done so for O1. One innovation that we have implemented for the advanced detector era is the creation of a stochastic monitoring webpage: stochmon[21]. Stochmon includes standard result plots as well as diagnostic plots such as coherence spectra; it provides detector characterization information that is important for the stochastic search, as well as the status of the correlation between pairs of interferometer data. Stochmon updates on an hourly basis. During engineering and observing runs stochmon is monitored by members of the stochastic group as part of "stochastic monitoring shifts." We will continue to use stochmon to track the sensitivity of the stochastic search and to identify as quickly as possible detector artifacts that may affect the analysis. Stochmon identified numerous noise issues in O1. We note that while stochmon facilitates the early study of stochastic data and provides helpful detector characterization information, it is not essential to carrying out the isotropic analysis. A mock data challenge has been conducted in order to validate the different aspects of the search [467]; no cause for concern has been displayed by this exercise. A stochastic detection checklist exists[22].

---

[20] http://tinyurl.com/kpmyruv

[21] https://svn.ligo.caltech.edu/svn/sgwb/trunk/stochmon

[22] https://dcc.ligo.org/LIGO-T1500251

3.24.6 Resources

Code infrastructure. The stochastic isotropic search utilizes the Matlab-based stochastic pipeline, which lives in matapps[23]. The code is reviewed and ready to be used for further advanced-detector analyses. Very minimal additions have been introduced to allow for the search of backgrounds with nonstandard polarizations, and will need nominally a review which we expect to be quite simple. These additions do not interfere with the standard pipeline. No development is required.

Person-power. The isotropic search requires the FTE of one postdoc or 1–2 graduate students plus a senior mentor. Additional members of the group, such as the chairs and the advisors of the the students/postdocs, are also actively involved in the analysis as well as data-quality efforts and validation. We do not expect the FTE requirements to grow considerably in coming observing runs.

Detector characterization for stochastic searches. The long integration time used in the stochastic analysis can reveal noise lines. Common noise lines at two sites can occur due to similar equipment in the laboratory, or common data acquisition systems. A strong line in one interferometer, along with a large random fluctuation in the other, can also produce an apparent narrowband signal in the stochastic search pipeline. In the advanced detector era, the coherence between pairs detectors' output will be calculated in near real time; (see the discussion of stochmon above). In this way noise lines that would affect the stochastic search (and by extension, also the CW search) can be identified during the science runs, and possibly addressed at the sites. We will continue to work with the detector characterization and continuous wave groups to identify and find the sources of noise lines using all available tools.

The calibration requirements for the stochastic group are described in [224]. They are comparable to what has been requested by other search groups for the advanced detector era.

We continue to investigate noise correlations between the LIGO Hanford and Livingston sites, as well as with Virgo. We have previously observed correlated magnetic fields in magnetometer channels at widely separated detectors [468]. The primary sources of these correlated fields are Schumann resonances [468]. Having documented this potential source of correlated noise, we will be careful to determine if correlated noise is affecting the stochastic search. Investigations are in progress to determine how well the magnetometers at LIGO and Virgo sites can measure the correlated Schumann resonance noise, and whether more antennas dedicated to Schumann resonance observations are needed. Noise subtraction techniques, especially with respect to the correlated electromagnetic noise, are being studied. If the correlated Schumann resonance magnetic fields are limiting the stochastic search, then it will be necessary to directly measure the Schumann resonance magnetic fields at each interferometer site and implement noise subtraction techniques. Data from radio frequency (RF) monitors at the sites will also be studied. Other physical and environment monitors will also be carefully observed.

Calibration. The calibration requirements for aLIGO have been detailed in LIGO-T1200562. The phase error is requested to be less than 9 degrees. The relative timing error is requested to be less than 24 μs. The amplitude error is requested to be less than 9%.

Review. The stochastic review committee has reviewed numerous upper limit papers. The code is unchanged, so code review will be trivial. Scientific conclusions about constraints placed on models because of the upper limits are always carefully reviewed, but the timescale is not prohibitive (note the pace of the S5 Nature paper [450] result). The review committee also carefully reviews and critiques the paper. There was a recent review associated with the published S6 stochastic isotropic analysis [410], and an ongoing O1 review. A detection result will certainly be more complicated, but there are numerous sanity checks available. The estimate is that a detection result will take an extra 2 to 4 months to review.

---

[23] http://tinyurl.com/kpmyruv

3.25 Directional Search for Persistent Gravitational Waves

3.25.1 Abstract

The stochastic directional search has several important goals. First, it provides a crucial follow-up for the isotropic search by characterizing the anisotropy present in a stochastic detection. Second, it facilitates the detection of highly anisotropic stochastic sources (e.g., clustered in the Galactic plane) that might be missed by the isotropic search. Third, it provides a robust and sensitive search for narrowband point signals from interesting sources such as nearby low-mass X-ray binaries like Sco X-1. While the isotropic background search focuses on the frequency content of the background, the directional search provides additional information on the anisotropy of the SGWB, hence providing a powerful tool to distinguish between different SGWB models. Searches for anisotropic SGWB have been carried out using data from initial LIGO and Virgo. Results from Advanced LIGO's first observing run are forthcoming. During Initial LIGO/Virgo, no signal was detected, but our results constrain the GW strain power at 90% CL with typical values $2-20\times10^{-50}$ strain^2 Hz^{-1} and $5-35\times10^{-49}\mathrm{strain}^2$ Hz^{-1} sr^{-1} for pointlike and extended sources respectively. In the same publication, we also searched for persistent narrowband signals from the Galactic Center, SN1987A, and Sco X-1. No signals were detected, but we placed upper limits on strain as a function of frequency. The limits on Sco X-1 and SN1987A are the most constraining to date while the Galactic Center results include parameter space not probed by other searches. The improved strain sensitivity and wider observation band of advanced detectors will facilitate dramatic improvements in the stochastic directional search, potentially facilitating the detection of an anisotropic background and/or a nearby point source. The fulfills an important role in support of the isotropic search. The recent detection of gravitational waves from binary black boles implies that a stochastic background may be detected by Advanced LIGO/Virgo.

3.25.2 Scientific Justification

The directional search has multiple targets. It provides a follow-up to characterize stochastic signals detected by the isotropic search, it targets highly anisotropic stochastic signals that might be missed by the isotropic search, and, when run in narrowband mode, it is used to search for persistent point sources, e.g., low-mass X-ray binaries such as Sco X-1. For O1/O2, we are extending the radiometer search to target *unknown*, narrowband point sources such as rotating neutron stars in binary systems using a new folded data scheme [469, 470], described below.

Stochastic gravitational wave backgrounds (SGWB) can be either cosmological or astrophysical in origin. In cosmological scenarios, gravitational-wave backgrounds can be created in the early universe from a variety of processes such as the amplification of vacuum fluctuations following inflation [413], mechanisms that terminate inflation and may give contributions at high frequencies [448, 449], phase transitions in the early universe [414, 415], cosmic strings [416, 417, 418, 419], and pre-Big Bang models [420, 421]. While in most models the SGWB is predicted to be isotropic, there are mechanisms that could introduce anisotropy [419, 471]. Astrophysical backgrounds may arise from binary mergers [452, 472, 438], core-collapse supernovae [473, 474], neutron-star excitations [475, 433], persistent emission from neutron stars [476, 477], and compact objects around supermassive black holes [444, 445]. The recent detection of gravitational waves from binary black holes implies that the stochastic background from unresolved binary black holes could be higher than previously expected and potentially detectable by Advanced LIGO/Virgo [412].

Depending on the rate and redshift distribution of these objects, the corresponding SGWB could be anisotropic or isotropic. For example, the superposition of all neutron stars in the Milky Way would lead to an extended (but anisotropic), broadband SGWB. Such an anisotropic signal may appear with greater statistical significance in the anisotropic search than in the isotropic search. The search provides information on the angular content of the SGWB in the form of a map of the gravitational-wave sky, and is therefore a powerful tool for distinguishing among different possible sources of the SGWB. The anisotropic search is a critical follow-up in the isotropic stochastic search (proposed elsewhere).

Previously, the narrowband search has been associated with particular direction on the sky such as the Galactic Center, Sco-X1, and Supernova 1987A. Sco X-1, a low-mass X-ray binary, and the brightest source of X-rays aside from the sun, exemplifies the kind of source we target with the narrowband radiometer. Sco X-1 is known to contain a neutron star with unknown period, which is likely to have been spun up through accretion torque. Since the phase evolution of the neutron star signal is unknown, and since it is modulated in a complicated way by its binary motion (and possibly spin wandering), cross correlation provides a powerful and robust tool for detecting this persistent, but difficult-to-model, source. The robustness of the Sco X-1 radiometer search makes it a highly complementary to CW searches targeting the same source.

Recent work [470] demonstrates that data compressed using sidereal folding [469] can be used to facilitate an extremely efficient narrowband search looking in all directions and at all frequencies. The all-sky, all-frequency extension to the radiometer will target unknown neutron stars in binary systems as we well as all other narrowband searches that do not conform to a canonical CW template. In this way, the stochastic radiometer provides a sensitive tool for discovering *any* persistent point source, which does not conform to the assumptions made by template-based searches.

The detection of a cosmological background would yield arguably the most exciting science possible with gravitational-wave astronomy. There would be enormous interest from the wider physics and astronomy community, and the implications of the discovery would likely be far-reaching. By measuring gravitational waves from the early universe, we could infer the existence of previously conjectural objects such as cosmic strings or, even more exciting, probe physics at energy scales inaccessible through other means. The anisotropic stochastic search will be critical in establishing the origin of a signal detected in an isotropic search.

A detection of an astrophysical background would also be an important discovery. In this case, the anisotropic search could provide information about a variety of astrophysical objects. For example, detection of the stochastic background from compact binary coalescences is plausible with advanced detectors. Measurement of the angular content of this background (which is expected to be nearly isotropic) could provide information about the evolution of matter, and therefore inform population synthesis models. Similarly, measurement of the GW background generated by neutron stars within the Milky Way will allow us to estimate the number of neutron stars in the galaxy as well as to constrain the average ellipticity of neutron stars; both of these are important for understanding the evolution of matter and the state of the matter in neutron stars.

The search could also yield the discovery of a persistent gravitational-wave point source. The detection of gravitational waves from a known astrophysical object such as Sco X-1 would measure interesting astrophysical observables such as the neutron star's rotational period, which could facilitate a better understanding of the inner workings of low-mass X-ray binary systems. Gravitational wave detections from the Galactic Center and/or SN1987A would be similarly spectacular discoveries. Finally, it is worth noting that it may be possible to detect an unexpected point source.

The advanced detectors are expected to reach the sensitivity to normalized energy density of $\Omega_{\rm GW} \sim 10^{-9}$ or better. Many models of stochastic background predict amplitudes that would be within reach of this sensitivity. This includes some inflationary models where the physics of the late stages of inflation generates a boost in GW production that may be detectable in the LIGO/Virgo band [448, 449]. Similarly, a large fraction of the parameter space in cosmic (super)string models, based on GWs produced by cusps and kinks in the string loops, will be within reach of the advanced detector sensitivity [450, 478]. Among the astrophysical models, the GW background due to compact binary coalescences (dominated by binaries at redshifts of 1-2) is probably the most likely to be accessible to advanced detectors [452], although parts of the parameter space in magnetar- or pulsar-based models will also be within reach [479].

There is therefore a very real prospect for detection of stochastic GW background with advanced detectors, and the anisotropic search will play a critical role in understanding the angular structure of the detected background, and therefore in distinguishing between different models/sources of the background. Even the null result will be very interesting as it would rule out significant parts of the parameter space in these models (not constrained by other observations), constraining the relevant physics and providing guidance for future development of these models.

In the case of individual astrophysical sources, the uncertainties in the expected signal amplitude are significantly larger, stemming from the complex nature of the accretion processes or unknown ellipticities of neutron stars. Even in this case, though, we expect to reach interesting sensitivities, for example reaching ellipticities of order 10^{-7}.

The anisotropic stochastic search will build on the past two completed anisotropic searches using LIGO/Virgo data [401, 402]. Advanced LIGO operating at design sensitivity is expected to lead to improvements in the sensitivity of the anisotropic search by 2-3 orders of magnitude, and to allow (frequency-dependent) improvements in the angular resolution of the measured background.

3.25.3 Search Description

Similarly to the isotropic search, the anisotropic SGWB search estimates the energy density of the stochastic background, but keeps the directional information [402]:

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f} = \frac{2\pi^2 f^3}{3H_0^2}\int d\hat{\Omega}\; H(f)\; P(\hat{\Omega}) \tag{11}$$

where $\rho_{\rm GW}$ is the energy density of gravitational waves, ρ_c is the critical density of the universe, f is the frequency, H_0 is the Hubble parameter and $\hat{\Omega}$ is sky location. The frequency spectrum is typically assumed to be a power law in the frequency band of GW detectors: $H(f) = (f/f_0)^\beta$. For a given value of the power index β (typically $\beta = -3$ for cosmological models and $\beta = 0$ for astrophysical models), the objective of the search is to estimate $P(\hat{\Omega})$. Two approaches are pursued. In the radiometer algorithm, we assume the signals is characterized by a point source

$$P(\hat{\Omega}) = \eta(\hat{\Omega}_0)\delta^2(\hat{\Omega}, \hat{\Omega}_0), \tag{12}$$

and in the spherical harmonic decomposition (SHD) algorithm we assume that the signal can be written as a superposition of spherical harmonics

$$P(\hat{\Omega}) = \sum_{lm} P_{lm} Y_{lm}(\hat{\Omega}). \tag{13}$$

In either basis, we can compute the "dirty map" X_ν and the corresponding Fisher matrix $\Gamma_{\mu\nu}$:

$$X_\nu = \sum_{ft} \gamma_\nu^*(f,t)\frac{H(f)}{P_1(f,t)P_2(f,t)}C(f,t) \tag{14}$$

$$\Gamma_{\mu\nu} = \sum_{ft} \gamma_\mu^*(f,t)\frac{H^2(f)}{P_1(f,t)P_2(f,t)}\gamma_\nu(f,t) \tag{15}$$

where the indices μ, ν run over the lm's in the SHD algorithm and over the pixels on the sky in the radiometer algorithm, $C(f,t)$ is the cross spectral density for two GW detectors (evaluated at frequencies f and at the times t), and $P_i(f,t)$ ($i = 1, 2$) are the power spectral densities for the two detectors. The functions

$\gamma_\mu(f,t)$ capture the angular decomposition of the overlap reduction function, and can be computed in either basis [402]. Likelihood maximization then leads to the estimators of the angular content in the two bases:

$$\hat{\eta}_{\hat{\Omega}} = \left(\Gamma_{\hat{\Omega}\hat{\Omega}}\right)^{-1} X_{\hat{\Omega}} \tag{16}$$

$$\hat{P}_{lm} = \sum_{l'm'} (\Gamma^{-1})_{lm,l'm'} X_{l'm'} \tag{17}$$

Analyses using folded data proceed in much the same way except that the data are pre-processed to produce on sideral day's worht of data for the entire observing run; see [469, 470] for additional details.

In order to handle gaps in the data, non-stationarity, and for purposes of computational feasibility, the data for an interferometer pair are divided into many segments of equal duration (typically $60\,\mathrm{s}$), and the above estimators are calculated for each segment. The data are resampled from $16384\,\mathrm{Hz}$ to $4096\,\mathrm{Hz}$ and high-passed filtered with a $9\,\mathrm{Hz}$, $n = 16$ Butterworth filter[24]. They are also Hann-windowed to avoid spectral leakage from strong lines present in the data. Since Hann-windowing effectively reduces the interval length by 50%, the data segments are overlapped by 50% to recover the original signal-to-noise ratio.

The power spectral densities for each segment are calculated using the two neighboring segments. (This approach avoids a bias that would otherwise exist due to a non-zero covariance between the cross-power and the power spectra estimated from the same data.) Furthermore, by comparing the variance calculated using the neighboring segments with the variance calculated using each segment by itself (not its neighbors), we identify segments containing large noise transients and reject them from the analysis. In addition to this stationarity cut, we impose some data-quality flags (such as $30\,\mathrm{s}$ before lock-loss), a large-σ cut (rejecting particularly noisy time-periods), and we ignore frequency bins which are determined to contain instrumental correlations. The segments that pass all the data-quality cuts ($\gtrsim 95\%$) are combined using a weighted average to yield final estimators.

The stochastic group has developed a single data analysis pipeline to search for anisotropies in the stochastic background and for excess coherence from point sources. However, the spherical harmonic decomposition algorithm is compared with the radiometer algorithm algorithm as a cross-check. In the event of an observed signal, the stochastic group will employ a detection checklist[25]. In the event of an observed anisotropic stochastic signal, the result will be checked for consistency with the isotropic analysis. In the event of a point source detection, the result will be checked with the appropriate CW pipelines, which may be able to provide confirmation if, for example, the signal is from a neutron star in a binary system.

3.25.4 Publication Plan

At the end of an extended (~ 1 year) science run at the expected Advanced LIGO sensitivity we expect to improve on our initial LIGO/Virgo sensitivity by 2-3 orders of magnitude. In the event of an unambiguous detection, we plan to publish as quickly as we can vet the detection and produce a paper describing the implications of the discovery. Detection claims will be vetted through standard cross-checks to make sure that the signal behaves as expected in frequency/time and that it cannot be accounted for due to data quality artifacts such as correlated noise. If no signal is present, we plan to publish after we have achieved at least a factor of two improvement in sensitivity for P_{lm}'s and $\eta_{\hat{\Omega}}$ *and* we have reached a convenient milestone in data collection, e.g., the end of a science run. (One science run with a factor of eight improvement in sensitivity will yield one paper, not three.) Sensitivity to gravitatiional-wave energy density is expected to evolve rapidly during the commissioning phase for advanced LIGO. At design sensitivity, we anticipate a sensitivity of $\Omega_{\mathrm{gw}} \sim 6 \times 10^{-10}$ after one year of integration. Rapid progress is expected at every commissioning stage,

---

[24] http://tinyurl.com/kgbffx7

[25] https://dcc.ligo.org/LIGO-T1500251

justifying publishing upper limits at the end of each observational run during the commissioning era—if there is no evidence of a signal.

A *detection paper* will establish that a stochastic signal is present and it will constrain its angular distribution. It will discuss the statistical significance of the measured angular distribution and the data-quality and sanity-check steps we have taken to ensure that the signal is real. Other cross checks will include comparisons of the SHD and radiometer results, comparisons of the statistics in different parts of the sky (e.g. top vs bottom hemisphere), tests of the time variability in the measured angular distribution etc. We will also comment on possible origins of the signal, whether it is an object in a specific direction in the sky (appropriate if detecting a point source) or consistency with isotropy (appropriate when a signal is detected, but no angular structure is observed).

In the event of a *marginal detection*, we advocate collecting more data since the stochastic signal-to-noise ratio grows like the square root of observation time. If this is not possible, we advocate publishing with the data available and stressing that the apparent signal is marginal.

In the event of a *null result*, we will present upper limit maps on the energy density, similarly to what was done with initial detector data [401, 402].

The anisotropic stochastic pipeline is well established. It runs quickly and reliably, and the statistics of the relevant estimators is well understood, allowing straightforward interpretation of the results. We have many years of experience running this analysis. Thus, we plan to analyze data as it is collected.

If no signal is apparent, we plan to produce paper drafts to submit for review within $\approx 4\,\mathrm{months}$ after meeting the requirements for a new paper (see above). In the event of a detection, we will carry out additional tests to make sure the detection is real. We expect this extra work to take an additional two to four months. Due to the potentially far-reaching implications, we recommend publishing a detection paper in a high-visibility journal .

Upper-limit papers can be submitted to a variety of journals. We leave for future discussion the question of what constitutes an important milestone as this will depend in part on the state of the literature (theoretical and observational) at the time of publication.

The narrowband radiometer search overlaps with multiple efforts in the CW group. The radiometer search team participated in a CW-led mock data challenege to study the sensitivity of different pipelines to gravitational waves from Sco X-1 [393]. We will continue to coordinate this search with related CW searches.

3.25.5 Technical Requirements and Development Plan

The stochastic pipeline is Matlab-based code that lives in the matapps repository[26]. The main function is stochastic.m. The stochastic radiometer pipeline can be traced back to S4 [401], with the SHD algorithm added in the S5 analysis [402]. The pipeline has not evolved much since then, excepting relatively minor modifications to include a more intelligent frequency binning algorithm, which will result is improvements in sensitivity to some of the point sources. Hence, the vast majority of the code that will be used in searches with advanced detector data has already been reviewed, and has been stable for several years.

As noted above, minor development of the anisotropic stochastic search code is expected, in order to improve the frequency binning (and therefore improve the sensitivity to some of the point sources). This upgrade is implemented. The anisotropic stochastic pipeline has been run on O1 data (both the SHD search and the narrowband radiometer). The results are under review.

---

[26] http://tinyurl.com/kpmyruv

3.25.6 Resources

Code infrastructure. The stochastic anisotropic search utilizes the Matlab-based stochastic pipeline, which lives in matapps. The code is reviewed and ready to be used for advanced-detector analyses. Minor modifications have been implemented to allow for overlapping frequency bins.

Person-power. The anisotropic search requires the FTE of one postdoc and one graduate students plus a senior mentor. Additional members of the group, such as the chairs and the advisors of the the students/postdocs, are also actively involved in the analysis as well as data-quality efforts and validation. We do not expect the FTE requirements to grow considerably in the advanced detector era.

Detector characterization for stochastic searches. The long integration time used in the stochastic analysis can reveal noise lines. Common noise lines at two sites can occur due to similar equipment in the laboratory, or common data acquisition systems. A strong line in one interferometer, along with a large random fluctuation in the other, can also produce an apparent narrowband signal in the stochastic search pipeline. In the advanced detector era, the coherence between pairs detectors' output will be calculated in near real time; (see the discussion of stochmon in the search plan for isotropic stochastic search). In this way noise lines that would affect the stochastic search (and by extension, also the CW search) can be identified during the science runs, and possibly addressed at the sites. We will work with the detector characterization and continuous wave groups to identify and find the sources of noise lines using all available tools.
We continue to investigate noise correlations between the LIGO Hanford and Livingston sites, as well as with Virgo. We have previously observed correlated magnetic fields in magnetometer channels at widely separated detectors [468]. The primary sources of these correlated fields are Schumann resonances [468]. Having documented this potential source of correlated noise, we will be careful to determine if correlated noise is affecting the stochastic search. Investigations are in progress to determine on how well the magnetometers at LIGO and Virgo sites can measure the correlated Schumann resonance noise, and whether more antennas dedicated to Schumann resonance observations are needed. Noise subtraction techniques, especially with respect to the correlated electromagnetic noise, are being studied. If the correlated Schumann resonance magnetic fields are limiting the stochastic search, then it will be necessary to directly measure the Schumann resonance magnetic fields at each interferometer site and implement noise subtraction techniques. (A preliminary study of the necessary resources has been made [480].) Data from radio frequency (RF) monitors at the sites will also be studied. Other physical and environment monitors will also be carefully observed. While optimal re-weighting techniques can be used to help ameliorate the effect of correlated magnetic field noise for searches for broadband signals, they will provide no help for cross-correlation searches for narrowband signals. Correlated magnetic field noise could be a significant problem for coherent directional searches below 25 Hz with advanced LIGO and advanced Virgo. Diminishing the magnetic coupling to the interferometer masses will help to address this problem, as would low noise detection of the Schumann resonances and the subsequent implementation of noise subtraction (Wiener filtering) methods.

Calibration. The calibration requirements for aLIGO have been detailed in LIGO-T1200562. The phase error is requested to be less than 9 degrees. The relative timing error is requested to be less than 24 μs. The amplitude error is requested to be less than 9%.

Review. The stochastic review committee has reviewed numerous upper limit papers. The code will not change much, so code review will be trivial. Scientific conclusions about constraints placed on models because of the upper limits are always carefully reviewed, but the timescale is not prohibitive (note the pace of the S5 Nature paper [450] result). The review committee also carefully reviews and critiques the paper. A detection result will certainly be more complicated, but there are numerous sanity checks available. The estimate is that a detection result will take an extra 2 to 4 months to review. The group will be requesting a review of the data folding procedure [469] used for the all-sky, all-frequency extension [470].

3.26 Contributions of long transient gravitational waves to the stochastic background search

3.26.1 Abstract

The search for an isotropic stochastic background includes contributions from different gravitational-wave frequencies, from different directions in the sky, and from different data segments. Each of these parameters—frequency, direction, and time—can be thought of as variable, over which the isotropic search integrates. By carrying out all but one integral, it is possible to gain insights into the nature of the stochastic signal while potentially revealing hidden signals diluted through integration. For example, the spherical harmonic decomposition search shows how the stochastic background varies across the sky. Analogously, the directed radiometer search shows how the stochastic signal varies with frequency at a given point on the sky. Here, we describe an analysis designed to explore time-dependent features of the stochastic background. The search characterizes the temporal behavior of an apparent stochastic signal while potentially identifying very long-lived transient signals ($\gtrsim 10\,\mathrm{hr}$, to as long as months) that might be otherwise overlooked.

3.26.2 Scientific Justification

The scientific rationale for this search is based on the following observation: one or more long-lived transient signals (or coherent long-duration noise) can produce an apparent signal in either isotropic or directional stochastic searches, while simultaneously evading detection in searches for short-duration transients. Thus, a dedicated search is necessary to understand the origin of apparent stochastic signals. Consider, for example, a $11\,\mathrm{hr}$-long signal observed during a $90\,\mathrm{day}$ science run. A $11\,\mathrm{hr}$-long signal, with a stochastic signal-to-noise ratio [463] of SNR $= 40$, would produce an SNR $= 3$ signal through dilution [481]. The same signal would produce only a SNR $= 0.20$ signature in a short $1\,\mathrm{s}$-long data segment. This back-of-the-envelope argument illustrates how long signals can influence stochastic measurements while producing little trace of their existence on short time scales.

The astrophysics of very-long transients, spanning hours to weeks, was first explored in [482][27]. The authors of [482] review a number of somewhat speculative scenarios associated with neutron stars including gravitational-wave emission lasting days to months from non-axisymmetric Ekman flow following a glitch [483, 484, 485], Alfvén oscillations from giant magnetic flares (also lasting days to months) [486, 487], emission from free precession (with a damping time possibly lasting from weeks to years) [488, 489, 490], magnetic instabilities in newborn neutron stars (lasting days) [491], and gravitational-waves from r-modes [492, 493]. Generic rotational instabilities in newborn neutron stars, potentially powered by fallback accretion [194, 494], may persist on a timescale of hours [192]. Somewhat more speculatively, we note that observations of intermittent pulsars, which become quiescent on timescales of days (e.g., [495]), suggest that neutron star dynamics vary on the timescales considered here, motivating exploration of this region of parameter space. Similarly, variability in accretion on these timescales may affect gravitational-wave emission from accretion-supported mountains [496]. Finally, it is worthwhile to be prepared for a surprise: a very long lived transient signal from an unexpected source. Recent work proposing gravitational-wave emission from gravitationally bound axion clouds [497], potentially starting and stopping on the timescale of a few years, serves to illustrate this possibility. The method we propose below is also applicable to quasi-infinite signals turning on or off during an observing run as well as repeating sources with long-lasting emission periods.

Most previous work on long-duration transients has focused on signals in the regime of $\approx$10–3000 s. The reality, let alone the detectability of such very long signals is admittedly speculative and highly uncertain. A back-of-the-envelope calculation [481] suggests that a very long transient associated with Scorpius X-1 would produce a signal about ten times too weak in strain to detect assuming a hypothesized accretion-torque

---

[27] This paragraph is from [481].

balance scenario [496]. Detection would require a source that is either significantly closer or significantly brighterin gravitational waves. That said, it is important to note that detecting *any* gravitational waves from neutron stars such as Scorpius X-1 is a challenging proposition for a variety of search techniques [393].

However, it is imperative for the stochastic search to confirm whether or not signal of long duration are contributing to a signal from a search for an isotropic stochastic background of gravitational waves. This is part of an *eyes wide open* search strategy. We also note that *non-astrophysical* signals may persist on these time scales as well, e.g., from correlated noise due to time-dependent magnetic phenomena [468, 480]. Finally, it is worthwhile to be prepared for asurprise: a very long lived transient signal not predicted.

Taken together, the stochastic searches tell us: 1) if the LIGO-Virgo detectors exhibit higher than expected correlation, 2) the contribution to this excess from a persistent stochastic background, 3) the contribution from correlated noise, 4) the contribution from persistent sources that are resolvable in sky location, 5) the contribution from non-persistent (transient) sources. Analyzing the time-dependence of cross-correlated data (along with the frequency and directional information) is crucial for understanding both the detector and the signal. It is essential that we understand all of these degrees of freedom in order to confidently make a stochastic detection and to be sure that the signal is a stochastic background and not something else (astrophysical in origin or not).

Relationship to other searches. This search is designed to provide information on the time-dependence of an apparent stochastic signal while potentially revealing very long-lived transient signals. Like the directional search and the narrowband radiometer, this is a core activity of the Stochastic search group, which allows us to parse the stochastic signal in several different ways. This search complements dedicated burst searches, which target signals of shorter duration (less than an hour). There is also an overlap with the CW group, which is currently developing a search for glitching pulsars and type I bursts in accreting millisecond pulsars, which could result in transient signals on very long durations (up to weeks). However, this method is complementary to CW techniques as we allow for significant variation in the frequency evolution of the gravitational-wave signal, which allows us to probe a completely different parameter space compared to continuous wave searches, which assume very limited changes in the neutron star spin: $\lesssim 6 \times 10^{-9}\,\mathrm{Hz\,s^{-1}}$ versus $\lesssim 300\,\mathrm{Hz\,s^{-1}}$.

Search Description

This search plan is designed to uncover transient contributions to an apparent stochastic signal while potentially revealing very long-lived signals that might otherwise be missed. To that end, we will constrain the energy density Ω_{gw} [463] due to transient phenomena. We will determine the relative contributions in our data from noise, from a persistent stochastic background, and from astrophysical transient phenomena.

The baseline plan is to carry out these searches using STAMP [191, 207, 201, 195, 196]. STAMP is a Matlab-based code package that resides in the Matapps svn repository [208]. STAMP works by cross-correlating data from two detectors to produce cross-power spectrograms [191]. Gravitational-wave signals appears as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [191, 498, 195, 196, 499]) in order to identify statistically significant clusters of pixels. One of these clustering algorithms, which we shall refer to below, is called Stochtrack [195]. Stochtrack works by calculating the coherence between two detectors on randomly drawn curves on a spectrogram to identify tracks left by gravitational-wave signals.

Much of the infrastructure was originally adapted from Stochastic code, though, the pipeline is now used by members of the Bursts, Detchar, and Stochastic Groups. The pipeline was reviewed for an initial LIGO analysis studying long-lived transients coincident with long gamma-ray bursts, which was ultimately published in Physical Review D [201].

A project to carry out an all-sky long duration signal search with initial LIGO data is complete [210]; the review of this search was initiated in July 2014, and we completed at the end of 2015. The STAMP all-sky team has made great strides to demonstrate an all-sky search for long-lived transient signals including: managing the computational cost of the search for signals of duration down to 10 sec, understanding the background and minimizing the effect of noise transients to a level approaching Gaussian noise, and investigating the applicability of the search to eccentric binary waveforms [210]. The STAMP pipeline was used to search for long duration (10 to $500s$) in LIGO S5 and S6 data, and the results were published [209]. The pipeline has also successfully analyzed the Advanced LIGO observing run 1 (O1) data, and those results will be published soon.

The code for a new seedless clustering algorithm [195, 196] will require review, but the new code makes up a small addition to the previously reviewed code package: two functions consisting of $<$500 lines of new code along with a handful of minor changes to existing code (estimated FTE=0.5 over the span of a month). The seedless clustering code is highly parallel, and recent work [196] demonstrates that GPUs and multi-core CPUs facilitate dramatic speed-ups. Seedless clustering was used in the analysis of the Advanced LIGO O1 data, but a review of the method still needs to be completed.

We will analyze data on timescales of $\approx 10\,\mathrm{hr}$–$1\,\mathrm{month}$ in order to determine if there are individual long-lived transient signals contributing to the isotropic or directional stochastic measurements. We will run STAMP in all-sky mode on all the recently acquired O1 data used in the stochastic search, as well as the upcoming data from future observing runs. In order to analyze these very long signals, we will add an extra stage of pre-processing in which the data are compressed through time-averaging as described in [481]. This new pre-processing step will require minimal new infrastructure/review. This extension will also be made available to STAMP-PEM, a detector characterization application of the STAMP algorithm. STAMP-PEM will then be used to search for instrumentally or environmentally caused long transients in the observing run data, for example due to magnetic field effects, on the time scales longer than $\approx 10\,\mathrm{hr}$. This effort will have a direct impact on the long-duration studies discussed here, as well as on understanding the origin of apparent stochastic signals. The compressed data will be analyzed using seedless clustering algorithm described in [196].

3.26.3 Publication plan

We foresee several possible scenarios:

- If a stochastic signal is observed (either isotropic or directional) and no evidence is found for long-duration transient signals, then the results of this search will be used to characterize the observed stochastic signal as persistent. The discovery of a stochastic background should be submitted to a high-impact journal.

- If a stochastic signal is observed (either isotropic or directional) and we find evidence for one or more possible very long transient signals, we will estimate the energy density contribution of these transient signals to the overall stochastic signal, as well as the residual persistent stochastic signal. In this very positive scenario, we anticipate submitting two papers to high-impact journals, one on the stochastic background and one on the very long transient(s). In the event of a very long transient identification, we will coordinate with the Burst and CW groups to interpret the event.

- If the observing run data are consistent with noise, we will place constraints on the energy density and the rate of the long-lived transient phenomena. We recommend publishing a paper with limits if/when the constraints on energy density improve by a factor of at least ten *and* there is a convenient break in data-taking (the end of a run).

3.26.4 Technical requirements and development plan

Pipeline. The baseline plan is to carry out the analysis with STAMP [191, 207, 201, 209]. STAMP (and Stochtrack) are Matlab-based code. They are part of Matapps [208]. Most of the STAMP code was reviewed for the published initial LIGO targeted analysis [201], and some recent additions relevant for all-sky searches are currently being reviewed as a part of the S5/S6 STAMP all-sky review [209]. The new Stochtrack clustering algorithm [195, 196] will require review, but the job is modest: two (very well-documented) functions with $<$500 lines of code. The new clustering algorithms and their performance are documented in publications [195, 196]. There are a handful of changes to the existing code suite, but they are minor. Future changes to facilitate the analysis of longer-duration signals, lasting from hours to months, are also expected to require only small additions to the processing code.

Data quality. We do not anticipate that the long-transient search will require significant detector characterization work beyond what is already planned for other searches. During initial LIGO, STAMP searches were shown to produce well-behaved noise distributions (similar to stationary Gaussian noise) through the application of notches for instrumental lines, basic data quality flags, and a glitch identification flag [207, 201]. This is attributable to the long time scales probed by the search as well as the fact that STAMP uses cross-correlation [207]. Similar strategies have been used to clean the Advanced LIGO O1 data. Subsequent investigations have applied seedless clustering techniques to recolored initial LIGO noise leading to comparable results [195, 196]. There are no special requirements for calibration beyond what has already been requested by the Stochastic Group [224].

Manpower. The analysis will require the full-time attention of at least one graduate student or postdoc. The attention of a mentoring advisor is also required. Continued code maintenance and support should be strong and steady. There is an active community of STAMP users from multiple analysis groups including $\gtrsim 7$ regular/expert users with a wide base of experience.

Early testing. The upgraded seedless clustering code has been tested and benchmarked with both Monte Carlo and recolored noise [195, 196]; it has also been applied to Advanced LIGO O1 data. In order to catch problems early and facilitate a smooth analysis, we plan to continue analyzing data immediately as it becomes available with a goal of estimating the background and sensitivity on an approximately biweekly basis. We will coordinate with potentially overlapping efforts to maintain a mock dataset with long-lived injections in order to compare the domain of utility of different searches/algorithms.

Broader impact. The STAMP code package has produced spin-off technology that has proven useful for detector characterization [500, 501] and follow-up/visualization of CBC triggers [499]. We expect continued development and maintenance of STAMP will be broadly useful for Stochastic Group activities and the wider LSC/Virgo community.

4 Characterization of the Detectors and Their Data

4.1 LSC Detector Characterization

4.1.1 Introduction

LIGO: LIGO's sensitivity to gravitational-wave signals is limited by noise from the instruments and their environment. Continued detection, the vetting of candidate signals, and the accuracy of parameter estimation is *crucially* dependent on the quality of the data searched and the collaboration's knowledge of the instrument and environment. The LIGO Detector Characterization group is focused on working together with the astrophysical search groups and the detector groups to (i) deliver the data quality information necessary to clean the data sets, veto false positives, and allow candidate follow up for gravitational-wave searches and (ii) characterize the early Advanced LIGO detectors to help to identify data quality issues early enough that they can be addressed in the instruments to improve future instrument and search performance.

Search Data Quality: LIGO data contain non-Gaussian components such as noise transients and quasi-periodic lines that have a negative impact on astrophysical searches. Transient noise in the detector data can mimic or mask transient signals from Compact Coalescing Binaries and more generic Burst sources, interfering with detection and the accuracy of the source parameters recovered. To minimize these negative effects, LIGO data must be cleaned of transient data quality issues. The primary forms of data quality information that must be delivered to the astrophysical search groups are: *state segments* that indicate which data should be analyzed, based on the state of the instrument and its calibration; *veto segments* that indicate periods of poor quality data; and *data quality triggers* that identify short durations where the data are likely to contain a non-astrophysical disturbance. Searches will use veto segments and data quality triggers to either ignore problematic data or to reduce confidence in any search triggers associated with these times. For continuous-wave and stochastic backgrounds searches, frequency bins that are contaminated by non-astrophysical disturbances must be identified and removed, and low-level, broadband contamination from correlated magnetic noise must be mitigated.

Automation of Data Quality assessment: With the anticipated signal rate for O2, and the need for low-latency data to support multi-messenger astronomy, the Detector Characterization group must develop automated approaches to respond to items on the Detection Checklist. The objective is to reduce to a minimum the amount of manual sorting through signals, flagging of problems, and identification of sources of defects in the data. This will be the main focus of the group during O2, with partners in the astrophysical search groups collaborating on both identifying pipeline needs and sensitivities to data defects.

aLIGO Instrument Characterization: The Detector Characterization group works with the detector commissioning and engineering groups to identify and resolve issues in the aLIGO subsystems related to glitch and noise contamination, channel signal fidelity and robustness, etc. This work has led to early data quality improvements and helped to train a wider pool of scientists who are familiar with the instruments. Continued work aims to facilitate aLIGO detections by ensuring that the detectors are well understood and that fixes for data quality issues are aggressively pursued.

1. **Highest priority.** The highest priority of the LIGO Detector Characterization group is to provide timely data quality information to the LSC-Virgo search groups that designate what data should be analyzed, remove egregious data quality issues, and identify periods/frequencies of poor data quality. Automation is central to success in this activity.

2. **High priorities.** Complement and collaborate on commissioning with tools and insights to help find sources of transient and CW data defects. Use the non-interferometer sensors to find, quantify, and mitigate coupling to the environment. Maintain and extend the software infrastructure required to provide needed data quality information to online searches.

3. **Priorities.** Develop improved methods to uncover the causes of the noise transients which most impact the searches, with the goal of mitigating them or producing vetoes. Pursue, when motivated, exploration of new approaches to data quality issues.

To accomplish these priorities, the LIGO Detector Characterization group requires

- search group participation to call out sensitivities in the pipelines to data defects
- data quality experts to identify data defects and establish relationships to instrument events
- code developers to establish both infrastructures and specific modules to recognize and flag defects
- instrument characterization experts to quantify the sensitivity of the instrument to the environment, establish coupling coefficients, and to identify mitigation where needed

4.2 Detailed LIGO Detector Characterization priorities

The detector characterization (detchar) group has the dual responsibilities of investigating and mitigating misbehavior in the instrument, and providing data quality information to the gravitational-wave searches to reduce the impact of artifacts in the data. In addition, the detchar group must help to validate the quality of the data around the time of candidate detections. The remainder of this section lays out in a sparse format the priorities for the work in 2016-2017.

4.3 Overarching goals

- Automate as much as possible of the data quality assessment process, in low latency
- Document and make available codes used to the whole group, and aim for interoperability of codes
- Validate new methods on recent data
- Rigorously show that a search is improved by the data quality information

4.4 Characterizing Instrumental Artifacts

There are three main areas of investigation: Ongoing work (Physical and Environmental Monitoring (PEM), subsystem characterization, DQ shifts), focused but open-ended investigations (find particular noise source or cause of glitch), and method development (ETGs, statistics and classifiers)

4.4.1 Highest Priorities

- Characterize data quality around the time of event candidates – at low- and offline-latency; and for transient and for CW/Stochastic sources
- Support commissioners from offsite
- Undertake subsystem characterization and documentation
- Maintain and document PEM monitors, characterize environmental couplings

4.4.2 Priorities

- Develop human resources (esp. mentors), and perform DQ shifts to identify changes in or problems with the instruments and to maintain currency in understanding of the instrument in the DetChar group
- Search for causes of short isolated glitches which are the largest background of the transient searches
- Mitigate spectral lines and features which are coherent/coincident between the two sites
- Investigate variations in the noise floor, and attempt to predict noise performance based on instrument state

4.4.3 Suggested papers as outcomes of these studies

- Tracking and Mitigating Scattered Light
- RF Interference in aLIGO (may include either or both of RF beatnotes/RF45 modulation troubles)
- Investigating Causes of Short Transient Artifacts in aLIGO
- Mitigation of Line Features in aLIGO
- Mitigation of Coherent Noise between Detectors due to GPS Synchronization
- Predicting Spectral Variations of aLIGO Noise from Varying Instrument State and Alignment
- Isolation of aLIGO from the Local Environment

4.4.4 Additional thoughts

Developing a deep and current understanding of each component subsystem is crucial to enabling diagnosis of instrumental and environmental artifacts as well as data quality veto development. For each subsystem the subsystem leads are jointly responsible for:

- Ensuring a complete, meaningful, and representative set of auxiliary channels is included in the detector characterization channel list
- Monitoring subsystem states accurately and robustly
- Checking signal fidelity of channels included in the detector characterization channel list and the science frames
- Maintaining documentation of the subsystems and the relevant channels for detector characterization reference
- Interfacing with commissioners and instrument experts to propagate instrument changes and developments to detector characterization investigations and monitoring

In addition to focusing on noise artifacts in h(t), the detector characterization group will characterize the performance of the component subsystems, particularly any behavior that is potentially limiting to interferometer performance. For example:

- Improving monitors for excess mirror motion leading to scattered light
- Improving monitoring and reporting of digital and analog overflows, reaching software limits, and other kinds of saturations; monitoring and reporting of real-time data handling errors (timing, dropped data, etc.)
- Searching for causes of short isolated glitches which are the largest background of the transient searches
- Searching for causes of non-stationary noise and of excess low and mid frequency noise
- Searching for physical causes of lines and spectral combs which harm continuous-wave searches

The detector characterization portion of the detection checklist is essential in demonstrating that the candidate signal cannot be due to global coincident noise and is unlikely to be due to other non-astrophysical noise. The detection checklist, refined by the O1 experience, requires detector characterization experts to evaluate key studies and tests of the data surrounding the time of a candidate event.

4.5 Improving search data quality

The over-arching goals here are to rigorously evaluate the effect of data quality on the searches and parameter estimation, and to target our attention on making the largest possible gains in detection rate and detection confidence.

4.5.1 Highest Priorities

- Identify outliers and artifacts which are most damaging to the primary gravitational-wave searches
- Provide data quality in low-latency to the EM followup searches
- Provide effective, documented offline data quality information for searches

4.5.2 Priorities

- Develop rigorous criteria for evaluating effect of data quality on search performance
- Develop methods for cleaning data of artifacts
- Quantify effects of bad data quality on parameter estimation

4.5.3 Suggested Papers

- Which Data Artifacts are Most Detrimental to [Search]
- Optimally Cleaning Data of Loud Outliers / Lines
- Effects of Varying Background on the Performance of [Search]
- Can Data Artifacts Subtly Affect Estimated Parameters of Detected Signals?
- Optimizing Signal-Based Vetoes Based on Knowledge of Likely Glitches
- How does Search Sensitivity Compare to Ideal Case of Stationary Gaussian Noise?

4.5.4 Additional Thoughts

Data quality shifts and detection validation are key to improving the performance of the astrophysical searches and enabling confident detection statements.

Data quality shifts will be the primary means of ensuring full coverage of h(t) data quality analysis for both detectors during O2, including limiting factors to interferometer performance such as weather or earthquakes. Data quality shifters must invest first in training, and a qualified mentor must be identified.

Additional investigations might include:

- Looking into worst offenders from single-detector or time-slid backgrounds
- Investigating effects of possible data quality issues on the search: isolated glitch, scattered light, non-stationary PSD, wandering lines

4.6 Essential Software and Automation

Fundamentally necessary software:

- The summary pages
- The DMT (including the new low-latency DMT DQ vector infrastructure)
- The segment database
- Omicron triggers, including in low-latency, delivered with very high reliability
- Robustly accurate Guardian states, including for configuration changes made between or during lock stretches (i.e. SEI blend filter state or suspension damping state)

High priority software:

- Automated low latency data quality checks (iDQ, automated Omegascans)
- GWpy
- ligoDV web
- Omegascans

- Channel Information System
- VET
- Suite of remote access tools (remote MEDM, remote EPICS, remote DataViewer)
- ODC (or potentially an alternative for key information at low latency)
- Mapping of overflow channels
- LigoCAM

Low latency tier-3 automation tasks requiring additional personpower ahead of O2:

- Automatically look at the spectrum in the neighborhood of the trigger
- Drops in range
- Glitch rate summary from multiple ETGs

The summary pages are fundamental to data quality shifts, the launching point for investigations into data quality features, and an invaluable resource in the control rooms and for a remote view of interferometer performance and the behavior of the data. The summary pages infrastructure also enables automation of key tool results and plot generation is critical in order to support both effective data quality shifts and viably efficient checks on candidate events.

In addition there are a number of tools which continue to be of use, such as stamp-pem automated coherence, FScans and auxiliary post-processing scripts, and NoEMi, that the group will maintain.

This list relies on software dependencies maintained by DASWG, low latency data streaming, the Virgo Collaboration, the remote data access group, and the Guardian. While those software elements are not in the scope of DetChar, they are of the highest priority to enable LIGO science

Low latency automation tasks requiring additional personpower ahead of O2:

- Automatically look at the spectrum in the neighborhood of the trigger
- Drops in range
- Glitch rate summary from multiple ETGs

https://wiki.ligo.org/DetChar/DetCharProductsForAndInterfaceWithEMFollowActivities

4.7 Development of New Methods

This section includes longer-term projects that should be explored as secondary priorities.

- Citizen science for identifying new instrumental features
- Development of Event Trigger Generators
- New veto methods and advanced signal processing
- Machine learning
- Computing support for new methods

Citizen Science: GravitySpy is a citizen-science prjoect, operating on the Zooniverse platform. It allows volunteers from outside the LSC to look at glitches in the gravtiational-wave channel and attempt to classify them into categories. These classifications are then available to seed detchar investigations, or for training machine-learning classifiers. The detchar group should get involved by providing feedback to the GravitySpy people on how to best select and represent glitches for classification. In addition, the detchar group should apply its standard veto generators to single categories of classified glitches, in the hopes that a purified list of one type of glitches will make it possible to identify causes of those glitches.

ETG development: The detchar group uses a few different algorithms to detect glitches and other short transients in the gravitational-wave and auxiliary channels. The primary method is the sine-Gaussian basis used by Omega and Omicron. Further development can still be done on better methods for pre-processing and whitening the data before it is used in the ETG, different tilings for placing the sine-Gaussian tiles, better methods for clustering significant tiles into a single description of a glitch, and on improved visual display of the data. Along the same lines, the BayesWaveBurst method uses a similar decomposition with a Bayesian method for reconstructing glitches in the detector. The detchar group should continue to use this method to reconstruct interesting glitches and find their intrinsic shape uncorrupted by noise.

Veto methods: Evidently new veto methods will be needed, both to deal with news kinds of data defects (which will certainly appear as the instruments are improved), and to improve the reliability and speed of identification of currently recognized data defects. Methods should be brought to bear, in prototype form, on real data early in the 'lifetime' of the development process; success should be demonstrated before significant human or computing resources are committed.

Machine learning: Machine learning and 'big data' are very popular topics today. These methods can be useful in detchar, as long as certain considerations are respected. The features input to the classfiers must be carefully chosen and conditioned to extract only the useful information in those channels. The classifiers must optimize a reasonable cost function, so that they are targeted at identifying important glitch classes or data quality effects, and providing information that maximally improves the search sensitvity.

Computing support for new methods: As new Detector Characterization methods become more mature, they will need to be incorporated into our suite of automated tools and checks. This requires integration with the summary pages, and the online and offline generation of data quality products in an efficient and stable manner. Additionally, as new methods increase in complexity and scale, particularly with application machine learning codes, effort will be required to optimize these codes to ensure efficient use of computing resources.

4.7.1 Suggested publications

- Improved clustering of LIGO Triggers
- Tuning [ETG] for improved performance on [important glitch class]
- An Optimized Cost Function for Machine Learning to Improve [Search]
- Interesting Instrument Behaviors Identified by GravitySpy
- Mechanical Couplings Identified by a Machine Learning Algorithm
- Using Machine Learning to Identify Sources of Excess Noise in O1
- A Comparison of ML Classifiers against a Single Glitch Dataset
- Generating Good Features for Training ML for Detchar

4.8 Ongoing Tasks

These are tasks that require constant time commitment of people throughout the run. The DQ shifts are the primary way for new people (or people without much detchar experience) to contribute. In addition, support is needed from experienced DQ shifters to mentor and train new people.

4.8.1 DQ shifts

Data quality shifts and detection validation are key to improving the performance of the astrophysical searches and enabling confident detection statements.

Data quality shifts will be the primary means of ensuring full coverage of h(t) data quality analysis for both detectors during O2, including limiting factors to interferometer performance such as weather or earthquakes. New data quality shift volunteers must invest first in training, and a qualified mentor must be identified; the data quality shift policy is LIGO-L1500110. A list of data quality shift volunteers, and where they are in their training, is kept on the detchar wiki (https://wiki.ligo.org/DetChar/DataQuality/DQShiftVolunteers). Volunteers liaise with LSC Fellows who can provide real time support in identifying egregious features in the interferometer data. This close relationship proved extremely useful during O1, bridging the gap between the LIGO sites and the broader LSC.

4.8.2 Validating detections

The detector characterization portion of the detection checklist is essential in demonstrating that the candidate signal cannot be due to global coincident noise and is unlikely to be due to other non-astrophysical noise. The detection checklist requires detector characterization experts to evaluate key studies and tests of the data surrounding the time of a candidate event.

4.8.3 Rapid Response to validate EM Triggers

Detector characterization will field appointed representatives to the Rapid Response Team, responsible for evaluating and signing off on data quality at the time of an identified low-latency candidate event, as was provided in O1. This effort relies on the support of low latency data quality tools such as iDQ and the automation of tools like Omegascan.

4.9 Roles

There are many active roles within the LIGO detector characterization group, and often some people have more than just one role either due to expertise or people limitations. There are two LIGO detchar co-chairs who oversee and steer the entire group. Working alongside them are a small committee who chair the data quality and instrumentation sub-groups. Within the instrumentation sub-group are subsystem leads, each of whom are responsible for understanding and maintaining the eleven subsystems from the detchar perspective. Each subsystem typically has one lead person; however the more complicated subsystems have two leads. There is also a small group of people who oversee, maintain and develop the key software required by the detchar group. The structure of the detchar group is viewable in the LSC Organisation Chart LIGO-M1200248.

5 Calibration

5.1 LIGO calibration

For the LIGO interferometers, *calibration* involves converting data streams from channels that monitor the feedback control loop that maintains the differential arm length into a derived time series that represents the inferred differential arm length variations, h(t), which is normalized to the average arm length, approximately 4000m. h(t) is referred to as *interferometer strain* or just *strain*. The analog and digital filters used in h(t) production are first produced in the frequency domain by the calibration and commissioning team.

Calibration of the LIGO interferometers is a task critical to the success of the data analysis algorithms, and the confidence associated with their results. As such, the LSC created in its bylaws a Calibration Committee, separate from the Detector Characterization group. The goal of the Calibration Committee is to provide calibrated h(t) with sufficiently small uncertainties in amplitude and phase. The current tentative goal is to have maximum calibration errors of roughly 10 percent in amplitude and a few degrees in phase.

Calibration of a detector is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. The time-domain calibrated data is the main data product, and its generation is sufficiently complex that it needs a dedicated team for calibration and another one for review. The Calibration Committee is therefore co-chaired by a time-domain chair and an experimental chair, and includes LIGO Laboratory and other LSC scientists. It works along with a dedicated Calibration Review Committee which provides advice and vetting of this work. The Calibration Committee's results are posted and documented on a web page[502] available to the LSC, and as with previous science runs, will continue to be recorded in the electronic logs, software repositories, and LIGO documents[503].

Estimation and reduction of the errors in the calibration data products will be a major effort in aLIGO. Towards that end multiple methods of calibration will be used, including a method using auxiliary laser pressure actuation ("photon calibrator")[**?**] and a method using interferometer laser frequency modulation[**?**], both of which were used in initial LIGO science runs. The aLIGO photon calibrator subsystem has been installed and has been used successfully as the primary calibrator during aLIGO's early observing runs. The photon calibrator will remain the primary source for calibration accuracy and precision in upcoming observing runs.

Production and analysis of the time-dependent calibration coefficients is an essential tool for calibration validations. They can be used to estimate the systematic and statistical uncertainties of the calibration as well as the time offset changes. These studies will be continued in the future. Development of on-line tools to monitor the time-dependent calibration factors, and more generally h(t) data quality, is essential.

Phase calibration and end-to-end interferometer model verification (performed e.g., through direct test mass excitation using the photon calibrator[504]) are important. If the interferometer model used for calibration is incorrect, it could skew the phase of LIGO data. Therefore the calibration group's tasks include developing and testing injection techniques, and characterization of analog modules in order to determine accuracy of the interferometer model for calibration.

The Calibration Committee's membership has been augmented in recent years by graduate students and scientists alike from several LSC institutions. Each site will have a dedicated LIGO lab person responsible for the calibration, but the Calibration Committee expects additional manpower of about 3 people per site, on time scales of 6-8 weeks per year, to be necessary to get calibration out and vetted in a timely manner around science runs. This manpower would be in addition to those working on the calibration software pipelines and those maintaining close communication with various aLIGO subsystem groups. This work provides students valuable instrumental training. It would be highly desirable to sustain this broad participation.

In anticipation of the aLIGO science runs we will be creating and maintaining communication channels between aLIGO and other projects' calibration teams and reviewers. In collaboration with Virgo and GEO, the calibration team will also work on improving h(t) generation techniques, and the development of pre-processed h(t) products such as whitened, cleaned, and coherent data streams. Also important is an exchange of ideas about the review process.

The work of the calibration team is currently focused on preparations for the advanced detector era. New techniques are being commissioned to produce h(t) data with second and sub-second latencies. These techniques include moving the generation of h(t) to the front end of the interferometer (CDS) and a gstreamer-based algorithm. In addition, online tools to monitor the quality of the data produced on the fly, and the development of pre-processed h(t) products (e.g. whitened, cleaned, and coherent data streams) are being developed.

The front end calibration effort is intended to develop the necessary code to perform time domain calibration on the CDS computers that directly run the interferometer. This code is directly embedded in the controls code. This method has the advantage of providing the lowest latency possible as it works directly with the data before it is sent on to be recorded, and can thus be included directly in the recorded frame data. The disadvantage of this method is that has difficultly handling the effects of poles and zeros in the actuation and sensing functions above the nyquist frequency that the front end models run at.

The calibration team is commissioning a low-latency gstreamer-based pipeline for time domain calibration in aLIGO. This is a robust pipeline with both frame file and shared memory I/O capabilities, thus allowing for the same pipeline to run for both online and offline calibration. The online infrastructure required for the aLIGO gstreamer-based calibration pipeline was the primary producer for h(t), both in low-latency and offline, during aLIGO's first observing run. The calibration team is continuing to commission and improve the infrastructure required for and the inner-workings of the low-latency aLIGO time domain calibration pipeline.

The current plan for the second observing run is to combine the front end calibration code outputs with the low-latency gststreamer pipline, as was done during the first observing run. The front end code was easy for the calibrators on site, who did the calibration measurements of the interferometer, to keep up to date with changes in the actuation and sensing of the interferometer. The low-latency gstlal calibration pipeline is able to take data products from that front end code and properly apply poles and zeros above the nyquist frequency, as well as properly handle time delay, and generate the final h(t) stream. In the case where calibration needs to be recalculated after data taking due to errors, the offline gstreamer pipeline is capable of producing from just the raw differential arm control signals the same data products as the front end code. This mode of operation was used successfully and compared to the front end calibration code during the first observing run.

5.2 LIGO timing diagnostics

Traceable and closely monitored timing performance of the GW detectors is mission critical for reliable interferometer operation, astrophysical data analysis, and discoveries. For example, (a) timing jitter of digitization of the GW signal could directly contribute to the noise level degrading the astrophysical reach of the LIGO interferometers, (b) coincident and coherent observation using the network of GW detectors is only possible if the absolute timing of the data streams agree within a high degree of accuracy, (c) a network of interferometric GW detectors can only recover both the polarization and sky direction information for a detected event if the absolute timing of their data-streams are known, and (d) multimessenger astronomy with external observatories also require traceable and accurate absolute timing.

The Timing Group includes scientists from both the LSC and the LIGO Laboratory. The group is responsible for (a.) the availability and diagnostics of timing information and signals provided for various subsystems (e.g., LSC, OMC, etc.), (b.) measuring and documenting the timing performance, (c.) the documented certification of the software implementation of precise timing information by the timing distribution system, (d.) documentation of timing related parts, (e.) verifying that the precision of the distribution of timing is according to specification.

The timing distribution system extends until it passes the timing pulses to the advanced LIGO data acquisition system. (Please note that the accuracy of subsystem components beyond the boundaries of the timing distribution system can introduce errors that factor into the phase calibration or data recording of aLIGO detectors and those studies are the responsibility of the calibration and CDS teams.)

The construction and testing of the timing distribution system as well as the associated timing diagnostics tasks have already provided fertile ground for undergraduate and graduate student research involvement and diversity in the program is strongly encouraged for the future.

Critical timing diagnostic tasks in the era of regular gravitational-wave detections are the following:

- verifying traceable performance of the timing distribution system
- checking the status of the independent timing diagnostic hardware, and providing upgrades when necessary,
- assuring the availability of timing witness signals,
- verifying the validity and accuracy of the recorded time-stamp
- verifying the accuracy of the distributed timing signals
- expanding the capabilities of data monitoring tools related to timing,
- availability of timing diagnostics for various subsystems,
- measuring and documenting the timing performance,
- reviewing the physical/software implementation and documentation of the timing distribution and timing diagnostics components.

References

[1] the LIGO Scientific Collaboration, the Virgo Collaboration: J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese, C. Adams, R. Adhikari, and et al. All-sky search for gravitational-wave bursts in the second joint LIGO-Virgo run. *Physical Review D*, 85(12):122007, June 2012.

[2] S. Klimenko, S. Mohanty, M. Rakhmanov, and G. Mitselmakher. Constraint likelihood analysis for a network of gravitational wave detectors. *Phys. Rev. D*, 72:122002, 2005.

[3] S. Klimenko et al. A coherent method for detection of gravitational wave bursts. *Class. Quantum Grav.*, 25(11):114029–+, June 2008.

[4] S. Klimenko, G. Vedovato, M. Drago, G. Mazzolo, G. Mitselmakher, C. Pankow, G. Prodi, V. Re, F. Salemi, and I. Yakushin. Localization of gravitational wave sources with networks of advanced detectors. *Phys. Rev. D*, 83:102001, May 2011.

[5] P. J. Sutton, G. Jones, S. Chatterji, P. Kalmus, I. Leonor, S. Poprocki, J. Rollins, A. Searle, L. Stein, M. Tinto, and M. Was. X-Pipeline: an analysis package for autonomous gravitational-wave burst searches. *New Journal of Physics*, 12:053034–+, 2010.

[6] E. Thrane and M. Coughlin. Seedless clustering in all-sky searches for gravitational-wave transients. *ArXiv e-prints*, January 2014. arXiv:1401.8060.

[7] S. Chamberlin et al. Applications of the ExcessPower Data Analysis Pipeline to Gravitational Wave Detection Efforts, 2013.

[8] S. Chatterji, L. Blackburn, G. Martin, and E. Katsavounidis. Multiresolution techniques for the detection of gravitational-wave bursts. *Classical and Quantum Gravity*, 21:S1809, 2004.

[9] Tyson B. Littenberg and Neil J. Cornish. Separating gravitational wave signals from instrument artifacts. *Phys. Rev. D*, 82:103007, Nov 2010.

[10] J. Aasi, J. Abadie, B.P. Abbott, R. Abbott, T. Abbott, et al. Constraints on cosmic strings from the LIGO-Virgo gravitational-wave detectors. *Phys.Rev.Lett.*, 112:131101, 2014.

[11] B. P. Abbott et al. *Phys. Rev. X*, 6:041015, Oct 2016.

[12] Feryal Ozel, Dimitrios Psaltis, Ramesh Narayan, and Jeffrey E. McClintock. The Black Hole Mass Distribution in the Galaxy. *Astrophys.J.*, 725:1918–1927, 2010.

[13] W. M. Farr, N. Sravan, A. Cantrell, L. Kreidberg, C. D. Bailyn, I. Mandel, and V. Kalogera. The Mass Distribution of Stellar-Mass Black Holes. *ArXiv e-prints*, November 2010.

[14] Laura Kreidberg, Charles D. Bailyn, Will M. Farr, and Vassiliki Kalogera. Mass Measurements of Black Holes in X-Ray Transients: Is There a Mass Gap? *Astrophys.J.*, 757:36, 2012.

[15] K. Belczynski, G. Wiktorowicz, C. Fryer, D. Holz, and V. Kalogera. Missing Black Holes Unveil The Supernova Explosion Mechanism. *Astrophys.J.*, 757:91, 2012.

[16] C.L. Fryer, K. Belczynski, G. Wiktorowicz, M. Dominik, V. Kalogera, et al. Compact Remnant Mass Function: Dependence on the Explosion Mechanism and Metallicity. *Astrophys.J.*, 749:91, 2012.

[17] Krzysztof Belczynski et al. On The Maximum Mass of Stellar Black Holes. *Astrophysical Journal*, 714:1217–1226, 2010.

[18] Michal Dominik, Krzysztof Belczynski, Christopher Fryer, Daniel Holz, Emanuele Berti, et al. Double Compact Objects I: The Significance of the Common Envelope on Merger Rates. *Astrophys.J.*, 759:52, 2012.

[19] Michal Dominik and Krzysztof Belczynski. Private communication, 2012.

[20] K. Belczynski, A. Buonanno, M. Cantiello, C. L. Fryer, D. E. Holz, I. Mandel, M. C. Miller, and M. Walczak. The Formation and Gravitational-wave Detection of Massive Stellar Black Hole Binaries. *Astrophysical Journal*, 789:120, July 2014.

[21] J.M. Miller, C.S. Reynolds, A.C. Fabian, G. Miniutti, and L.C. Gallo. Stellar-mass Black Hole Spin Constraints from Disk Reflection and Continuum Modeling. *Astrophys.J.*, 697:900–912, 2009.

[22] R. Shafee, J. E. McClintock, R. Narayan, S. W. Davis, L.-X. Li, and R. A. Remillard. Estimating the Spin of Stellar-Mass Black Holes by Spectral Fitting of the X-Ray Continuum. *Astrophysical Journal Letters*, 636:L113–L116, January 2006.

[23] Jeffrey E. McClintock et al. The Spin of the Near-Extreme Kerr Black Hole GRS 1915+105. *Astrophysical Journal*, 652:518–539, 2006.

[24] J. Liu, J. E. McClintock, R. Narayan, S. W. Davis, and J. A. Orosz. Erratum: “Precise Measurement of the Spin Parameter of the Stellar-mass Black Hole M33 X-7”. *Astrophysical Journal Letters*, 719:L109, August 2010.

[25] L. Gou, J. E. McClintock, J. Liu, R. Narayan, J. F. Steiner, R. A. Remillard, J. A. Orosz, S. W. Davis, K. Ebisawa, and E. M. Schlegel. A Determination of the Spin of the Black Hole Primary in LMC X-1. *Astrophysical Journal*, 701:1076–1090, August 2009.

[26] S. W. Davis, C. Done, and O. M. Blaes. Testing Accretion Disk Theory in Black Hole X-Ray Binaries. *Astrophysical Journal*, 647:525–538, August 2006.

[27] L.-X. Li, E. R. Zimmerman, R. Narayan, and J. E. McClintock. Multitemperature Blackbody Spectrum of a Thin Accretion Disk around a Kerr Black Hole: Model Computations and Comparison with Observations. *ApJS*, 157:335–370, April 2005.

[28] Jeffrey E. McClintock, Ramesh Narayan, Shane W. Davis, Lijun Gou, Akshay Kulkarni, et al. Measuring the Spins of Accreting Black Holes. *Class.Quant.Grav.*, 28:114009, 2011.

[29] Jeffrey E. McClintock, Ramesh Narayan, and James F. Steiner. Black Hole Spin via Continuum Fitting and the Role of Spin in Powering Transient Jets. *Space Sci. Rev.*, pages 1–28, July 2013.

[30] James F. Steiner and Jeffrey E. McClintock. Modeling the Jet Kinematics of the Black Hole Microquasar XTE J1550-564: A Constraint on Spin-Orbit Alignment. *Astrophys.J.*, 745:136, 2012.

[31] T. Fragos, M. Tremmel, E. Rantsiou, and K. Belczynski. Black Hole Spin-Orbit Misalignment in Galactic X-ray Binaries. *Astrophysical Journal Letters*, 719:L79–L83, August 2010.

[32] Krzysztof Belczynski, Matthew Benacquista, and Tomasz Bulik. Double Compact Objects as Low-frequency Gravitational Wave Sources. *Astrophys.J.*, 725:816–823, 2010.

[33] V. Kalogera. Spin-orbit misalignment in close binaries with two compact objects. *Astrophysical Journal*, 541:042003, 2000.

[34] J. Abadie et al. Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors. *Class. Quantum Grav.*, 27:173001, March 2010.

[35] Bulent Kiziltan, Athanasios Kottas, and Stephen E. Thorsett. The Neutron Star Mass Distribution, 2010.

[36] Ph. Podsiadlowski, N. Langer, A. J. T. Poelarends, S. Rappaport, A. Heger, and E. Pfahl. The effects of binary evolution on the dynamics of core collapse and neutron star kicks. *The Astrophysical Journal*, 612(2):1044, 2004.

[37] E. P. J. van den Heuvel. Double neutron stars: Evidence for two different neutron-star formation mechanisms. *AIP Conference Proceedings*, 924(1):598–606, 2007.

[38] S.E. Woosley, A. Heger, and T.A. Weaver. The evolution and explosion of massive stars. *Rev.Mod.Phys.*, 74:1015–1071, 2002.

[39] M. Kramer and N. Wex. The double pulsar system: a unique laboratory for gravity. *Classical and Quantum Gravity*, 26:073001, 2009.

[40] Jason W.T. Hessels, Scott M. Ransom, Ingrid H. Stairs, Paulo Cesar Carvalho Freire, Victoria M. Kaspi, et al. A radio pulsar spinning at 716-hz. *Science*, 311:1901–1904, 2006.

[41] J. M. Lattimer. The Nuclear Equation of State and Neutron Star Masses. *Annual Review of Nuclear and Particle Science*, 62:485–515, November 2012.

[42] Jocelyn S. Read, Luca Baiotti, Jolien D. E. Creighton, John L. Friedman, Bruno Giacomazzo, et al. Matter effects on binary neutron star waveforms. *Phys.Rev.*, D88:044042, 2013.

[43] Paul D. Lasky, Brynmor Haskell, Vikram Ravi, Eric J. Howell, and David M. Coward. Nuclear Equation of State from Observations of Short Gamma-Ray Burst Remnants. *Phys.Rev.*, D89:047302, 2014.

[44] M. Tanaka, K. Hotokezaka, K. Kyutoku, S. Wanajo, K. Kiuchi, Y. Sekiguchi, and M. Shibata. Radioactively Powered Emission from Black Hole-Neutron Star Mergers. *Astrophysical Journal*, 780:31, January 2014.

[45] B. D. Metzger and E. Berger. What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger? *Astrophysical Journal*, 746:48, February 2012.

[46] Jonathan Grindlay, Simon Portegies Zwart, and Stephen McMillan. Short gamma-ray bursts from binary neutron star mergers in globular clusters. *Nature Physics*, 2:116–119, 2006.

[47] Aleksander Sadowski, Krzysztof Belczynski, Tomasz Bulik, Natalia Ivanova, Frederic A. Rasio, et al. The Total Merger Rate of Compact Object Binaries In The Local Universe. *Astrophys.J.*, 2007.

[48] William H. Lee, Enrico Ramirez-Ruiz, and Glenn van de Ven. Short gamma-ray bursts from dynamically-assembled compact binaries in globular clusters: pathways, rates, hydrodynamics and cosmological setting. *Astrophys.J.*, 720:953–975, 2010.

[49] Matthew J. Benacquista and Jonathan M.B. Downing. Relativistic Binaries in Globular Clusters. *Living Rev.Rel.*, 16:4, 2013.

[50] Krzysztof Belczynski, Tomasz Bulik, Ilya Mandel, B.S. Sathyaprakash, Andrzej A. Zdziarski, et al. Cyg X-3: a Galactic double black hole or black hole-neutron star progenitor. *Astrophys.J.*, 764:96, 2013.

[51] J. Abadie et al. Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors. *Classical & Quantum Gravity*, 27:173001, 2010.

[52] Emmanouela Rantsiou, Shiho Kobayashi, Pablo Laguna, and Frederic Rasio. Mergers of Black Hole - Neutron Star binaries. 1. Methods and First Results. *Astrophys.J.*, 680:1326, 2008.

[53] Koutarou Kyutoku, Hirotada Okawa, Masaru Shibata, and Keisuke Taniguchi. Gravitational waves from spinning black hole-neutron star binaries: dependence on black hole spins and on neutron star equations of state. *Phys.Rev.*, D84:064018, 2011.

[54] Zachariah B. Etienne, Vasileios Paschalidis, and Stuart L. Shapiro. General relativistic simulations of black hole-neutron star mergers: Effects of tilted magnetic fields. *Phys.Rev.*, D86:084026, 2012.

[55] Francois Foucart, Matthew D. Duez, Lawrence E. Kidder, Mark A. Scheel, Bela Szilagyi, et al. Black hole-neutron star mergers for 10 solar mass black holes. *Phys.Rev.*, D85:044015, 2012.

[56] Francois Foucart, M. Brett Deaton, Matthew D. Duez, Lawrence E. Kidder, Ilana MacDonald, et al. Black hole-neutron star mergers at realistic mass ratios: Equation of state and spin orientation effects. *Phys.Rev.*, D87:084006, 2013.

[57] Francois Foucart, Luisa Buchman, Matthew D. Duez, Michael Grudich, Lawrence E. Kidder, et al. First direct comparison of nondisrupting neutron star-black hole and binary black hole merger simulations. *Phys.Rev.*, D88(6):064017, 2013.

[58] Luciano Rezzolla, Bruno Giacomazzo, Luca Baiotti, Jonathan Granot, Chryssa Kouveliotou, et al. The missing link: Merging neutron stars naturally produce jet-like structures and can power short Gamma-Ray Bursts. *Astrophys.J.*, 732:L6, 2011.

[59] B. D. Metzger and E. Berger. What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger? *Astrophysical Journal*, 746:48, February 2012.

[60] J. Clark, H. Evans, S. Fairhurst, I. W. Harry, E. Macdonald, D. Macleod, P. J. Sutton, and A. R. Williamson. Prospects for joint gravitational wave and short gamma-ray burst observations. 2014.

[61] E. Berger, W. Fong, and R. Chornock. An r-process Kilonova Associated with the Short-hard GRB 130603B. *Astrophys.J.*, 774:L23, 2013.

[62] I. Leonor, P. J. Sutton, R. Frey, G. Jones, S. Marka, et al. Estimating detection rates for the LIGO-Virgo search for gravitational-wave burst counterparts to gamma-ray bursts using inferred local GRB rates. *Class.Quant.Grav.*, 26:204017, 2009.

[63] D. Wanderman and T. Piran. The luminosity function and the rate of Swift's Gamma Ray Bursts. *Mon. Not. Roy. Astron. Soc.*, 406:1944–1958, 2010.

[64] R. Chapman, N. R. Tanvir, R. S. Priddey, and A. J. Levan. How common are long Gamma-Ray Bursts in the Local Universe? *Mon. Not. R. Astron. Soc.*, L21:382, 2007.

[65] S. Desai, E.O. Kahya, and R.P. Woodard. Reduced time delay for gravitational waves with dark matter emulators. *Phys.Rev.*, D77:124041, 2008.

[66] B. F. Schutz. Determining the Hubble constant from gravitational wave observations. *Nature*, 323:310, September 1986.

[67] N. Dalal, D. E. Holz, S. A. Hughes, and B. Jain. Short GRB and binary black hole standard sirens as a probe of dark energy. *Phys.Rev.*, D74:063006, 2006.

[68] D. H. Weinberg, M. J. Mortonson, D. J. Eisenstein, C. Hirata, A. G. Riess, et al. Observational Probes of Cosmic Acceleration. *Phys.Rept.*, 530:87–255, 2013.

[69] Michal Was, Patrick J. Sutton, Gareth Jones, and Isabel Leonor. Performance of an externally triggered gravitational-wave burst search. *Phys.Rev.*, D86:022003, 2012.

[70] F. Pannarale and F. Ohme. Prospects for joint gravitational-wave and electromagnetic observations of neutron-star–black-hole coalescing binaries. *Astrophys.J.*, 791:L7, 2014.

[71] Patrick J. Sutton, Gareth Jones, Shourov Chatterji, Peter Michael Kalmus, Isabel Leonor, et al. X-Pipeline: An Analysis package for autonomous gravitational-wave burst searches. *New J.Phys.*, 12:053034, 2010.

[72] Ian W. Harry and Stephen Fairhurst. A targeted coherent search for gravitational waves from compact binary coalescences. *Phys. Rev.*, D83:084002, 2011.

[73] Andrew Williamson et al. A search for gravitational waves associated with short gamma-ray bursts. *Phys.Rev.*, D, 2014.

[74] IceCube Collaboration. `http://gcn.gsfc.nasa.gov/gcn3/14520.gcn3`.

[75] B. Abbott et al. Implications for the Origin of GRB 070201 from LIGO Observations. *ApJ*, 681:1419–1428, 2008.

[76] J. Aasi et al. Search for long-lived gravitational-wave transients coincident with long gamma-ray bursts. *Phys.Rev.*, D88:122004, 2013.

[77] E. Thrane and M. Coughlin. Searching for gravitational-wave transients with a qualitative signal model: seedless clustering strategies. Preprint arXiv:1308.5292, 2013.

[78] M. C. Miller and E. J. M. Colbert. Intermediate-Mass Black Holes. *International Journal of Modern Physics D*, 13:1–64, January 2004.

[79] N. W. C. Leigh, N. Lützgendorf, A. M. Geller, T. J. Maccarone, C. Heinke, and A. Sesana. On the coexistence of stellar-mass and intermediate-mass black holes in globular clusters. *MNRAS*, 444:29–42, October 2014.

[80] J. M. Fregeau, S. L. Larson, M. C. Miller, R. O'Shaughnessy, and F. A. Rasio. Observing IMBH-IMBH Binary Coalescences via Gravitational Radiation. *Astrophysical Journal Letters*, 646:L135–L138, August 2006.

[81] P. Amaro-Seoane and M. Freitag. Intermediate-Mass Black Holes in Colliding Clusters: Implications for Lower Frequency Gravitational-Wave Astronomy. *Astrophysical Journal Letters*, 653:L53–L56, December 2006.

[82] Jonathan R. Gair, Ilya Mandel, M. Coleman Miller, and Marta Volonteri. Exploring intermediate and massive black-hole binaries with the Einstein Telescope. *Gen.Rel.Grav.*, 43:485–518, 2011.

[83] K. Belczynski, A. Buonanno, M. Cantiello, C. L. Fryer, D. E. Holz, I. Mandel, M. C. Miller, and M. Walczak. The Formation and Gravitational-wave Detection of Massive Stellar Black Hole Binaries. *Astrophysical Journal*, 789:120, July 2014.

[84] Andrea Taracchini, Yi Pan, Alessandra Buonanno, Enrico Barausse, Michael Boyle, et al. Prototype effective-one-body model for nonprecessing spinning inspiral-merger-ringdown waveforms. *Phys.Rev.*, D86:024011, 2012.

[85] J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, T. Accadia, F. Acernese, K. Ackley, C. Adams, T. Adams, and et al. Search for gravitational radiation from intermediate mass black hole binaries in data from the second LIGO-Virgo joint science run. *Physical Review D*, 89(12):122003, June 2014.

[86] J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese, C. Adams, R. Adhikari, C. Affeldt, and et al. Search for gravitational waves from intermediate mass binary black holes. *Physical Review D*, 85(10):102004, May 2012.

[87] The LIGO Scientific Collaboration, the Virgo Collaboration, J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, and et al. Search for gravitational wave ringdowns from perturbed intermediate mass black holes in LIGO-Virgo data from 2005-2010. *ArXiv e-prints*, March 2014. arXiv:1403.5306.

[88] J. Abadie et al. Search for gravitational waves from binary black hole inspiral, merger and ringdown. *Physical Review D*, 83:122005, 2011.

[89] J. Aasi, J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese, C. Adams, T. Adams, and et al. Search for gravitational waves from binary black hole inspiral, merger, and ringdown in LIGO-Virgo data from 2009-2010. *Physical Review D*, 87(2):022002, January 2013.

[90] Gstreamer plugins for the LSC Algorithm Library.

[91] S. Privitera, S. R. P. Mohapatra, P. Ajith, K. Cannon, N. Fotopoulos, M. A. Frei, C. Hanna, A. J. Weinstein, and J. T. Whelan. Improving the sensitivity of a search for coalescing binary black holes with non-precessing spins in gravitational wave data. *ArXiv e-prints*, October 2013.

[92] Sergey Klimenko and Chris Pankow. Detection statistic for multiple algorithms, networks and data sets. Technical Report LIGO-T1300869, LIGO Project, 2013.

[93] J. Veitch, V. Raymond, B. Farr, W. Farr, P. Graff, et al. Parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library. *Phys.Rev.*, D91(4):042003, 2015.

[94] J. Abadie et al. Evidence for the Direct Detection of Gravitational Waves from a Black Hole Binary Coalescence. Technical Report LIGO-P1000146, LIGO Scientific Collaboration and Virgo Collaboration, 2011.

[95] E. A. Huerta and D. A. Brown. Effect of eccentricity on binary neutron star searches in advanced LIGO. *Phys. Rev. D*, 87(12):127501, 2013.

[96] C. Hopman and T. Alexander. The Effect of Mass Segregation on Gravitational Wave Sources near Massive Black Holes. *Astrophys. J.*, 645:L133–L136, July 2006.

[97] Ryan M. O'Leary, Bence Kocsis, and Abraham Loeb. Gravitational waves from scattering of stellar-mass black holes in galactic nuclei. *Mon. Not. Roy. Astron. Soc.*, 395:2127–2146, 2009.

[98] Bence Kocsis and Janna Levin. Repeated bursts from relativistic scattering of compact objects in galactic nuclei. *Phys. Rev. D*, 85:123005, Jun 2012.

[99] A. C. Fabian, J. E. Pringle, and M. J. Rees. Tidal capture formation of binary systems and X-ray sources in globular clusters. *Mon. Not. Roy. Astron. Soc.*, 172:15P–+, August 1975.

[100] D. Pooley, W. H. G. Lewin, S. F. Anderson, H. Baumgardt, A. V. Filippenko, B. M. Gaensler, L. Homer, P. Hut, V. M. Kaspi, J. Makino, B. Margon, S. McMillan, S. Portegies Zwart, M. van der Klis, and F. Verbunt. Dynamical Formation of Close Binary Systems in Globular Clusters. *Astrophys. J.*, 591:L131–L134, July 2003.

[101] W. H. Lee, E. Ramirez-Ruiz, and G. van de Ven. Short Gamma-ray Bursts from Dynamically Assembled Compact Binaries in Globular Clusters: Pathways, Rates, Hydrodynamics, and Cosmological Setting. *Astrophys. J.*, 720:953–975, September 2010.

[102] Linqing Wen. On the Eccentricity Distribution of Coalescing Black Hole Binaries Driven by the Kozai Mechanism in Globular Clusters. *Astrophys. J.*, 598:419–430, 2003.

[103] M. Coleman Miller and Douglas P. Hamilton. Four-body effects in globular cluster black hole coalescence. *Astrophys. J.*, 576(2):894, 2002.

[104] S. J. Aarseth. Mergers and ejections of black holes in globular clusters. *Mon. Not. Roy. Astron. Soc.*, 422:841–848, May 2012.

[105] Fabio Antonini and Hagai B. Perets. Secular evolution of compact binaries near massive black holes: Gravitational wave sources and other exotica. *Astrophys. J.*, 757(1):27, 2012.

[106] T. A. Thompson. Accelerating Compact Object Mergers in Triple Systems with the Kozai Resonance: A Mechanism for ”Prompt” Type Ia Supernovae, Gamma-Ray Bursts, and Other Exotica. *Astrophys. J.*, 741:82, November 2011.

[107] S. Naoz, B. Kocsis, A. Loeb, and N. Yunes. Resonant Post-Newtonian Eccentricity Excitation in Hierarchical Three-body Systems. *Astrophysical Journal*, 773:187, August 2013.

[108] B. Katz and S. Dong. The rate of WD-WD head-on collisions may be as high as the SNe Ia rate. *ArXiv e-prints*, November 2012.

[109] P. C. Peters. Gravitational radiation and the motion of two point masses. *Phys. Rev.*, 136:B1224–B1232, 1964.

[110] Neil J. Cornish and Tyson B. Littenberg. BayesWave: Bayesian Inference for Gravitational Wave Bursts and Instrument Glitches, 2014.

[111] Kai Sheng Tai, Sean T. McWilliams, and Frans Pretorius. Detecting gravitational waves from highly eccentric compact binaries. *Physical Review D*, 90:103001, 2014.

[112] M. Millhouse, N. Cornish, and T. Littenberg, 2014. In preparation.

[113] E. A. Huerta, P. Kumar, S. T. McWilliams, R. O'Shaughnessy, and N. Yunes. Accurate and efficient waveforms for compact binaries on eccentric orbits, 2014. arXix:1408.3406 [gr-qc].

[114] M. Coughlin, E. Thrane, and N. Christensen. Detecting compact binary coalescences with seedless clustering. *Phys. Rev. D*, 90:083005, 2014.

[115] I. Mandel, D. A. Brown, J. R. Gair, and M. C. Miller. Rates and Characteristics of Intermediate Mass Ratio Inspirals Detectable by Advanced LIGO. *Astrophysical Journal*, 681:1431–1447, July 2008.

[116] D. A. Brown, J. Brink, H. Fang, J. R. Gair, C. Li, G. Lovelace, I. Mandel, and K. S. Thorne. Prospects for Detection of Gravitational Waves from Intermediate-Mass-Ratio Inspirals. *Physical Review Letters*, 99(20):201102–+, November 2007.

[117] C. L. Rodriguez, I. Mandel, and J. R. Gair. Verifying the no-hair property of massive compact objects with intermediate-mass-ratio inspirals in advanced gravitational-wave detectors. *Physical Review D*, 85(6):062002, March 2012.

[118] L. S. Finn and K. S. Thorne. Gravitational waves from a compact star in a circular, inspiral orbit, in the equatorial plane of a massive, spinning black hole, as observed by LISA. *Physical Review D*, 62(12):124021, December 2000.

[119] J. Aasi et al. Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories. *arXiv:1304.0670*, 2013. `http://arxiv.org/abs/1304.0670`.

[120] E. A. Huerta and J. R. Gair. Importance of including small body spin effects in the modelling of extreme and intermediate mass-ratio inspirals. *Physical Review D*, 84(6):064023, September 2011.

[121] E. A. Huerta, J. R. Gair, and D. A. Brown. Importance of including small body spin effects in the modelling of intermediate mass-ratio inspirals. II. Accurate parameter extraction of strong sources using higher-order spin effects. *Physical Review D*, 85(6):064023, March 2012.

[122] E. A. Huerta and J. R. Gair. Intermediate-mass-ratio inspirals in the Einstein Telescope. I. Signal-to-noise ratio calculations. *Physical Review D*, 83(4):044020, February 2011.

[123] J. Veitch, M. Pürrer, and I. Mandel. Measuring intermediate mass black hole binaries with advanced gravitational wave detectors. *ArXiv e-prints*, March 2015.

[124] I. Mandel and J. R. Gair. Can we detect intermediate mass ratio inspirals? *Classical and Quantum Gravity*, 26(9):094036, May 2009.

[125] Alessandra Buonanno et al. Toward faithful templates for non-spinning binary black holes using the effective-one-body approach. *Phys. Rev. D*, 76:104049, 2007.

[126] Y. Pan, A. Buonanno, M. Boyle, L. T. Buchman, L. E. Kidder, H. P. Pfeiffer, and M. A. Scheel. Inspiral-merger-ringdown multipolar waveforms of nonspinning black-hole binaries using the effective-one-body formalism. *Physical Review D*, 84(12):124052, December 2011.

[127] A. Taracchini, A. Buonanno, Y. Pan, T. Hinderer, M. Boyle, D. A. Hemberger, L. E. Kidder, G. Lovelace, A. H. Mroué, H. P. Pfeiffer, M. A. Scheel, B. Szilágyi, N. W. Taylor, and A. Zenginoglu. Effective-one-body model for black-hole binaries with generic mass ratios and spins. *Physical Review D*, 89(6):061502, March 2014.

[128] T. Callister. Improving models of eccentric compact binary inspirals, MPhil Thesis (Cambridge University), LIGO-DCC-P1400238, 2014.

[129] R. J. E. Smith, I. Mandel, and A. Vecchio. Studies of waveform requirements for intermediate mass-ratio coalescence searches with advanced gravitational-wave detectors. *Physical Review D*, 88(4):044010, August 2013.

[130] Y. Aso, Z. Márka, C. Finley, J. Dwyer, K. Kotake, and S. Márka. Search method for coincident events from LIGO and IceCube detectors. *Classical and Quantum Gravity*, 25(11):114039–+, June 2008.

[131] T. Pradier. Coincidences between Gravitational Wave Interferometers and High Energy Neutrino Telescopes. *ArXiv e-prints*, 807, July 2008. arXiv:0807.2562.

[132] V. van Elewyck, S. Ando, Y. Aso, B. Baret, M. Barsuglia, I. Bartos, E. Chassande-Mottin, I. di Palma, J. Dwyer, C. Finley, K. Kei, A. Kouchner, S. Marka, Z. Marka, J. Rollins, C. D. Ott, T. Pradier, and A. Searle. Joint Searches Between Gravitational-Wave Interferometers and High-Energy Neutrino Telescopes:. Science Reach and Analysis Strategies. *Int. J. Mod. Phys. D*, 18:1655–1659, 2009.

[133] B. Baret, I. Bartos, B. Bouhou, A. Corsi, I. D. Palma, C. Donzaud, V. V. Elewyck, C. Finley, G. Jones, A. Kouchner, S. Márka, Z. Márka, L. Moscoso, E. Chassande-Mottin, M. A. Papa, T. Pradier, P. Raffai, J. Rollins, and P. Sutton. Bounding the time delay between high-energy neutrinos and gravitational-wave transients from gamma-ray bursts. *Astropart. Phys.*, 35(1):1 – 7, 2011.

[134] Imre Bartos, Chad Finley, Alessandra Corsi, and Szabolcs Márka. Observational constraints on multimessenger sources of gravitational waves and high-energy neutrinos. *Phys. Rev. Lett.*, 107:251101, Dec 2011.

[135] Shin'ichiro Ando et al. Multimessenger astronomy with gravitational waves and high-energy neutrinos. *Rev. Mod. Phys.*, 85(4):1401–1420, 2013.

[136] E. Waxman and J. Bahcall. High Energy Neutrinos from Cosmological Gamma-Ray Burst Fireballs. *Physical Review Letters*, 78:2292–2295, March 1997.

[137] E. Waxman and J. N. Bahcall. Neutrino Afterglow from Gamma-Ray Bursts: 10^{18} eV. *Astrophys. Journal*, 541:707, October 2000.

[138] P. Mészáros and E. Waxman. TeV Neutrinos from Successful and Choked Gamma-Ray Bursts. *Phys. Rev. Lett.*, 87(17):171102–+, October 2001.

[139] P. Mészáros, S. Kobayashi, S. Razzaque, and B. Zhang. High Energy Photons, Neutrinos and Gravitational Waves from Gamma-Ray Bursts. In R. Ouyed, editor, *Beaming and Jets in Gamma Ray Bursts*, page 30, 2002.

[140] S. Razzaque, P. Mészáros, and E. Waxman. High Energy Neutrinos from Gamma-Ray Bursts with Precursor Supernovae. *Phys. Rev. Lett.*, 90(24):241103–+, June 2003.

[141] S. Razzaque, P. Mészáros, and E. Waxman. Neutrino tomography of gamma ray bursts and massive stellar collapses. *Phys. Rev. D*, 68(8):083001, October 2003.

[142] S. Ando and J. F. Beacom. Revealing the Supernova Gamma-Ray Burst Connection with TeV Neutrinos. *Phys. Rev. Lett.*, 95(6):061103, August 2005.

[143] S. Razzaque, P. Mészáros, and E. Waxman. High Energy Neutrinos from a Slow Jet Model of Core Collapse Supernovae. *Mod. Phys. Lett. A*, 20:2351–2367, 2005.

[144] M. G. Aartsen, R. Abbasi, Y. Abdou, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, D. Altmann, J. Auffenberg, X. Bai, and et al. First Observation of PeV-Energy Neutrinos with IceCube. *Physical Review Letters*, 111(2):021103, July 2013.

[145] S. Adrián-Martínez, I. A. Samarai, A. Albert, M. André, M. Anghinolfi, G. Anton, S. Anvar, M. Ardid, T. Astraatmadja, J.-J. Aubert, and et al. A first search for coincident gravitational waves and high energy neutrinos using LIGO, Virgo and ANTARES data from 2007. *JCAP*, 6:8, June 2013.

[146] B Baret et al. Multimessenger sources of gravitational waves and high-energy neutrinos: Science reach and analysis method. *Journal of Physics: Conference Series*, 363(1):012022, 2012.

[147] H. B. J. Koers and R. A. M. J. Wijers. Enhanced high-energy neutrino emission from choked gamma-ray bursts due to meson and muon acceleration. *ArXiv e-prints*, 711, November 2007. arXiv:0711.4791.

[148] S. Horiuchi and S. Ando. High-energy neutrinos from reverse shocks in choked and successful relativistic jets. *Physical Review D*, 77(6):063007, March 2008.

[149] J Ahrens et al. Sensitivity of the IceCube detector to astrophysical sources of high energy muon neutrinos. *Astroparticle Physics*, 20(5):507 – 532, 2004.

[150] I. Bartos, B. Dasgupta, and S. Márka. Probing the structure of jet-driven core-collapse supernova and long gamma-ray burst progenitors with high-energy neutrinos. *Physical Review D*, 86(8):083007, October 2012.

[151] B. Baret, I. Bartos, B. Bouhou, E. Chassande-Mottin, A. Corsi, I. Di Palma, C. Donzaud, M. Drago, C. Finley, G. Jones, S. Klimenko, A. Kouchner, S. Márka, Z. Márka, L. Moscoso, M. A. Papa, T. Pradier, G. Prodi, P. Raffai, V. Re, J. Rollins, F. Salemi, P. Sutton, M. Tse, V. Van Elewyck, and G. Vedovato. Multimessenger science reach and analysis method for common sources of gravitational waves and high-energy neutrinos. *Physical Review D*, 85(10):103004, May 2012.

[152] T. W. B. Kibble. Topology of Cosmic Domains and Strings. *J.Phys.A*, A9:1387–1398, 1976.

[153] A. Vilenkin and E. Shellard. *Cosmic strings and other Topological Defects*. Cambridge University Press, 1994.

[154] I. B. Zeldovich. Cosmological fluctuations produced near a singularity. *Mon. Not. R. Astron. Soc.*, 192:663–667, sep 1980.

[155] Mark Wyman, Levon Pogosian, and Ira Wasserman. Bounds on cosmic strings from WMAP and SDSS. *Phys.Rev.*, D72:023513, 2005.

[156] Neil Bevis, Mark Hindmarsh, Martin Kunz, and Jon Urrestilla. Fitting CMB data with cosmic strings and inflation. *Phys.Rev.Lett.*, 100:021301, 2008.

[157] Richard Battye, Bjorn Garbrecht, and Adam Moss. Tight constraints on F- and D-term hybrid inflation scenarios. *Phys.Rev.*, D81:123512, 2010.

[158] Richard Battye and Adam Moss. Updated constraints on the cosmic string tension. *Phys.Rev.*, D82:023521, 2010.

[159] P.A.R. Ade et al. Planck 2013 results. XXV. Searches for cosmic strings and other topological defects, 2013.

[160] Andrei D. Linde. Hybrid inflation. *Phys.Rev.*, D49:748–754, 1994.

[161] Edmund J. Copeland, Andrew R. Liddle, David H. Lyth, Ewan D. Stewart, and David Wands. False vacuum inflation with Einstein gravity. *Phys.Rev.*, D49:6410–6433, 1994.

[162] G.R. Dvali, Q. Shafi, and Robert K. Schaefer. Large scale structure and supersymmetric inflation without fine tuning. *Phys.Rev.Lett.*, 73:1886–1889, 1994.

[163] Saswat Sarangi and S.H. Henry Tye. Cosmic string production towards the end of brane inflation. *Phys.Lett.*, B536:185–192, 2002.

[164] Rachel Jeannerot, Jonathan Rocher, and Mairi Sakellariadou. How generic is cosmic string formation in SUSY GUTs. *Phys.Rev.*, D68:103514, 2003.

[165] Edward Witten. Cosmic superstrings. *Physics Letters B*, 153(4???5):243 – 246, 1985.

[166] Edmund J. Copeland, Levon Pogosian, and Tanmay Vachaspati. Seeking String Theory in the Cosmos. *Class.Quant.Grav.*, 28:204009, 2011.

[167] N. Kaiser and A. Stebbins. Microwave anisotropy due to cosmic strings. *Nature*, 310:391–393, 1984.

[168] Amy S. Lo and Edward L. Wright. Signatures of cosmic strings in the cosmic microwave background, 2005.

[169] E. Jeong and G. F. Smoot. The Validity of the Cosmic String Pattern Search with the Cosmic Microwave Background. *The Astrophysical Journal Letters*, 661(1):L1, 2007.

[170] Jon Urrestilla, Neil Bevis, Mark Hindmarsh, and Martin Kunz. Cosmic string parameter constraints and model analysis using small scale Cosmic Microwave Background data. *JCAP*, 1112:021, 2011.

[171] J. Dunkley, R. Hlozek, J. Sievers, V. Acquaviva, P.A.R. Ade, et al. The Atacama Cosmology Telescope: Cosmological Parameters from the 2008 Power Spectra. *Astrophys.J.*, 739:52, 2011.

[172] Thibault Damour and Alexander Vilenkin. Gravitational radiation from cosmic (super)strings: Bursts, stochastic background, and observational windows. *Phys.Rev.*, D71:063510, 2005.

[173] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys.Rev.*, D81:104028, 2010.

[174] Mark G. Jackson, Nicholas T. Jones, and Joseph Polchinski. Collisions of cosmic F and D-strings. *JHEP*, 0510:013, 2005.

[175] T. Kibble. *The formation and evolution of cosmic strings*, chapter Cosmic strings – An overview. Cambridge Univ. Press, gibbons, g. and hawking, s edition, 1990.

[176] Thibault Damour and Alexander Vilenkin. Gravitational wave bursts from cosmic strings. *Phys.Rev.Lett.*, 85:3761–3764, 2000.

[177] David P. Bennett and Francois R. Bouchet. Evidence for a Scaling Solution in Cosmic String Evolution. *Phys.Rev.Lett.*, 60:257, 1988.

[178] Christophe Ringeval, Mairi Sakellariadou, and Francois Bouchet. Cosmological evolution of cosmic string loops. *JCAP*, 0702:023, 2007.

[179] Jose J. Blanco-Pillado, Ken D. Olum, and Benjamin Shlaer. The number of cosmic string loops. *Phys.Rev.*, D89:023512, 2014.

[180] V. Berezinsky, B. Hnatyk, and A. Vilenkin. Superconducting cosmic strings as gamma-ray burst engines, 2000.

[181] Thibault Damour and Alexander Vilenkin. Gravitational wave bursts from cusps and kinks on cosmic strings. *Phys.Rev.*, D64:064008, 2001.

[182] J. Aasi et al. The characterization of Virgo data and its impact on gravitational-wave searches. *Class.Quant.Grav.*, 29:155002, 2012.

[183] T. Accadia et al. Virgo Document VIR-0128A-12, 2012.

[184] P. Binetruy, A. Bohe, T. Hertog, and D. A. Steer. Gravitational wave signatures from kink proliferation on cosmic (super-) strings. *Phys.Rev.*, D82:126007, 2010.

[185] Xavier Siemens, Jolien Creighton, Irit Maor, Saikat Ray Majumder, Kipp Cannon, et al. Gravitational wave bursts from cosmic (super)strings: Quantitative analysis and constraints. *Phys.Rev.*, D73:105001, 2006.

[186] Bruce Allen. A chi**2 time-frequency discriminator for gravitational wave detection. *Phys.Rev.*, D71:062001, 2005.

[187] Kipp C. Cannon. A Bayesian coincidence test for noise rejection in a gravitational-wave burst search. *Class.Quant.Grav.*, 25:105024, 2008.

[188] Tristan L. Smith, Elena Pierpaoli, and Marc Kamionkowski. A new cosmic microwave background constraint to primordial gravitational waves. *Phys.Rev.Lett.*, 97:021301, 2006.

[189] B.P. Abbott et al. An Upper Limit on the Stochastic Gravitational-Wave Background of Cosmological Origin. *Nature*, 460:990, 2009.

[190] Frederick A. Jenet, G.B. Hobbs, W. van Straten, R.N. Manchester, M. Bailes, et al. Upper bounds on the low-frequency stochastic gravitational wave background from pulsar timing observations: Current limits and future prospects. *Astrophys.J.*, 653:1571–1576, 2006.

[191] E Thrane, S Kandhasamy, C D Ott, et al. Long gravitational-wave transients and associated detection strategies for a network of terrestrial interferometers. *Phys. Rev. D*, 83:083004, 2011.

[192] A. Corsi and P. Mészáros. Gamma-ray burst afterglow plateaus and gravitational waves: multi-messenger signature of a millisecond magnetar? *Astrophys. J.*, 702:1171, 2009.

[193] A. L. Piro and C. D. Ott. Supernova fallback onto magnetars and propeller-powered supernovae. *Astrophys. J.*, 736:108, 2011.

[194] A. L. Piro and E. Thrane. Gravitational Waves from Fallback Accretion onto Neutron Stars. *Astrophys. J.*, 761:63, 2012.

[195] E Thrane and M Coughlin. Searching for gravitational-wave transients with a qualitative signal model: seedless clustering strategies. *Phys. Rev. D*, 88:083010, 2013.

[196] E. Thrane and M. Coughlin. Seedless clustering in all-sky searches for gravitational-wave transients. *Phys. Rev. D*, 89:063012, 2014.

[197] K Kiuchi, M Shibata, P J Montero, and J A Font. Gravitational waves from the Papaloizou-Pringle instability in black hole-torus systems. *Phys. Rev. Lett.*, 106:251102, 2011.

[198] M. H. P. M. van Putten. Proposed Source of Gravitational Radiation from a Torus around a Black Hole. *Phys. Rev. Lett.*, 87:091101, 2001.

[199] M. H. P. M. van Putten. Gravitational Waveforms of Kerr Black Holes Interacting with High-Density Matter. *Astrophys. J. Lett.*, 684:91, 2008.

[200] A. L. Piro and E. Pfahl. Fragmentation of Collapsar Disks and the Production of Gravitational Waves. *Astrophysical Journal*, 658:1173, April 2007.

[201] J Aasi et al. Search for long-lived gravitational-wave transients coincident with long gamma-ray bursts. *Phys. Rev. D*, 88:122004, 2013.

[202] C. D. Ott. The gravitational-wave signature of core-collapse supernovae. *Class. Quantum Grav.*, 26:063001, 2009.

[203] R. M. O'Leary, B. Kocsis, and A. Loeb. Gravitational waves from scattering of stellar-mass black holes in galactic nuclei. *Mon. Not. R. Ast. Soc.*, 395:2127, 2009.

[204] S. Sutton, I. S. Heng, G. Prodi, and E. Chassande-Motin. Search Plan: All-Sky Burst Search. *LIGO-T1400192*, 2014.

[205] Robert Coyne, Alessandra Corsi, and Benjamin J. Owen. Cross-correlation method for intermediate duration gravitational wave searches associated with gamma-ray bursts. *Phys. Rev.*, D93(10):104059, 2016.

[206] Eric Thrane, Vuk Mandic, and Nelson Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. 2015.

[207] T. Prestegard, E. Thrane, et al. Identification of noise artifacts in searches for long-duration gravitational-wave transients. *Class. Quantum Grav.*, 29:095018, 2012.

[208] `http://ligo-vcs.phys.uwm.edu/wsvn/MatApps/packages/stochastic/trunk/stamp2/`.

[209] B. P. Abbott et al. All-sky search for long-duration gravitational wave transients with initial ligo. *Phys. Rev. D*, 93:042005, Feb 2016.

[210] T. Prestegard for the STAMP all-sky working group. The STAMP all-sky search for long-transient gravitational waves, 2014.
`https://dcc.ligo.org/LIGO-G1400176`.

[211] The LSC and Virgo. All-sky search for long-duration gravitational-wave transients with ligo, 2014. `https://dcc.ligo.org/LIGO-P1400138`.

[212] Michael Coughlin, Patrick Meyers, Shivaraj Kandhasamy, Eric Thrane, and N. Christensen. Prospects for searches for long-duration gravitational-waves without time slides. *Phys. Rev. D*, 92:043007, Aug 2015.

[213] B. P. Abbott, R. Abbott, F. Acernese, et al. Search for gravitational-wave bursts associated with gamma-ray bursts using data from ligo science run 5 and virgo science run 1. *The Astrophysical Journal*, 715(2):1438, 2010.

[214] M. S. Briggs, V. Connaughton, K. C. Hurley, P. A. Jenke, A. von Kienlin, A. Rau, X.-L. Zhang, The LIGO Scientific Collaboration, Virgo Collaboration: J. Abadie, B. P. Abbott, and et al. Search for gravitational waves associated with gamma-ray bursts during LIGO science run 6 and Virgo science runs 2 and 3. *Astrophysical Journal*, 760:12, November 2012.

[215] S. Adrián-Martínez et al. A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, Virgo and ANTARES data from 2007. *Journal of Cosmology and Astroparticle Physics*, 2013(06):008, 2013.

[216] J. Abadie, B. P. Abbott, T. D. Abbott, R. Abbott, M. Abernathy, C. Adams, R. Adhikari, C. Affeldt, P. Ajith, B. Allen, and et al. Implications for the Origin of GRB 051103 from LIGO Observations. *Astrophysical Journal*, 755:2, August 2012.

[217] J. Aasi et al. Search for gravitational waves associated with gamma-ray bursts detected by the Inter-Planetary Network. *Physical Review Letters*, 113:011102, 2014.

[218] J. Aasi et al. Methods and results of a search for gravitational waves associated with gamma-ray bursts using the GEO600, LIGO, and Virgo detectors. *Physical Review D*, 89:122004, 2014.

[219] Kipp C. Cannon. Efficient algorithm for computing the time-resolved full-sky cross power in an interferometer with omnidirectional elements. *Phys.Rev.*, D75:123003, 2007.

[220] Mark Edwards. On the search for intermediate duration gravitational waves using the spherical harmonic basis. 2013. https://dcc.ligo.org/LIGO-P1300227.

[221] P. Sutton et al. X-Pipeline All-Sky Burst Search: Optimisation. 2015. `https://dcc.ligo.org/T1500033`.

[222] N. Cornish and T. Littenberg. BayesWave: Bayesian Inference for Gravitational Wave Bursts and Instrument Glitches. *Submitted to Class. Quantum Grav., LIGO-P1400185*, 2014.

[223] LSC/Virgo Burst Analysis Group. LALInference_Burst. *https://wiki.ligo.org/Bursts/LIB/WebHome*, 2014.

[224] E. Thrane for the The Stochastic Group. Calibration requirements for stochastic searches in the advanced detector era, 2014.
`https://dcc.ligo.org/LIGO-T1200562`.

[225] E. P. Mazets, S. V. Golentskii, V. N. Ilinskii, R. L. Aptekar, and I. A. Guryan. Observations of a flaring X-ray pulsar in Dorado. *Nature*, 282:587–589, December 1979.

[226] Y. T. Tanaka, T. Terasawa, N. Kawai, A. Yoshida, I. Yoshikawa, Y. Saito, T. Takashima, and T. Mukai. Comparative Study of the Initial Spikes of Soft Gamma-Ray Repeater Giant Flares in 1998 and 2004 Observed with Geotail: Do Magnetospheric Instabilities Trigger Large-Scale Fracturing of a Magnetar's Crust? *Astrophysical Journal Letters*, 665:L55–L58, August 2007.

[227] T. Terasawa, Y. T. Tanaka, Y. Takei, N. Kawai, A. Yoshida, K. Nomoto, I. Yoshikawa, Y. Saito, Y. Kasaba, T. Takashima, T. Mukai, H. Noda, T. Murakami, K. Watanabe, Y. Muraki, T. Yokoyama, and M. Hoshino. Repeated injections of energy in the first 600ms of the giant flare of SGR1806 - 20. *Nature*, 434:1110–1111, April 2005.

[228] O. Benhar, V. Ferrari, and L. Gualtieri. Gravitational wave asteroseismology reexamined. *Physical Review D*, 70(12):124015–+, December 2004.

[229] G. L. Israel, T. Belloni, L. Stella, Y. Rephaeli, D. E. Gruber, P. Casella, S. Dall'Osso, N. Rea, M. Persic, and R. E. Rothschild. The discovery of rapid x-ray oscillations in the tail of the sgr 1806-20 hyperflare. *The Astrophysical Journal Letters*, 628(1):L53, 2005.

[230] A. L. Watts and T. E. Strohmayer. Detection with RHESSI of High-Frequency X-Ray Oscillations in the Tail of the 2004 Hyperflare from SGR 1806–20. *Astrophysical Journal Letters*, 637:L117–L120, February 2006.

[231] N. Andersson, J. Baker, K. Belczynski, S. Bernuzzi, E. Berti, L. Cadonati, P. Cerdá-Durán, J. Clark, M. Favata, L. S. Finn, C. Fryer, B. Giacomazzo, J. A. González, M. Hendry, I. S. Heng, S. Hild, N. Johnson-McDaniel, P. Kalmus, S. Klimenko, S. Kobayashi, K. Kokkotas, P. Laguna, L. Lehner, J. Levin, S. Liebling, A. MacFadyen, I. Mandel, S. Marka, Z. Marka, D. Neilsen, P. O'Brien, R. Perna, J. Read, C. Reisswig, C. Rodriguez, M. Ruffert, E. Schnetter, A. Searle, P. Shawhan, D. Shoemaker, A. Soderberg, U. Sperhake, P. Sutton, N. Tanvir, M. Was, and S. Whitcomb. The transient gravitational-wave sky. *Classical and Quantum Gravity*, 30(19):193002, October 2013.

[232] B. Abbott et al. Search for gravitational-wave bursts from soft gamma repeaters. *Physical Review Letters*, 101(21):211102, 2008.

[233] B. P. Abbott et al. Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm. *Astrophysical Journal Letters*, 701:L68–L74, August 2009.

[234] J. Abadie et al. Search for Gravitational Wave Bursts from Six Magnetars. *The Astrophysical Journal Letters*, 734(2):L35, 2011.

[235] J. Abadie et al. Search for gravitational waves associated with the august 2006 timing glitch of the vela pulsar. *Physical Review D*, 83(4):042001, Feb 2011.

[236] B. Abbott and for the LIGO Scientific Collaboration. Implications for the Origin of GRB 070201 from LIGO Observations. *Astrophysical Journal*, 681:1419–1428, 2008.

[237] B. Abbott et al. Search for gravitational wave radiation associated with the pulsating tail of the SGR 1806–20 hyperflare of 27 December 2004 using LIGO. *Physical Review D*, 76:062003, 2007.

[238] M. Shibata. Constraining Nuclear Equations of State Using Gravitational Waves from Hypermassive Neutron Stars. *Physical Review Letters*, 94(20):201101, May 2005.

[239] L. Baiotti, B. Giacomazzo, and L. Rezzolla. Accurate evolutions of inspiralling neutron-star binaries: Prompt and delayed collapse to a black hole. *Physical Review D*, 78:084033, Oct 2008.

[240] K. Hotokezaka, K. Kyutoku, H. Okawa, M. Shibata, and K. Kiuchi. Binary neutron star mergers: Dependence on the nuclear equation of state. *Physical Review D*, 83(12):124008, June 2011.

[241] A. Bauswein, H.-T. Janka, K. Hebeler, and A. Schwenk. Equation-of-state dependence of the gravitational-wave signal from the ring-down phase of neutron-star mergers. *Physical Review D*, 86(6):063001, September 2012.

[242] N. Stergioulas, A. Bauswein, K. Zagkouris, and H.-T. Janka. Gravitational waves and non-axisymmetric oscillation modes in mergers of compact object binaries. *MNRAS*, 418:427–436, November 2011.

[243] K. Hotokezaka, K. Kiuchi, K. Kyutoku, T. Muranushi, Y. Sekiguchi, M. Shibata, and K. Taniguchi. Remnant massive neutron stars of binary neutron star mergers: Evolution process and gravitational waveform. *Physical Review D*, 88(4):044026, August 2013.

[244] A. Bauswein, N. Stergioulas, and H.-T. Janka. Revealing the high-density equation of state through binary neutron star mergers. *Physical Review D*, 90(2):023002, July 2014.

[245] J. Clark, A. Bauswein, L. Cadonati, H.-T. Janka, C. Pankow, and N. Stergioulas. Prospects for high frequency burst searches following binary neutron star coalescence with advanced gravitational wave detectors. *Physical Review D*, 90(6):062004, September 2014.

[246] S. Dall'Osso, B. Giacomazzo, R. Perna, and L. Stella. Gravitational waves from massive magnetars formed in binary neutron star mergers. *ArXiv e-prints*, July 2014.

[247] C. Ott. Analytic CCSN Waveforms: 1. Barmode. *LIGO-T1000553*, 2013.

[248] K. Kotake. Multiple physical elements to determine the gravitational-wave signatures of core-collapse supernovae. *Comptes Rendus Physique*, 14:318, 2013.

[249] C. D. Ott. TOPICAL REVIEW: The gravitational-wave signature of core-collapse supernovae. *Class. Quantum Grav.*, 26:063001, 2009.

[250] C. D. Ott. Probing the core-collapse supernova mechanism with gravitational waves. *Class. Quant. Grav.*, 26(20):204015, October 2009.

[251] J. Logue, C. D. Ott, I. S. Heng, P. Kalmus, and J. Scargill. Inferring Core-Collapse Supernova Physics with Gravitational Waves. *Physical Review D*, 86(4):044023, 2012.

[252] E. Abdikamalov, S. Gossan, A. M. DeMaio, and C. D. Ott. Measuring the angular momentum distribution in core-collapse supernova progenitors with gravitational waves. *Physical Review D*, 90(4):044001, 2014.

[253] W. J. Engels, R. Frey, and C. D. Ott. Multivariate regression analysis of gravitational waves from rotating core collapse. *Physical Review D*, 90(12):124026, December 2014.

[254] J. W. Murphy, C. D. Ott, and A. Burrows. A Model for Gravitational Wave Emission from Neutrino-Driven Core-Collapse Supernovae. *Astrophysical Journal*, 707:1173, 2009.

[255] B. Müller, H.-T. Janka, and A. Marek. A New Multi-dimensional General Relativistic Neutrino Hydrodynamics Code of Core-collapse Supernovae. III. Gravitational Wave Signals from Supernova Explosion Models. *Astrophysical Journal*, 766:43, 2013.

[256] K. N. Yakunin, P. Marronetti, A. Mezzacappa, S. W. Bruenn, C.-T. Lee, M. A. Chertkow, W. R. Hix, J. M. Blondin, E. J. Lentz, O. E. Bronson Messer, and S. Yoshida. Gravitational waves from core collapse supernovae. *Class. Quantum Grav.*, 27:194005, October 2010.

[257] T. Fischer, S. C. Whitehouse, A. Mezzacappa, F.-K. Thielemann, and M. Liebendörfer. The neutrino signal from protoneutron star accretion and black hole formation. *Astronomy & Astrophysics*, 499:1–15, 2009.

[258] C. D. Ott, C. Reisswig, E. Schnetter, E. O'Connor, U. Sperhake, F. Löffler, P. Diener, E. Abdikamalov, I. Hawke, and A. Burrows. Dynamics and Gravitational Wave Signature of Collapsar Formation. *Phys. Rev. Lett.*, 106:161103, 2011.

[259] S. E. Gossan, P. Sutton, A. Stuver, M. Zanolin, K. Gill, and C. D. Ott. Observing gravitational waves from core-collapse supernovae in the advanced detector era. *Phys. Rev. D*, 93:042002, Feb 2016.

[260] J. Aasi et al. Targeted search for Gravitational-Waves from Core-Collapse Supernovae in initial LIGO and Virgo data. *Submitted to Phys. Rev. D., LIGO-P1400208*, 2014.

[261] G. Pagliaroli, F. Vissani, E. Coccia, and W. Fulgione. Neutrinos from Supernovae as a Trigger for Gravitational Wave Search. *Phys. Rev. Lett.*, 103(3):031102, July 2009.

[262] J. F. Beacom and P. Vogel. Can a supernova be located by its neutrinos? *Physical Review D*, 60(3):033007, 1999.

[263] Pietro Antonioli, Richard Tresch Fienberg, Fabrice Fleurot, Yoshiyuki Fukuda, Walter Fulgione, et al. SNEWS: The Supernova Early Warning System. *New J.Phys.*, 6:114, 2004.

[264] S. Klimenko. Coherent WaveBurst 2G Update. *LIGO-G1400993*, 2014.

[265] C. D. Ott, E. Abdikamalov, P. Mösta, R. Haas, S. Drasco, E. P. O'Connor, C. Reisswig, C. A. Meakin, and E. Schnetter. General-relativistic Simulations of Three-dimensional Core-collapse Supernovae. *Astrophysical Journal*, 768:115, May 2013.

[266] C.L. Fryer, D.E. Holz, and S.A. Hughes. Gravitational Wave Emission from Core Collapse of Massive Stars. *Astrophysical Journal*, 565:430, 2002.

[267] IceCube. http://icecube.wisc.edu.

[268] T. Gaisser and F. Halzen. Icecube. *Ann. Rev. Nuc. Part. Sc.*, 64(1):101, 2014.

[269] Large Volume Detector, `http://www.bo.infn.it/lvd`.

[270] C. Vigorito [LVD Collaboration]. Galactic supernovae monitoring at LVD. *Nuc. Phys. B Proc. Suppl.*, 221:410, December 2011.

[271] Borexino, `http://borex.lngs.infn.it`.

[272] G. Alimonti et al. [BOREXINO Collaboration]. The Borexino detector at the Laboratori Nazionali del Gran Sasso. *Nuc. Inst. Meth. Phys. Res. A*, 600:568, March 2009.

[273] F Acernese et al. Search for gravitational waves associated with grb 050915a using the virgo detector. *Classical & Quantum Gravity*, 25(22):225001, 2008.

[274] F. Acernese et al. Gravitational wave burst search in the Virgo C7 data. *Classical & Quantum Gravity*, 26:085009, 2008.

[275] M. Ikeda et al. Search for Supernova Neutrino Bursts at Super-Kamiokande. *Astrophysical Journal*, 669:519, November 2007.

[276] Super-Kamiokande, `http://neutrino.phys.washington.edu/superk`.

[277] J. Powell, S. Gossan, Logue J., and I. S. Heng. Inferring the core-collapse supernova explosion mechanism with gravitational waves. *LIGO-P1600289*, 2016.

[278] E. O'Connor and C. D. Ott. Black Hole Formation in Failing Core-Collapse Supernovae. *Astrophysical Journal*, 730:70, April 2011.

[279] S. Mukherjee and L. Salazar. New Method for Enhanced Efficiency in Detection of Gravitational Waves from Supernovae Using Coherent Network of Detectors. *LIGO-P1400116*, 2014.

[280] D. Thornton, B. Stappers, M. Bailes, B. Barsdell, S. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, D. J. Champion, P. Coster, N. D'Amico, A. Jameson, S. Johnston, M. Keith, M. Kramer, L. Levin, S. Milia, C. Ng, A. Possenti, and W. van Straten. A Population of Fast Radio Bursts at Cosmological Distances. *Science*, 341:53–56, July 2013.

[281] E. Petroff, E. D. Barr, A. Jameson, E. F. Keane, M. Bailes, M. Kramer, V. Morello, D. Tabbara, and W. van Straten. Frbcat: The fast radio burst catalogue. *arXiv:1601.03547*.

[282] B. P. Abbott et al. *arXiv:1605.01707*, 2016.

[283] E. Petroff, E. F. Keane, E. D. Barr, J. E. Reynolds, J. Sarkissian, P. G. Edwards, J. Stevens, C. Brem, A. Jameson, S. Burke-Spolaor, S. Johnston, N. D. R. Bhat, P. Chandra, S. Kudale, and S. Bhandari. Identifying the source of perytons at the Parkes radio telescope. *Mon. Not. R. Astron. Soc.*, 451:3933, 2015.

[284] L. G. Spitler, P. Scholz, J. W. T. Hessels, S. Bogdanov, A. Brazier, F. Camilo, S. Chatterjee, J. M. Cordes, F. Crawford, J. Deneva, R. D. Ferdman, P. C. C. Freire, V. M. Kaspi, P. Lazarus, R. Lynch, E. C. Madsen, M. A. McLaughlin, C. Patel, S. M. Ransom, A. Seymour, I. H. Stairs, B. W. Stappers, J. van Leeuwen, and W. W. Zhu. A repeating fast radio burst. *Nature*, 531:202, 2016.

[285] E.F. Keane. Fast Radio Bursts - I: Initial Cogitation, 2014.

[286] V. Predoi, J. Clark, T. Creighton, E. Daw, S. Fairhurst, I. S. Heng, J. Kanner, T. Regimbau, P. Shawhan, X. Siemens, P. Sutton, A. Vecchio, D. White, and G. Woan. Prospects for joint radio telescope and gravitational-wave searches for astrophysical transients. *Classical and Quantum Gravity*, 27(8):084018, April 2010.

[287] V. Berezinsky, B. Hnatyk, and A. Vilenkin. Superconducting cosmic strings as gamma-ray burst engines. *Baltic Astronomy*, 13:289, 2004.

[288] Yun-Wei Yu, Kwong-Sang Cheng, Gary Shiu, and Henry Tye. Implications of fast radio bursts for superconducting cosmic strings, 2014.

[289] Tanmay Vachaspati. Cosmic sparks from superconducting strings. *Physical Review Letters*, 101(14):141301, Sep 2008.

[290] Thibault Damour and Alexander Vilenkin. Gravitational wave bursts from cosmic strings. *Phys. Rev. Lett.*, 85(18):3761–3764, Oct 2000.

[291] V. M. Lipunov and I. E. Panchenko. Pulsars revived by gravitational waves. *Astronomy & Astrophysics*, 312:937, August 1996.

[292] M.S. Pshirkov and K.A. Postnov. Radio precursors to neutron star binary mergings. *Astrophysics and Space Science*, 330(1):13–18, 2010.

[293] B. M. S. Hansen and M. Lyutikov. Radio and X-ray signatures of merging neutron stars. *MNRAS*, 322:695, April 2001.

[294] J. Moortgat and J. Kuijpers. Gravitational waves in magnetized relativistic plasmas. *Phys. Rev. D*, 70:023001, Jul 2004.

[295] J. Moortgat and J. Kuijpers. Indirect visibility of gravitational waves in magnetohydrodynamic plasmas. *Proceedings of the XXII Texas Symposium on Relativistic Astrophysics, Stanford University, Palo Alto, USA, December 13-17 2004*, pages 1225–1230, 2005.

[296] Lucia M. Franco, Bennett Link, and Richard I. Epstein. Quaking neutron stars. *The Astrophysical Journal*, 543(2):987, 2000.

[297] K.D. Kokkotas and B.G. Schmidt. Quasi-normal modes of stars and black holes. *Living Rev. Rel.*, 2:2, 1999.

[298] J. Middleditch, F. E. Marshall, Q. D. Wang, E. V. Gotthelf, and W. Zhang. Predicting the starquakes in psr j0537-ĂŞ6910. *The Astrophysical Journal*, 652(2):1531, 2006.

[299] Abbott, B. and others. Search for Gravitational Wave Bursts from Soft Gamma Repeaters. *Physical Review Letters*, 101:211102, 2008.

[300] E.F. Keane, M. Kramer, A.G. Lyne, B.W. Stappers, and M.A. McLaughlin. Rotating Radio Transients: new discoveries, timing solutions and musings. *Mon. Not. R. Astron. Soc.*, 415:3065, 2011.

[301] A.G. Lyne et al. Unusual glitch activity in the RRAT J1819?1458: an exhausted magnetar? *Mon. Not. R. Astron. Soc.*, 400:1439, 2009.

[302] P. Weltevrede, S. Johnston, and C.M. Espinoza. The glitch-induced identity changes of PSR J1119-6127. *AIP Conference Proceedings*, 1357:109, 2011.

[303] J. Aasi et al. Search for gravitational waves associated with gamma-ray bursts detected by the Inter-Planetary Network. 2014.

[304] J. Aasi et al. Methods and results of a search for gravitational waves associated with gamma-ray bursts using the GEO600, LIGO, and Virgo detectors. *Phys.Rev.*, D89(12):122004, 2014.

[305] J. Abadie, B. P. Abbott, R. Abbott, T. Accadia, F. Acernese, R. Adhikari, P. Ajith, B. Allen, G. Allen, E. Amador Ceron, and et al. All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run. *Phys. Rev. D*, 81(10):102001, May 2010.

[306] J. Abadie et al. Search for compact binary coalescences in LIGO and Virgo data from S5 and VSR1. *Physical Review D*, 82:102001, 2010.

[307] J. Abadie et al. Search for Gravitational Waves from Low Mass Compact Binary Coalescence in LIGO's Sixth Science Run and Virgo's Science Runs 2 and 3. *Phys.Rev.*, D85:082002, 2012.

[308] M. S. Briggs et al. Search for gravitational waves associated with gamma-ray bursts during LIGO science run 6 and Virgo science runs 2 and 3. *Astrophysical Journal*, 760:12, November 2012.

[309] L. Bildsten. Gravitational radiation and rotation of accreting neutron stars. *Astrophys.J.*, 501:L89, 1998.

[310] G. Ushomirsky, C. Cutler, and L. Bildsten. Deformations of accreting neutron star crusts and gravitational wave emission. *Mon.Not.Roy.Astron.Soc.*, 319:902, 2000.

[311] B. J. Owen. Maximum elastic deformations of compact stars with exotic equations of state. *Phys.Rev.Lett.*, 95:211101, 2005.

[312] C. Cutler. Gravitational waves from neutron stars with large toroidal B fields. *Phys.Rev.*, D66:084025, 2002.

[313] A. Melatos and D.J.B. Payne. Gravitational radiation from an accreting millisecond pulsar with a magnetically confined mountain. *Astrophys.J.*, 623:1044–1050, 2005.

[314] B. J. Owen, L. Lindblom, C. Cutler, B. F. Schutz, A. Vecchio, et al. Gravitational waves from hot young rapidly rotating neutron stars. *Phys.Rev.*, D58:084020, 1998.

[315] N. Andersson, K. D. Kokkotas, and N. Stergioulas. On the relevance of the r mode instability for accreting neutron stars and white dwarfs. *Astrophys.J.*, 516:307, 1999.

[316] D.I. Jones and N. Andersson. Gravitational waves from freely precessing neutron stars. *Mon.Not.Roy.Astron.Soc.*, 331:203, 2002.

[317] B. Abbott et al. Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: Results from the second LIGO science run. *Phys.Rev.*, D76:082001, 2007.

[318] R. Narayan. The birthrate and initial spin period of single radio pulsars. *Astrophysical Journal*, 319:162–179, August 1987.

[319] D. R. Lorimer. Binary and millisecond pulsars. *Living Reviews in Relativity*, 8(7), 2005.

[320] J. M. Cordes and D. F. Chernoff. Neutron Star Population Dynamics. II. Three-dimensional Space Velocities of Young Pulsars. *Astrophysical Journal*, 505:315–338, September 1998.

[321] R. N. Manchester, G. B. Hobbs, A. Teoh, and M. Hobbs. The Australia Telescope National Facility Pulsar Catalogue. *Astronomical Journal*, 129:1993–2006, April 2005. See also `http://www.atnf.csiro.au/research/pulsar/psrcat/`.

[322] B. Knispel and B. Allen. Blandford's Argument: The Strongest Continuous Gravitational Wave Signal. *Phys.Rev.*, D78:044031, 2008.

[323] B. Abbott et al. All-sky search for periodic gravitational waves in LIGO S4 data. *Phys.Rev.*, D77:022001, 2008.

[324] V. Dergachev. Description of PowerFlux Algorithms and Implementation, 2005. LIGO-T050186, available in `http://admdbsrv.ligo.caltech.edu/dcc/`.

[325] P. R. Brady and T. Creighton. Searching for periodic sources with LIGO. 2. Hierarchical searches. *Phys.Rev.*, D61:082001, 2000.

[326] V. Dergachev. On blind searches for noise dominated signals: a loosely coherent approach. *Class.Quant.Grav.*, 27:205017, 2010.

[327] V. Dergachev. Loosely coherent searches for sets of well-modeled signals. *Phys.Rev.*, D85:062003, 2012.

[328] B. Krishnan, A. M. Sintes, M. A. Papa, B. F. Schutz, S. Frasca, et al. The Hough transform search for continuous gravitational waves. *Phys.Rev.*, D70:082001, 2004.

[329] B. Abbott et al. The Einstein@Home search for periodic gravitational waves in LIGO S4 data. *Phys.Rev.*, D79:022001, 2009.

[330] J. Aasi et al. Application of a Hough search for continuous gravitational waves on data from the fifth LIGO science run. *Class.Quant.Grav.*, 31:085014, 2014.

[331] Llucia Sancho de la Jordana and Alicia M. Sintes. A chi**2 veto for continuous wave searches. *Class.Quant.Grav.*, 25:184014, 2008.

[332] S. Frasca, P. Astone, and C. Palomba. Evaluation of sensitivity and computing power for the Virgo hierarchical search for periodic sources. *Class.Quant.Grav.*, 22:S1013–S1019, 2005.

[333] P. Astone, S. Frasca, and C. Palomba. The short FFT database and the peak map for the hierarchical search of periodic sources. *Class.Quant.Grav.*, 22:S1197–S1210, 2005.

[334] C. Palomba, P. Astone, and S. Frasca. Adaptive Hough transform for the search of periodic sources. *Class.Quant.Grav.*, 22:S1255–S1264, 2005.

[335] F. Antonucci, P. Astone, S. D'Antonio, S. Frasca, and C. Palomba. Detection of periodic gravitational wave sources by Hough transform in the f versus f(.) plane. *Class.Quant.Grav.*, 25:184015, 2008.

[336] P. Jaranowski, A. Krolak, and B. F. Schutz. Data analysis of gravitational - wave signals from spinning neutron stars. 1. The Signal and its detection. *Phys.Rev.*, D58:063001, 1998.

[337] J. Aasi et al. Implementation of an F-statistic all-sky search for continuous gravitational waves in Virgo VSR1 data. *Class.Quant.Grav.*, 31:165014, 2014.

[338] B.P. Abbott et al. Einstein and Home search for periodic gravitational waves in early S5 LIGO data. *Phys.Rev.*, D80:042003, 2009.

[339] B.P. Abbott et al. Results of the deepest all-sky survey for continuous gravitational waves on LIGO S6 data running on the Einstein at Home volunteer distributed computing project. 2016.

[340] S. Walsh et al. A comparison of methods for the detection of gravitational waves from unknown neutron stars. 2016.

[341] S. Dhurandhar, B. Krishnan, H. Mukhopadhyay, and J. T. Whelan. Cross-correlation search for periodic gravitational waves. *Phys.Rev.*, D77:082001, 2008.

[342] J. Aasi, B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, and et al. Search of the Orion spur for continuous gravitational waves using a loosely coherent algorithm on data from LIGO interferometers. *Physical Review D*, 93(4):042006, February 2016.

[343] J. Abadie et al. All-sky Search for Periodic Gravitational Waves in the Full S5 LIGO Data. *Phys.Rev.*, D85:022001, 2012.

[344] M. Shaltev and R. Prix. Fully coherent follow-up of continuous gravitational-wave candidates. *Phys.Rev.*, D87(8):084057, 2013.

[345] J. Aasi et al. Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data. *Phys.Rev.*, D87(4):042001, 2013.

[346] J. Aasi et al. Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories. Preprint arXiv:1304.0670, 2013.

[347] B. Abbott et al. All-sky LIGO Search for Periodic Gravitational Waves in the Early S5 Data. *Phys.Rev.Lett.*, 102:111102, 2009.

[348] The LIGO Scientific Collaboration, the Virgo Collaboration, B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, and et al. Comprehensive All-sky Search for Periodic Gravitational Waves in the Sixth Science Run LIGO Data. *ArXiv e-prints*, May 2016.

[349] V. Dergachev. Novel universal statistic for computing upper limits in an ill-behaved background. *Phys.Rev.*, D87(6):062001, 2013.

[350] B. Abbott et al. First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform. *Phys.Rev.*, D72:102004, 2005.

[351] The LIGO Scientific Collaboration, the Virgo Collaboration, J. Aasi, B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, and et al. First low frequency all-sky search for continuous gravitational wave signals. *ArXiv e-prints*, October 2015.

[352] T. Accadia, F. Acernese, M. Agathos, P. Astone, G. Ballardin, et al. The NoEMi (Noise Frequency Event Miner) framework. *J.Phys.Conf.Ser.*, 363:012037, 2012.

[353] J. Aasi et al. Gravitational waves from known pulsars: results from the initial detector era. *Astrophys.J.*, 785:119, 2014.

[354] B.J. Owen. Detectability of periodic gravitational waves by initial interferometers. *Class.Quant.Grav.*, 23:S1–S8, 2006.

[355] J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, T. Adams, and et al. Narrow-band search of continuous gravitational-wave signals from Crab and Vela pulsars in Virgo VSR4 data. *Physical Review D*, 91(2):022004, January 2015.

[356] B. Abbott et al. Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO 600 and LIGO detectors. *Phys.Rev.*, D69:082004, 2004.

[357] B. Abbott et al. Limits on gravitational wave emission from selected pulsars using LIGO data. *Phys.Rev.Lett.*, 94:181103, 2005.

[358] B. Abbott et al. Upper limits on gravitational wave emission from 78 radio pulsars. *Phys.Rev.*, D76:042001, 2007.

[359] B. Abbott et al. Beating the spin-down limit on gravitational wave emission from the Crab pulsar. *Astrophys.J.*, 683:L45–L50, 2008.

[360] B.P. Abbott et al. Searches for gravitational waves from known pulsars with S5 LIGO data. *Astrophys.J.*, 713:671–685, 2010.

[361] J. Abadie et al. Beating the spin-down limit on gravitational wave emission from the Vela pulsar. *Astrophys. J.*, 737:93, 2011.

[362] Dupuis, R.J. *Bayesian Searches for Gravitational Waves from Pulsars*. PhD thesis, University of Glasgow, 2004. LIGO-P050014-00-R.

[363] M. Pitkin and G. Woan. Binary system delays and timing noise in searches for gravitational waves from known pulsars. *Phys.Rev.*, D76:042006, 2007.

[364] P. Jaranowski and A. Krolak. Search for gravitational waves from known pulsars using $\mathcal{F}$ and $\mathcal{G}$ statistics. *Class.Quant.Grav.*, 27:194015, 2010.

[365] P. Astone, S. D'Antonio, S. Frasca, and C. Palomba. A method for detection of known sources of continuous gravitational wave signals in non-stationary data. *Class.Quant.Grav.*, 27:194016, 2010.

[366] M. Pitkin, C. Gill, J. Veitch, E. Macdonald, and G. Woan. A new code for parameter estimation in searches for gravitational waves from known pulsars. *J.Phys.Conf.Ser.*, 363:012041, 2012.

[367] Gill, C. D. *Searching for gravitational waves from pulsars*. PhD thesis, University of Glasgow, 2012.

[368] P. Astone, A. Colla, S. D'Antonio, S. Frasca, and C. Palomba. Coherent search of continuous gravitational wave signals: extension of the 5-vectors method to a network of detectors. *J.Phys.Conf.Ser.*, 363:012038, 2012.

[369] P. Astone, A. Colla, S. D'Antonio, S. Frasca, and C. Palomba, 2012. poster at GWPAW12.

[370] J. Ming, B. Krishnan, M. A. Papa, C. Aulbert, and H. Fehrmann. Optimal directed searches for continuous gravitational waves. *Physical Review D*, 93(6):064011, March 2016.

[371] K. Wette et al. Searching for gravitational waves from Cassiopeia A with LIGO. *Class.Quant.Grav.*, 25:235011, 2008.

[372] J. Abadie et al. First search for gravitational waves from the youngest known neutron star. *Astrophys.J.*, 722:1504–1513, 2010.

[373] Pinkesh Patel, Xavier Siemens, Rejean Dupuis, and Joseph Betzwieser. Implementation of barycentric resampling for continuous wave searches in gravitational wave data. *Phys.Rev.*, D81:084032, 2010.

[374] The LIGO Scientific Collaboration, the Virgo Collaboration, B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, and et al. Search for continuous gravitational waves from neutron stars in globular cluster NGC 6544. *ArXiv e-prints*, 2016.

[375] J. Aasi et al. A directed search for continuous Gravitational Waves from the Galactic Center. *Phys.Rev.*, D88:102002, 2013.

[376] C. Chung, A. Melatos, B. Krishnan, and J. T. Whelan. Designing a cross-correlation search for continuous-wave gravitational radiation from a neutron star in the supernova remnant SNR 1987A. *Mon. Not. R. Astron. Soc.*, 414:2650, 2011.

[377] R.V. Wagoner. Gravitational radiation from accreting neutron stars. *Astrophys. J.*, 278:345, 1984.

[378] J. Papaloizou and J.E. Pringle. Gravitational radiation and the stability of rotating stars. *Mon. Not. R. Ast. Soc.*, 184:501, 1978.

[379] Nils Andersson. A New class of unstable modes of rotating relativistic stars. *Astrophys.J.*, 502:708–713, 1998.

[380] J.L. Friedman and S.M. Morsink. Axial instability of rotating relativistic stars. *Astrophys. J.*, 502:714, 1998.

[381] Y. Levin. Runaway Heating by r-Modes of Neutron Stars in Low-Mass X-Ray Binaries. *Astrophys. J.*, 517:328, 1999.

[382] G.B. Cook, S.L. Shapiro, and S.A. Teukolsky. Rapidly rotating neutron stars in general relativity: Realistic equations of state. *Astrophys. J.*, 424:823, 1994.

[383] D. Chakrabarty et al. Nuclear-powered millisecond pulsars and the maximum spin frequency of neutron stars. *Nature*, 424:42–44, 2003.

[384] M. Vigelius and A. Melatos. Gravitational-wave spin-down and stalling lower limits on the electrical resistivity of the accreted mountain in a millisecond pulsar. *Astrophys. J.*, 717:404, 2010.

[385] P. Arras and et al. Saturation of the r-Mode Instability. *Astrophys. J.*, 591:1129, 2003.

[386] A. L. Watts, B. Krishnan, L. Bildsten, and B. F. Schutz. Detecting gravitational wave emission from the known accreting neutron stars. *MNRAS*, 389:839–868, September 2008.

[387] N. Andersson, D.I. Jones, and W.C.G. Ho. Implications of an r mode in xte j1751?305: mass, radius and spin evolution. *Mon. Not. R. Ast. Soc.*, 442:1786, 2014.

[388] U. Lee. Excitation of a non-radial mode in a millisecond X-ray pulsar XTE J1751-305. *Mon. Not. R. Ast. Soc.*, 442:3037, 2014.

[389] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell. String axiverse. *Physical Review D*, 81(12):123530, June 2010.

[390] A. Arvanitaki and S. Dubovsky. Exploring the string axiverse with precision black hole physics. *Physical Review D*, 83(4):044026, February 2011.

[391] Hirotaka Yoshino and Hideo Kodama. Probing the string axiverse by gravitational waves from Cygnus X-1, 2014.

[392] J. Aasi et al. Gravitational waves from known pulsars: results from the initial detector era. *Astrophys.J.*, 785:119, 2014.

[393] H.J. Bulten et al. Gravitational waves from Sco X-1 : A comparison of search methods. in preparation.

[394] J. Aasi et al. Directed search for gravitational waves from Scorpius X-1 with initial LIGO data. *Physical Review D*, 91(6):062008, March 2015.

[395] J.T. Whelan et al. A Model-Based Cross-Correlation Search for Gravitational Waves from Scorpius X-1. in preparation, LIGO Publication LIGO-P00142 (2015).

[396] G. Meadors, B. Krishnan, J. Whelan, Y. Zhang, and M.A. Papa. Sco X-1 prospects with cross-correlation resampling. presentation at 2016 GWPAW meeting, Cape Cod, Massachusetts, LIGO Document G1600920 (2016).

[397] L. Sammut, C. Messenger, A. Melatos, and B. J. Owen. Implementation of the frequency-modulated sideband search method for gravitational waves from low mass x-ray binaries. *Physical Review D*, 89(4):043001, February 2014.

[398] S. M. Ransom, J. M. Cordes, and S. S. Eikenberry. A New search technique for short orbital period binary pulsars. *Astrophys.J.*, 589:911–920, 2003.

[399] C. Messenger and G. Woan. A Fast search strategy for gravitational waves from low-mass X-ray binaries. *Class.Quant.Grav.*, 24:S469–S480, 2007.

[400] S. Suvorova, L. Sun, A. Melatos, W. Moran, and R. J. Evans. Hidden Markov model tracking of continuous gravitational waves from a neutron star with wandering spin. *ArXiv e-prints*, June 2016.

[401] B Abbott et al. Upper limit map of a background of gravitational waves. *Phys. Rev. D*, 76:082003, 2007.

[402] B Abbott et al. Directional limits on persistent gravitational waves using LIGO S5 science data. *Phys. Rev. Lett.*, 107:271102, 2011.

[403] E. Goetz and K. Riles. An all-sky search algorithm for continuous gravitational waves from spinning neutron stars in binary systems. *Class.Quant.Grav.*, 28:215006, 2011.

[404] The LIGO Scientific Collaboration, the Virgo Collaboration, J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, T. Accadia, F. Acernese, K. Ackley, et al. First all-sky search for continuous gravitational waves from unknown sources in binary systems. *Phys. Rev.*, D90:062010, May 2014.

[405] Neunzert, A. and Riles, K. Improving the Sensitivity of Searches for Continuous Gravitational Waves from Galactic Neutron Stars in Binary Systems. presentation at 2016 April APS meeting, Salt Lake City, Utah, LIGO Document G1600025 (2016).

[406] B. Haskell, N. Andersson, C. D'Angelo, N. Degenaar, K. Glampedakis, W. C. G. Ho, P. D. Lasky, A. Melatos, M. Oppenoorth, A. Patruno, and M. Priymak. Gravitational waves from rapidly rotating neutron stars. *ArXiv e-prints*, July 2014.

[407] S. van der Putten. *Thermal lensing in Virgo and Polynomial search: an all-sky search for gravitational waves from spinning neutron stars in binary systems*. PhD thesis, Free University Amsterdam, 2011. `http://www.nikhef.nl/pub/services/newbiblio/theses.php`.

[408] A. Vicere and M. Yvert. First tests of a moment autocorrelation method to detect gw from pulsars in binary systems – virgo technical note vir-0292c-13, October 2013. Virgo technical note VIR-0292C-13 (October 2013).

[409] G. Meadors, E. Goetz, and K. Riles. Directed and all-sky continuous wave searches in advanced detectors: Scorpius X-1 and neutron stars in binary systems. presentation at June 2015 Amaldi meeting, Gwangju, Korea, LIGO Document G1500524 (2015).

[410] J. Aasi et al. Improved Upper Limits on the Stochastic Gravitational–Wave Background from 2009–2010 LIGO and Virgo Data. *prl*, 113:231101, 2014.

[411] B. P. Abbott et al. Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.*, 116:061102, Feb 2016.

[412] B. P. Abbott et al. Gw150914: Implications for the stochastic gravitational-wave background from binary black holes. *Phys. Rev. Lett.*, 116:131102, Mar 2016.

[413] E. W. Kolb & M. S. Turner. *The Early Universe*. Westview Press, 1994.

[414] A. A. Starobinskii. Spectrum of relic gravitational radiation and the early state of the universe. *JETP Lett.*, 30, 1979.

[415] R. Bar-Kana. Limits on Direct Detection of Gravitational Waves. *Phys. Rev. D*, 50, 1994.

[416] T. W. B. Kibble. Topology of cosmic domains and strings. *J. Phys.*, A9, 1976.

[417] T. Damour & A. Vilenkin. Gravitational radiation from cosmic (super)strings: bursts, stochastic background, and observational windows. *Phys. Rev. D*, 71, 2005.

[418] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys. Rev. D*, 81:104028, 2010.

[419] S. Olmez, V. Mandic, and X. Siemens. Anisotropies in the Gravitational-Wave Stochastic Background. *J. Cosmol. Astropart. Phys.*, 2012:009, 2011.

[420] A. Buonanno. Spectrum of relic gravitational waves in string cosmology. *Phys. Rev. D*, 55, 1997.

[421] V. Mandic & A. Buonanno. Accessibility of the Pre-Big-Bang Models to LIGO. *Phys. Rev. D*, 73, 2006.

[422] T. Regimbau. The astrophysical gravitational wave stochastic background. *Research in Astronomy and Astrophysics*, 11:369–390, April 2011.

[423] A. Buonanno, G. Sigl, G. G. Raffelt, H.-T. Janka, and E. Müller. Stochastic gravitational-wave background from cosmological supernovae. *Physical Review D*, 72(8):084001, October 2005.

[424] P. Sandick, K. A. Olive, F. Daigne, and E. Vangioni. Gravitational waves from the first stars. *Physical Review D*, 73(10):104024, May 2006.

[425] S. Marassi, R. Schneider, and V. Ferrari. Gravitational wave backgrounds and the cosmic transition from Population III to Population II stars. *Monthly Notices of the Royal astronomical Society*, 398:293–302, September 2009.

[426] X.-J. Zhu, E. Howell, and D. Blair. Observational upper limits on the gravitational wave production of core collapse supernovae. *Monthly Notices of the Royal astronomical Society*, 409:L132–L136, November 2010.

[427] T. Regimbau and J. A. de Freitas Pacheco. Cosmic background of gravitational waves from rotating neutron stars. *Astronomy and Astrophysics*, 376:381–385, September 2001.

[428] P. A. Rosado. Gravitational wave background from rotating neutron stars. *Physical Review D*, 86(10):104007, November 2012.

[429] T. Regimbau and J. A. de Freitas Pacheco. Gravitational wave background from magnetars. *Astronomy and Astrophysics*, 447:1–7, February 2006.

[430] E. Howell, T. Regimbau, A. Corsi, D. Coward, and R. Burman. Gravitational wave background from sub-luminous GRBs: prospects for second- and third-generation detectors. *Monthly Notices of the Royal astronomical Society*, 410:2123–2136, February 2011.

[431] S. Marassi, R. Ciolfi, R. Schneider, L. Stella, and V. Ferrari. Stochastic background of gravitational waves emitted by magnetars. *Monthly Notices of the Royal astronomical Society*, 411:2549–2557, March 2011.

[432] C.-J. Wu, V. Mandic, and T. Regimbau. Accessibility of the stochastic gravitational wave background from magnetars to the interferometric gravitational wave detectors. *Physical Review D*, 87(4):042002, February 2013.

[433] G Sigl. Cosmological gravitational wave background from phase transitions in neutron stars. *J. Cosmol. Astropart. Phys.*, JCAP04:002, 2006.

[434] J. C. N. de Araujo and G. F. Marranghello. Gravitational wave background from neutron star phase transition. *General Relativity and Gravitation*, 41:1389–1406, June 2009.

[435] V. Ferrari, S. Matarrese, and R. Schneider. Stochastic background of gravitational waves generated by a cosmological population of young, rapidly rotating neutron stars. *Monthly Notices of the Royal astronomical Society*, 303:258–264, February 1999.

[436] X.-J. Zhu, X.-L. Fan, and Z.-H. Zhu. Stochastic Gravitational Wave Background from Neutron Star r-mode Instability Revisited. *Astrophysical Journal*, 729:59, March 2011.

[437] E. Howell, D. Coward, R. Burman, D. Blair, and J. Gilmore. The gravitational wave background from neutron star birth throughout the cosmos. *Monthly Notices of the Royal astronomical Society*, 351:1237–1246, July 2004.

[438] A. J. Farmer & E. S. Phinney. The gravitational wave background from cosmological compact binaries. *Mon. Not. R. Ast. Soc.*, 346:1197, 2003.

[439] X.-J. Zhu, E. Howell, T. Regimbau, D. Blair, and Z.-H. Zhu. Stochastic Gravitational Wave Background from Coalescing Binary Black Holes. *Astrophysical Journal*, 739:86, October 2011.

[440] P. A. Rosado. Gravitational wave background from binary systems. *Physical Review D*, 84(8):084004, October 2011.

[441] S. Marassi, R. Schneider, G. Corvino, V. Ferrari, and S. Portegies Zwart. Imprint of the merger and ring-down on the gravitational wave background from black hole binaries coalescence. *Physical Review D*, 84(12):124037, December 2011.

[442] C. Wu, V. Mandic, and T. Regimbau. Accessibility of the gravitational-wave background due to binary coalescences to second and third generation gravitational-wave detectors. *Physical Review D*, 85(10):104024, May 2012.

[443] X.-J. Zhu, E. J. Howell, D. G. Blair, and Z.-H. Zhu. On the gravitational wave background from compact binary coalescences in the band of ground-based interferometers. *Monthly Notices of the Royal astronomical Society*, 431:882–899, May 2013.

[444] L Barack & C Cutler. Confusion noise from LISA capture sources. *Phys. Rev. D*, 70:122002, 2004.

[445] G Sigl & J Schnittman & A Buonanno. Gravitational-wave background from compact objects embedded in AGN accretion disks. *Phys. Rev. D*, 75:024034, 2007.

[446] M Maggiore. Gravitational Wave Experiments and Early Universe Cosmology. *Phys. Rept.*, 331:283, 2000.

[447] V Mandic, E Thrane, S Giampanis, and T Regimbau. Parameter Estimation in Searches for the Stochastic Gravitational-Wave Background. *Phys. Rev. Lett.*, 109:171102, 2012.

[448] N. Barnaby, E. Pajer, and M. Peloso. Gauge Field Production in Axion Inflation: Consequences for Monodromy, non-Gaussianity in the CMB, and Gravitational Waves at Interferometers. *Phys. Rev. D*, 85:023525, 2012.

[449] J L Cook and L Sorbo. Particle production during inflation and gravitational waves detectable by ground-based interferometers. *Phys. Rev. D*, 85:023534, 2012.

[450] B. Abbott et al. Searching for Stochastic Gravitational Waves with LIGO. *Nature*, 460:990, 2009.

[451] J. Aasi et al. Constraints on cosmic strings from the LIGO-Virgo gravitational-wave detectors. *Physical Review Letters*, 112:131101, 2014.

[452] C. Wu, V. Mandic, and T. Regimbau. Accessibility of the gravitational-wave background due to binary coalescences to second and third generation gravitational-wave detectors. *Phys. Rev. D*, 85:104024, 2012.

[453] Kazuhiro Hayama and Atsushi Nishizawa. Model-independent test of gravity with a network of ground-based gravitational-wave detectors. *Phys. Rev. D*, 87:062003, Mar 2013.

[454] C. Brans and R.H. Dicke. Mach's principle and a relativistic theory of gravitation. *Phys.Rev.*, 124:925–935, 1961.

[455] Y. Fujii and K. Maeda. *The Scalar-Tensor Theory of Gravitation*. Cambridge Monograph on Mathematical Physics. Cambridge University Press, Cambridge, 2002.

[456] Thomas P. Sotiriou and Valerio Faraoni. f(R) Theories Of Gravity. *Rev.Mod.Phys.*, 82:451–497, 2010.

[457] Antonio De Felice and Shinji Tsujikawa. f(R) Theories. *Living Rev. Relativity*, 13(3), 2010.

[458] Matt Visser. Mass for the graviton. *General Relativity and Gravitation*, 30(12):1717–1728, 1998.

[459] Claudia de Rham, Gregory Gabadadze, and Andrew J. Tolley. Resummation of massive gravity. *Phys. Rev. Lett.*, 106:231101, Jun 2011.

[460] B Abbott et al. Searching for a Stochastic Background of Gravitational Waves with the Laser Interferometer Gravitational-Wave Observatory. *Astrophys. J.*, 659:918, 2007.

[461] J. Abadie et al. Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz. *Phys. Rev. D*, 85:122001, 2012.

[462] J. Aasi et al. Searching for stochastic gravitational waves using data from the two colocated LIGO Hanford detectors. *prd*, 91:022003, 2015.

[463] Bruce Allen and Joseph D. Romano. Detecting a stochastic background of gravitational radiation: Signal processing strategies and sensitivities. *Phys.Rev.*, D59:102001, 1999.

[464] N Christensen. Measuring the Stochastic Gravitational Radiation Background with Laser Interferometric Antennas. *Phys. Rev. D*, 46:5250, 1992.

[465] B Abbott et al. Analysis of first LIGO science data for stochastic gravitational waves. *Phys. Rev. D*, 69:122004, 2004.

[466] D Meacher, E Thrane, and T Regimbau. Statistical properties of astrophysical gravitational-wave background. *Phys. Rev. D*, 89:084063, 2014.

[467] D. Meacher et al. A Mock Data and Science Challenge for Detecting an Astrophysical Stochastic Gravitational Wave Background with Advanced LIGO and Advanced Virgo. *Physical Review D*, 92:063002, 2015.
`https://dcc.ligo.org/LIGO-P1500078`.

[468] E Thrane, N Christensen, and R Schofield. Correlated magnetic noise in global networks of gravitational-wave interferometers: observations and implications. *Phys. Rev. D*, 87:123009, 2013.

[469] A Ain, P Dalvi, and S Mitra. Fast gravitational wave radiometry using data folding. 2015. `http://xxx.tau.ac.il/abs/1504.01714`.

[470] E Thrane, S Mitra, N Christensen, V Mandic, and A Ain. All-sky, narrowband, gravitational-wave radiometry with folded data. *Accepted in Phys. Rev. D*, 2015.

[471] D Talukder, E Thrane, S Bose, and T Regimbau. Measuring neutron-star ellipticity with measurements of the stochastic gravitational-wave background. *Accepted for publication in Phys. Rev. D*, 2014. `http://arxiv.org/abs/1404.4025`.

[472] T Regimbau & B Chauvineaux. A stochastic background from extra-galactic double neutron stars. *Class. Quantum Grav.*, 24:627, 2007.

[473] E Howell et al. The gravitational wave background from neutron star birth throughout the cosmos. *Mon. Not. R. Ast. Soc.*, 351:1237, 2004.

[474] V Ferrari & S Matarrese & R Schneider. Gravitational wave background from a cosmological population of core-collapse supernovae. *Mon. Not. R. Ast. Soc.*, 303:258, 1999.

[475] V Ferrari & S Matarrese & R Schneider. Stochastic background of gravitational waves generated by a cosmological population of young, rapidly rotating neutron stars. *Mon. Not. R. Ast. Soc.*, 303:258, 1999.

[476] T Regimbau & J A de Freitas Pacheco. Cosmic background of gravitational waves from rotating neutron stars. *Astron. Astrophys.*, 376:381, 2001.

[477] T Regimbau & J A de Freitas Pacheco. Gravitational wave background from magnetars. *Astron. Astrophys.*, 447:1, 2006.

[478] J. Aasi et al. Constraints on cosmic strings from the LIGO-Virgo gravitational-wave detectors. *Phys.Rev.Lett.*, 112:131101, 2014.

[479] C. Wu, V. Mandic, and T. Regimbau. Accessibility of the stochastic gravitational wave background from magnetars to the interferometric gravitational wave detectors. *Phys. Rev. D*, 87:042002, 2013.

[480] E Thrane, N Christensen, R M S Schofield, and A Effler. Correlated noise in networks of gravitational-wave detectors: subtraction and mitigation. *Phys. Rev. D*, 90:023013, 2014.

[481] E Thrane, V Mandic, and N Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. *Phys. Rev. D*, 91:104021, 2015.

[482] R Prix, S Giampanis, and C Messenger. Search method for long-duration gravitational-wave transients from neutron stars. *Phys. Rev. D*, 84:023007, 2011.

[483] C A van Eysden and A Melatos. Gravitational radiation from pulsar glitches. *Class. Quantum Grav.*, 25:225020, 2008.

[484] M F Bennett, C A van Eysden, and A Melatos. Continuous-wave gravitational radiation from pulsar glitch recovery. *Mon. Not. R. Ast. Soc.*, 409:1705, 2010.

[485] A G Lyne, S L Shemar, and F G Smith. Statistical studies of pulsar glitches. *Mon. Not. R. Ast. Soc.*, 315:534, 2000.

[486] K Kashiyama and K Ioka. Magnetar asteroseismology with long-term gravitational waves. *Phys. Rev. D*, 83:081302, 2011.

[487] Y Levin and M van Hoven. On the excitation of f modes and torsional modes by magnetar giant flares. *Mon. Not. R. Ast. Soc.*, 418:659, 2011.

[488] P Jaranowski, A Kr'olak, and B F Schutz. Data analysis of gravitational-wave signals from spinning neutron stars: The signal and its detection. *Phys. Rev. D*, 58:063001, 1998.

[489] D I Jones and N Andersson. Gravitational waves from freely precessing neutron stars. *Mon. Not. R. Ast. Soc.*, 331:203, 2002.

[490] L Gualtieri, R Ciolfi, and V Ferrari. Structure, deformations and gravitational wave emission of magnetars, 2010. Prepared for 19th International Conference on General Relativity and Gravitation (GR19), Mexico City, Mexico, July 5-9, 2010, arxiv/1011.2778.

[491] S Dall'Osso, S N Shore, and L Stella. Early evolution of newly born magnetars with a strong toroidal field. *Mon. Not. R. Ast. Soc.*, 398:1869, 2009.

[492] N Andersson and K D Kokkotas. The r-mode instability in rotating neutron stars. *Int. J. Mod. Phys. D*, 10:381, 2001.

[493] R Bondarescu, S A Teukolsky, and I Wasserman. Spinning down newborn neutron stars: Nonlinear development of the r-mode instability. *Phys. Rev. D*, 79:104003, 2009.

[494] A Melatos and M Priymak. Gravitational radiation from magnetically funnelled supernova fallback onto a magnetar. *Astrophys. J.*, 794:170, 2014.

[495] F Camilo, S M Ransom, S Chatterjee, S Johnston, and P Demorest. PSR J1841-0500: A Radio Pulsar That Mostly Is Not There. *Astrophys. J.*, 746:63, 2012.

[496] L Bildsten. Gravitational radiation and rotation of accreting neutron stars. *Astrophys. J. Lett.*, 501:L89, 1998.

[497] A Arvanitaki, M Baryakhtar, and X Huang. Discovering the qcd axion with black holes and gravitational waves. *Phys. Rev. D*, 91:084011, 2015.

[498] T. Prestegard and E. Thrane. Burstegard: a hierarchical clustering algorithm. *LIGO DCC*, page L1200204, 2012. `https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=93146`.

[499] M. Coughlin, E. Thrane, and N. Christensen. Detecting compact binary coalescences with seedless clustering. *Phys.Rev.*, D90(8):083005, 2014.

[500] P. Meyers, M. W. Coughlin, and J. Luo. Investigating Environmental Noise Using the Stochastic Transient Analysis Multi-Detector Pipeline (STAMP-PEM), 2014. `https://dcc.ligo.org/LIGO-G1400354`.

[501] M. Coughlin for the LIGO Scientific Collaboration and the Virgo Collaboration. Identification of long-duration noise transients in LIGO and Virgo. *Class. Quantum Grav.*, 28:235008, 2011.

[502] LIGO calibration web page. `http://blue.ligo-wa.caltech.edu/engrun/Calib_Home/`.

[503] R. Adhikari *et al.*, “Calibration of the LIGO Detectors for the First LIGO Scientific Run”, LIGO-T030097 (2003);
G. Gonzalez *et al.*, “Calibration of the LIGO Detectors for S2”, LIGO-T040060 (2004);
G. Gonzalez *et al.*, “Calibration of the LIGO Detectors for S3”, LIGO-T050059 (2005);
A. Dietz *et al.*, “Calibration of the LIGO detectors for S4”, LIGO-T050262-01-D (2006).

[504] Y. Aso et al. Accurate measurement of the time delay in the response of the ligo gravitational wave detectors. *Classical and Quantum Gravity*, 26(5):055010, 2009.