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The LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics (Summer 2019 edition)

The LSC-Virgo Data Analysis Working Groups
and Data Analysis Council

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1 Overview and Executive Summary

Gravitational wave (GW) searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo Collaboration are organized into four working groups. The **Compact Binary Coalescence (CBC)** group searches for and studies signals from merging neutron stars and black holes by filtering the data with waveform templates. The **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 Gravitational-Wave Background (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin.

These groups also collaborate with the **Detector Characterization (DetChar)** group, which interfaces with the detector commissioning teams and works to improve GW signal searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals, as well as with the **Calibration** and **Computing & Software** teams.

Many members of the LSC and Virgo participate in one or more of the astrophysical search groups (CBC, Burst, CW, SGWB) and data analysis support operations groups (DetChar, Calibration, Computing & Software). Each working group is led by either two or three Co-Chairs, with at least one from each collaboration. (Data analysis will be increasingly coordinated with KAGRA Collaboration members in the coming year.) Internal review of science results is led and coordinated by a pair of Review Co-Chairs (one each from the LSC and Virgo) for each of the four astrophysical search groups. Each collaboration also appoints a Data Analysis Coordinator. All of these Co-Chairs, together with the Data Analysis Coordinators and Spokespersons (*ex officio*) from each collaboration, constitute the Data Analysis Council (DAC). The working groups have also established many subgroups (teams) focusing on various science goals and development activities, and these subgroups are typically led by two people each. Several of these subgroups span two or more working groups where the science suggests overlap in sources or methods.

FTE-months: 8.0 (DAC co-chairs)

This ***LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics***, which is updated yearly, describes the planned activities of the members of the four astrophysical search working groups, including science goals and methods. The subsections in sections 2 through 10 contain "activity plans" with a wide range of themes. Beginning with this 2019 version, each activity plan has a prefix which associates it with either Section 2 or Section 4 of the LIGO Scientific Collaboration Program 2019-2020:

- Section 2, *Scientific Operations and Scientific Results* (prefix "Op-"), includes all activities which we plan to implement in the production of observational results of the current Observing run 3 (O3), expected to occur before the completion of the public release of the O3 data set, 18 months after the end of data collection.
- Section 4, *Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics: Enhanced Analysis Methods* (prefix "LT-") includes all longer-term developments which we will pursue to advance the scientific frontiers of GW observational science in a post-O3 perspective.

The LSC Program Committee and Virgo Program Committee set specific goals for collaboration work on an annual basis, using this white paper and other inputs. For 2019, the *LSC-Virgo White Paper on GW Data Analysis and Astrophysics* only covers the activities of the four astrophysical search groups. LSC and Virgo activities in the domains of Commissioning, Calibration, Computing, Detector Characterization, LSC Fellows program, and Run Planning can be found in the *LSC-Virgo Operations White Paper* (LIGO-T1900521, VIR-0810A-19).

Direct detection of gravitational waves has followed decades of development for both instrumentation and data analysis methods. Substantial advances were made using data collected by the initial LIGO detectors

(2002–2010) and the initial Virgo detector (2007–2011), but no GW signals were detected. The era of GW detection, GW astronomy and astrophysics was enabled by the Advanced LIGO and Advanced Virgo upgrades. The first Advanced LIGO observing run, O1, began in September 2015 and immediately yielded the first detected event, GW150914. The second observing run (O2) took place in 2016–17, with Advanced Virgo joining the run for the month of August 2017. At the time of writing this White Paper, almost all the planned scientific analyses of the O1 and O2 data have been published, including the GWTC-1 catalog of detected events [1]. The third observing run (O3) began on April 1, 2019, with both LIGO detectors and the Virgo detector collecting data with better sensitivity than ever before. The O3 run will be divided roughly in half by a month-long commissioning break in October 2019. The data collected before the break is referred to as O3a, while the data after the break will be O3b. Some analyses will be run and published on each half run, while others will use the entire O3 data set.

Epoch	Run Name	Run Duration	Binary Neutron Star (BNS) Range (Mpc)		$E_{\mathrm{GW}} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		
			LIGO	Virgo	LIGO	Virgo	
2015–16	O1	4 months	80	–	50	–	actual
2016–17	O2	9 months	100	30	60	25	actual
2019–20	O3	12 months	110–130	50	80–90	35	actual
2021–23	O4	12 months	160–190	90–120	110–120	65–80	projected
2024–26	O5	TBD	330	150–160	210	100–155	projected

Table 1: Observing schedule, actual and expected sensitivities for the Advanced LIGO and Virgo detectors. Adapted from *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, curated by the LSC-Virgo Joint Run Planning Committee.

Scientific Operations and Observational Results

LSC-Virgo scientific activities which we plan to implement in the production of observational results of the current Observing run 3 are summarized in Table 2, by search group, and prioritized 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 lower detection probability but high scientific payoff.

Computing needs and resource allocations are derived, in part, from the science priorities presented in this table. Scientific motivations, details on methods and strategies for result validation are provided in the **activity plans** included in the later sections of this white paper.

We note that the LSC and Virgo Collaboration have adopted a *Multiple Pipeline Policy* [LIGO-M1500027], which calls for 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.

	LSC-Virgo Astrophysics Search Working Group			
	Burst	CBC	CW	SGWB
Highest priority	Search for short-duration GW bursts (both online and offline)	Cataloging detections of coalescence of neutron star and black hole binaries and their meaured parameters	Searches for high-interest known pulsars, e.g. Crab, Vela	Searches for an isotropic stochastic GW background
	Search for long-duration GW bursts	Characterizing the astrophysical distribution of compact binaries	Directed searches for high-interest point sources, e.g. Cassiopeia A, Scorpius X-1	Directional searches for anisotropic stochastic GW backgrounds
	Responding to exceptional GW burst and multi-messenger detections	Responding to exceptional CBC detections	All-sky searches for unknown sources, either isolated or in binary systems	Detector characterization, data quality, and correlated noise studies specific to SGWB searches
	Searches without templates from GWs from binary black holes	Public alerts to enable multi-messenger astronomy	Long-transient searches for emission from nearby post-merger neutron stars	
	GW burst signal characterization	Multimessenger search for CBC-GRB coincidences	Follow-up searches of any promising candidates found by other searches	
		Testing General Relativity with compact binaries	Detector characterization, data preparation, scientific software maintenance	
		Measuring the neutron star equation of state		
		Determination of the Hubble constant		
High priority	Triggered multi-messenger searches	Improved searches for intermediate mass black hole binaries and intermediate mass-ratio inspirals	Searches for other known pulsars, and non-tensor polarisations	Search for very long transients ($\sim$ 10 hr – days)
	Search for BNS post-merger signals	Search for sub-solar mass compact binary coalescences	Directed searches for other point sources	Data folding for efficient SGWB searches
	All-sky cosmic string search		Long-transient searches for emission from distant post-merger neutron stars	
Additional priority		CBC searches for binary mergers associated with fast radio bursts and high energy neutrinos	Searches for long-lived transient emission following a known pulsar glitch	
		Optimized search for stochastic background of gravitational waves from CBCs	Searches for continuous emission from axion clouds around black holes	

Table 2: **Scientific Operations and O3 Observational Results** priorities of the LIGO Scientific Collaboration and Virgo Collaboration, for the four astrophysical search groups: Burst, Compact Binary Coalescence (CBC), Continuous Waves (CW), and Stochastic Gravitational-Wave Background (SGWB). The targets are grouped into three categories (highest priority, high priority, additional priority) based on their detection potential. There is no additional ranking within each category in this table.

Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

Longer term developments which are pursued to advance the scientific frontiers of GW observational science in a post-O3 perspective are summarized in Table 3, by search group, and classified in two categories:

- **Essential:** developments considered necessary steps for enhancing the scientific return of future observing runs.
- **Exploratory:** developments which can further the science potential of future observing runs.

	LSC-Virgo Astrophysics Search Working Group			
	Burst	CBC	CW	SGWB
Essential	Improvement of existing pipelines and methods for GW burst searches	Parameter estimation acceleration	Further improvement and optimization of existing data analysis pipelines	Search for stochastic background from compact binary coalescence
	Plans for the detection of exceptional multi-messenger sources	Essential improvements to waveform models	Development of model-robust/agnostic data analysis methods	Implications and astrophysical modeling
		Improved models of population inference		Component separation
		Improvements to statistical measurement of the Hubble constant		All-sky all-frequency search for unmodeled persistent sources
		Essential enhancements to all-sky searches		
Exploratory	Development of new methods for GW burst searches	Research and development in parameter estimation methodology	Development of new and potentially more sensitive data analysis methods	Fully Bayesian stochastic search
		New tests for exotic black hole physics	Use mock data challenges to compare data analysis pipelines	Component separation using narrowband maps
		Long-term improvements to waveform models		Models for anisotropic backgrounds
		Robust population inference with marginal events		Dark photon search
		Real-time cosmology calculation		
		Exploratory enhancements to all-sky searches		

Table 3: **Enhanced Analysis Methods for Advancing Frontiers**: longer term R&D activities of the LIGO Scientific Collaboration and Virgo Collaboration, for the four astrophysical search groups: Burst, Compact Binary Coalescence (CBC), Continuous Waves (CW), and Stochastic Gravitational-Wave Background (SGWB). The targets are grouped into two categories (essential, exploratory). There is no ranking within each category in this table.

1.1 Searches for Generic Transients, or Bursts

FTE-months: 12.0 (Burst group co-chairs)

FTE-months: 4.0 (Burst review chairs)

The mission of the Burst group is to detect gravitational wave transients, or *bursts*, and to gain new information on populations, emission mechanisms, and source physics of the associated astrophysical objects. 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-modeled signals such as core-collapse supernovae (CCSN) 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 (GRBs) could be associated with a gravitational wave transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, the group employs 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, each search 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.

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. A variety of targeted searches are designed to increase sensitivity to expected classes of signals. Therefore, the group's science program involves an active collaboration with the theoretical astrophysics, source modeling, and numerical relativity communities.

Many potential gravitational-wave burst sources should also be observable in other astronomy channels, including γ-ray, X-ray, optical, radio, and 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 *multi-messenger* 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. An important component of this connection utilizes burst searches running in low-latency, with latencies of minutes to hours, and providing information on transient GW candidates to the astronomical community. The binary neutron star merger GW170817 illustrated the scientific value of this approach.

Once a confident gravitational-wave transient is identified, characterizing its properties becomes an important goal of the group. This includes producing waveform reconstruction, polarization, and source localization estimates for all observed transients. This information can then be used to learn about the nature of the astrophysical source.

1.1.1 Scientific Operations and O3 Observational results

The Scientific Operations and O3 Observational Results priorities of the Burst group are:

1. **Highest Priority**
    - **Search for short-duration GW bursts (both online and offline):** The Burst group will search for a broad class of short duration transients. Deliverables include low-latency triggers for EM follow-up, and papers describing search results. [Sections Op-2.1, Op-6.1]
    - **All-sky long duration search:** The Burst group will search for a broad class of long-duration transients. Deliverables include papers describing the search results. [Section Op-2.2]
    - **Responding to exceptional GW burst and multi-messenger detections (CCSN, BNS, GRB, Magnetar Flare, Neutrino):** In the event of an exceptional GW burst or astrophysical event with a reasonable expectation for detecting gravitational waves, the group will deliver a detection statement (or non-detection statement) in a timely manner, as well as waveform reconstruction and signal interpretation. Examples include a galactic core-collapse supernova, an unusually close binary neutron star merger or gamma-ray burst, or a highly energetic magnetar flare. [Sections Op-2.6, Op-2.5, Op-7.3, Op-7.5, Op-7.1]
    - **Searches without templates from GWs from binary black holes:** Although most expected BBH mergers will also be detected with CBC searches, burst algorithms are sensitive to a range of features not included in current template banks, including higher order modes, eccentricity, and spin precession. This is important to detect some classes of BBH events. Deliverables include the results of searches targeting both stellar mass and intermediate mass ($M > 100\ M_\odot$) black hole systems, with results to be included in papers written jointly with the CBC group. [Sections Op-2.3, Op-7.2]
    - **GW burst signal characterization:** For detected transients, a coherent waveform reconstruction, polarization estimates, and source localization enable many potential investigations. Deliverables include producing waveform reconstructions and localizations for all detected transients. [Section Op-2.4]
2. **High Priority**
    - **Triggered multi-messenger searches (CCSN, GRB, Magnetar Flare, Neutrino, Fast Radio Burst):** Using a known astrophysical event as a target can increase the sensitivity of a GW search, typically by 10-30% in range. The group will pursue a number of triggered searches. This includes some sub-threshold searches. Deliverables include papers describing the search results. [Sections Op-2.6, Op-2.5, Op-7.3, Op-7.5, Op-7.4]
    - **Search for BNS post-merger signals:** Following a BNS detection, the group will search for a post-merger signal. Finding (or limiting) such a signal provides a powerful equation-of-state measurement. Deliverables include the result of a search for a post-merger signal after each nearby BNS detection. [Sections Op-7.6, Op-7.1]
    - **All-sky cosmic string search:** The group will search for signals from cosmic strings, and interpret any upper limits as constraints on string parameters. Deliverables include papers describing search results. [Section Op-8.1]

Several of these science targets – including binary black hole mergers, gamma-ray bursts, and low-latency trigger production – overlap with the CBC group, while others – including long transient and cosmic string searches – overlap with the stochastic group. Joint teams are working together across the multiple groups on these targets.

1.1.2 Advanced Analysis Methods for Advancing Frontiers

The two main levels of longer term R&D activities of the Burst group comprise:

1. **Essential**
   - **Improvement of existing pipelines and methods for GW burst searches:** The group will maintain and improve the pipelines employed in GW burst searches and the methods used to produce high-priority results. Deliverables include technical notes and papers describing these improvements.
   - **Plans for the detection of exceptional multi-messenger sources:** In advance of an exceptional astrophysical event, the group will make plans for what types of statements to make in case of a multi-messenger detection, and develop software that will be used to produce the results.
2. **Exploratory**
   - **Development of new methods for GW burst searches:** The group will develop new methods and software to look for GW burst signals. Deliverables include technical notes and papers describing the algorithms and data analysis methods. Examples include searches for GW bursts with polarization states not allowed by General Relativity, GW memory effects and machine learning algorithms.

1.2 Searches for Signals from Compact Binary Coalescences

FTE-months: 12.0 (CBC group co-chairs)

FTE-months: 4.0 (CBC review chairs)

As of this writing, analyses of the first observing run (O1) and the second observing run (O2) have yielded the deteciton of several binary black hole coalescences and a binary neutron star merger. The latter event was observed nearly simultaneously in gamma-rays, and, within a day, an optical counterpart was discovered; this was followed by observations across the entire electromagnetic spectrum. The third observing run (O3) is now underway and is actively producing open public alerts to enable electromagnetic follow-up of compact binary coalescence. We are preparing to do more detailed estimation of population distributions of binary masses and spins and more sensitive tests of general relativity using a much larger statistical sample of signals; more precise measurements of neutron star (NS) equation of state through measurment of tidal interactions of neutron star binaries; and improved measurements of the Hubble constant through direct and statistical methods. Furthermore, we anticipate discovery of entirely new source classes such as coalescing black-hole + neutron-star binaries within the next few years, and we also target sources such as intermediate mass binary black holes and sub-solar mass binary black holes. The Compact Binary Coalescence (CBC) group aims to discover additional 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 the CBC 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 with analytical and numerical relativity. 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. A tremendous human effort is required to develop, deploy, run and interpret the results of low-latency and offline searches 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.

1.2.1 Scientific Operations and O3 Observational results

The Scientific Operations and O3 Observational Results priorities of the CBC group are:

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 new detections of binary neutron stars, the first detection of a neutron-star + black-hole binary, or intermediate-mass or sub-solar 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, improved measurement of the nuclear equation of state. Binaries with observed electromagnetic counterparts can significantly improve our estimate of Hubble constant using the standard-siren distance estimate.
   - **Producing a catalogue of detected compact binaries**.

     We will produce a summary of all compact binaries detected during each observing run 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 modeling with comparison to numerical relativity simulations. The catalog completeness will be improved by including uncertain signals along with their estimated significance.

     Eccentric binary systems are another potential class of source where the searches and waveforms are less mature. Templated searches and unmodeled searches can be combined to allow for more robust searches over a range of eccentricity.
   - **Characterizing the astrophysical distributions of compact objects**.

     As the number of detections 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 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 from general relativity such as the no-hair and area theorems, Lorentz violations of the graviton, and the speed of gravitational waves. As more detectors are added to the network we will also be able to make improved tests of the polarization states of gravitational waves.

- **Public alerts to enable multimessenger astronomy**.

  Observations of an electromagnetic or neutrino counterparts to a gravitational wave signal are of huge astrophysical importance to the field, so we will continue to pursue multi-messenger astronomy by providing public alerts to the astronomical community. This requires the continued development of low-latency pipelines for detection, localization, and estimation of parameters of sources, automatic detector quality checks, and the infrastructure associated with collating and distributing information about detection candidates.

- **Multimessenger search for gravitational waves associated with gamma-ray bursts**.

  The coincident detection of a gravitational wave with a gamma-ray burst ranks among the highest impact observations in the compact binary field. We will continue performing a deep coherent search for gravitational waves focused on the sky position of any known gamma-ray bursts, and pursue joint searches for gravitational-wave and GRB signals.

- **Probing the properties of matter in the extremes of physical limits**.

  Binary coalescences involving neutron stars are a unique laboratory for studying the behaviour of matter at super-nuclear densities and pressures. We will refine methods of constraining the neutron star equation of state by measuring its observable effects on the inspiral, merger and post-merger phases of the coalescence signal, and apply these to forthcoming neutron star merger observations.

- **Determination of the Hubble constant**.

  Gravitational waves provide a new way to measure the distance of extra-galactic binary coalescences. When these events are also observed electromagnetically, and the redshift of the host galaxy is measured, an estimate of the Hubble constant can be obtained. As such observations accumulate, this method is expected to provide a competitive and independent method for obtaining the Hubble constant. In addition, a statistical approach involving spatial correlations with a galaxy catalog can be used for merger events when no identified counterpart is available. With new observations, we will improve our estimate of the Hubble constant.

To enable these highest-priority activities we will engage in research and developemnt in infrastructure enabling low-latency generation of public alerts, compact binary coalescence search pipelines and parameter estimation, externally-triggered searches, waveform modelling, rate and population inference, tests of general relativity, measurement of cosmological parameters, and measurement of neutron star equation of state.

2. **High priority**

High priority activities are those which are less certain to produce a significant result in the near term, but where the potential payoff would be high.

- **Improved searches for intermediate mass black hole binaries & intermediate mass-ratio inspirals**.
  A goal of the CBC group is to search for intermediate mass black hole binaries. Especially at the highest masses, the success of any search will be sensitive to the effects of higher order modes and precession in the waveforms. An extension of the intermediate mass black hole binaries research is the development of refined searches for intermediate-mass-ratio inspirals and waveforms to describe them.
- **Search for sub-solar mass compact binary coalescences**.
  A speculative source is black hole binaries (or other compact object binaries) having component masses below one solar mass. Primordial black holes could be one channel by which such systems are formed, but there are other possibilities. Such systems might possibly constitute some fraction of the dark matter. A search for sub-solar mass binaries could reveal the existance of a new class of object, or place stronger constraints on the fraction of dark matter explained by sub-solar mass black hole binaries.

3. **Additional priority**

   Additional priority activities are activities that the Compact Binary Coalescence (CBC) group will undertake if resources are available.

   - **Multimessenger search for gravitational waves associated with fast radio bursts and high-energy neutrinos**.
     It is possible that fast radio bursts and high-energy neutrinos are produced during compact binary coalescence. The method for performing deep searches for gravitational waves associated with gamma-ray bursts can be extended to explore periods of time around triggers produced by fast radio bursts or high-energy neutrinos. Though the methods are similar, the time window to be explored will need to be reassessed.
   - **Stochastic background of gravitational waves from compact binary coalescences**.
     The superposition of a large number of weak signals arising from compact binary coalescences in the distant universe will produce a stochastic background of gravitational radiation. Such a background produced by binary black hole mergers is not truly continuous, though, as it originates from discrete signals that are not fully overlapping in time, and an optimized statistical search for such sub-threshold signals will be pursued.

1.2.2 Advanced Analysis Methods for Advancing Frontiers

The two main levels of longer term R&D activities of the CBC group comprise:

1. **Essential**

   - **Parameter Estimation Acceleration**.
     Parameter estimation engines need to be modernized and optimized to increase their utility, computational performance, and ease of use, in order to handle the future onslaught of events.
   - **Essential Improvements to Waveform Models**.
     With increasing sensitivity we will become increasingly dependent on highly accurate waveform models. Waveform models that capture sub-dominant modes of emission, improved models of precession, and eccentricity will be developed. In addition, inclusion of additional matter effects,

e.g., during the merger and post-merger phases, will be needed for modeling neutron star binary systems. Additionally, the computational performance of waveform simulation will be improved to enable faster parameter estimation.

- **Improved Models of Population Inference**.
  As the census of compact binary coalescences grows, more sophisticated models of the astrophysical population will become possible (e.g., with redshift evolution). New methods of population inference will be introduced to exploit the large number of detections anticipated.

- **Improvements to Statistical Measurement of the Hubble Constant**.
  There are a number of potentially biasing systematic effects present in the statistical method of measuring the Hubble constant. These effects will be studied and methods for mitigating them with be implemented in the cosmology code.

- **Essential Enhancements to All-Sky Searches**.
  As the network of detectors grows, with KAGRA possibly joining O3, and with improvements in the detector sensitivity curves, search pipelines need to be enhanced to make optimal use of the available data. This continued development will improve the search sensitivity of both online and offline pipelines.

2. **Exploratory**

- **Research and Development in Parameter Estimation Methodology**.
  Investigation of new algorithms and optimization has the potential to greatly improve the speed of the parameter estimation code and add scalability to allow for increasing number of parameters and more complex signal models.

- **New Tests for Exotic Black Hole Physics**.
  Tests for exotic speculative physics such as black hole mimickers or late time gravitational wave echos from black holes will be explored.

- **Long Term Improvements to Waveform Models**.
  In the long term, we seek waveforms containing the full set of possible physics, capable of modeling the inspiral, merger, and post-merger of precessing, eccentric (even hyperbolic), systems including, where applicable, matter effects and disruption.

- **Robust Population Inference with Marginal Events**.
  Additional information about the astrophysical population of compact binary coalescences can be gleaned by inclusion of marginal events, whose astrophysical origin is not certain. New methods for including marginal events in population inference will be explored.

- **Real-Time Cosmology Calculation**.
  As we move toward larger signal rates and longer stretches of continuous operation, a cosmology calculation that updates in real time as events occur (with or without a counterpart) will be a boon.

- **Exploratory Enhancements to All-Sky Searches**.
  Novel methods can be incorporated into the all-sky search pipelines. For example, searches using templates modelling precessing and sub-dominant emission modes; fully-coherent searches; and the use of machine learning to improve event ranking and detector characterization.

1.3 Searches for Continuous-Wave Signals

FTE-months: 12.0 (CW group co-chairs)

FTE-months: 4.0 (CW review chairs)

The LSC/Virgo Continuous Waves (CW) Group aims to measure gravitational wave signals that are long-lived, nearly sinusoidal, and extremely weak. The signals are believed to be emitted by rapidly rotating neutron stars in our galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including rotation with 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 (also known as *spindowns*) and distances, energy conservation sets an upper limit on gravitational wave strain amplitude, known as the *spindown limit*, albeit with significant uncertainties. Searches of LIGO and Virgo data have obtained high-confidence upper limits well below the spindown limits for many pulsars, including the Crab and Vela pulsars; as detector sensitivities improve the number of pulsar for which the spindown limit has been surpassed will continue to increase, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or 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.

There is much astrophysical uncertainty surrounding continuous wave emission mechanisms, in part because i) electromagnetic astronomers have detected only a small fraction (2–3000) of the population of neutron stars in the galaxy (believed to be 10^8–10^9), and ii) modeling the physics of the interiors of neutron stars, particularly beyond nuclear densities, is extremely difficult. To try to mitigate these uncertainties, the CW group maintains a broad program to search for gravitational wave emission from several distinct source categories, as described below. The CW group also encourages active research and development into further improvements to existing search pipelines, as well as formulating ideas for new search methods. Mock data challenges are carried out to rigorously compare the performance of data analysis pipelines targeting a particular source category.

The primary gravitational wave source categories targeted by the CW group are ordered below by decreasing prior information known about the sources, which generally leads to decreased sensitivity of the associated searches:

Searches for known pulsars use known ephemerides from radio, X-ray or γ-ray timing measurements, and can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans. Of high-interest are those pulsars with spindown limits within factors of a few of the achievable sensitivities. For these high-interest targets it is desirable to forego a small part of the sensitivity and, relaxing the strict assumption of phase coherence between the gravitational wave signal and the measured ephemeris, perform a search in small frequency and spindown bands around their nominal values. It is also of interest to search for evidence of non-tensor polarizations, which if detected would imply a violation of general relativity.

Directed searches use known sky locations of interesting astrophysical point sources but lack prior frequency or spindown information. They are therefore less sensitive that searches for known pulsars due to the computational expense and trials factor associated with searching over several parameters: the gravitational wave frequency, and potentially higher-order spindowns; and, if the target astrophysical source has a binary companion, parameters of the binary orbit where unknown. Important astrophysical sources in this category are: galactic supernova remnants which may contain a young neutron star, e.g. Cassiopeia A; low-mass X-ray binaries where accretion could over time have build up a detectable non-axisymmetry, e.g. Scorpius X-1; the region of the Galactic center, which may contain a large population of pulsars not detectable by electromagnetic surveys; and nearby globular clusters, where older neutron stars may acquire a detectable non-axisymmetry through debris accretion, e.g. NGC 6544.

All-sky searches use no prior astrophysical parameters, and instead perform broad surveys for undiscovered neutron stars. The sensitivity achievable with all-sky searches is further limited, with respect to directed searches, by the need to make sky-location-dependent corrections for the Doppler modulation of the detected source frequency due to the Earth's daily rotation and yearly orbit. The number of sky directions that must be searched to maintain accurate demodulation grows rapidly with the time span of the data set being analyzed, and the associated increase in computational cost is severe enough to preclude all-sky searches using fully-coherent matched filtering over the typical year-long time spans of observational runs. The use of semi-coherent methods – which partition the data set into shorter segments, perform matched filtering on each segment individually, them incoherently combine filters from each segment – makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Finally, in order to be sensitive to neutron stars with a binary companion, the parameters of the binary orbit must also be searched over, further enlarging the search parameter space and computational cost.

In addition to the categories above, the CW group is also interested in searching for gravitational waves from several other sources. Searches for *long-lived transients*, in collaboration with the Burst and Stochastic working groups (Section Op-2.2), could target emission from e.g. a remnant neutron star formed in a binary neutron star coalescence, or following a pulsar glitch. *Axion clouds around black holes* may also produce long-lived continuous wave signals.

1.3.1 Scientific Operations and O3 Observational Results

The CW group plans to undertake a comprehensive search program over the course of the O3 observing run, which is reflected in the following list of priority activities. The prioritization of each activity into different classes is arrived at by considering a number of factors: i) the prior likelihood of detecting a particular category of source; ii) the sensitivity achievable by searches targeting that source category, which in many cases is restricted by their computational cost; and iii) available human resources needed to produced a vetted observational result.

It is important to note that these factors contain several uncertainties. Prior likelihoods of detection are difficult to quantify and may be re-assessed over time. The sensitivity and computational cost of a particular search is often influenced by the specific data set under consideration, including its spectral noise, which may be hard to predict before the data is examined in detail. The availability of human resources, in particular to bring new analysis methods under development to maturity, may also be uncertain. For those reasons, the prioritization of activities that follows is a best guess at the time of writing, and is subject to change when extrapolated into the future. Finally, note that the ordering of activities within the same priority class in the list below does *not* imply any further prioritization *within* that class.

1. **Highest priority**
    - Targeted searches (Section Op-4.1) for all known pulsars for which upper limits within a factor of two of the spindown limit are likely to be achieved, e.g. the Crab and Vela pulsars. These searches will include searching at once and twice the pulsar spin frequency.
    - Narrow-band searches (Section Op-4.2) for high-interest pulsars, as above, which explore small frequency and spindown bands around the nominal parameters given by the known ephemerides.
    - Directed searches targeting as many high-interest astrophysical point sources as resource allow, in particular Cassiopeia A (Section Op-4.4) and Scorpius X-1 (Section Op-4.5).

- All-sky searches for undiscovered sources, either isolated (Section Op-4.7) or in binary systems (Section Op-4.8).
- Long-transient searches for emission from post-merger neutron stars (Section Op-4.9) where the estimated distance is similar to or closer than GW170817.
- Follow-up searches of any promising continuous wave candidates found by other searches (Section Op-4.12).
- Support CW searches through detector characterization (Section Op-4.13), data preparation (Section Op-4.14), and scientific software maintenance (Section Op-4.15).

2. **High priority**
    - Targeted searches (Section Op-4.1) for known pulsars for which the spindown limit is unlikely to be surpassed. [1]
    - Targeted searches for known pulsars sensitive to non-tensor polarizations (Section Op-4.3).
    - Directed searches for other point sources of interest, including but not limited to: galactic supernova remnants (Section Op-4.4), sources in low-mass X-ray binaries (Section Op-4.5), sources near the Galactic center (Section Op-4.6), and sources in nearby globular clusters.
    - Long-transient searches for emission from post-merger neutron stars (Section Op-4.9) at estimated distances larger than GW170817.
3. **Additional priority**
    - Searches for long-lived transient emission following a pulsar glitch (Section Op-4.10).
    - Searches for continuous emission from axion clouds around black holes (Section Op-4.11).

1.3.2 Advanced Analysis Methods for Advancing Frontiers

The search for continuous gravitational waves sources is a challenging scientific problem. In particular, when parameters of the sources are unknown and therefore must be searched for over wide parameter spaces, the achievable sensitivity of the theoretically-optimal method (e.g. matched filtering) is severely limited by finite computational resources. Sub-optimal but computationally-cheaper algorithms must therefore be utilized. The problem of determining the most sensitive search method, given a fixed computational budget, is not easily solved – yet its solution may prove critical to a first detection of continuous waves. Furthermore, many sources may exhibit behaviors which deviate from the usual continuous wave signal model, e.g. spin wandering in low-mass X-ray binaries, or sources with intermittent gravitational emission. Investment in *optimization of existing pipelines*, as well as *development of new, potentially more sensitive and/or robust methods*, is therefore of critical importance.

The CW group aims to support at least two independent search methods/pipelines for each source target; more may be supported as resources allow. This redundancy provides greater robustness against incorrect assumptions in signal modeling and against non-optimal handling of instrumental artifacts.

1. **Essential**
    - Further improvement and optimization of existing data analysis pipelines (Section LT-4.16).
    - Development of model-robust/agnostic data analysis methods (Section LT-4.17).
2. **Exploratory**

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[1] Note that, due to the maturity and insignificant computational cost of the targeted search pipelines, there is virtually no practical benefit to separating the high-interest targets from the others and delivering two separate sets of results.

- Development of new and potentially more sensitive data analysis methods (Section LT-4.18).
- Use mock data challenges to compare data analysis pipelines (Section LT-4.19).

1.4 Searches for Stochastic Backgrounds

FTE-months: 12.0 (SGWB group co-chairs)
FTE-months: 4.0 (SGWB review chairs)

A stochastic gravitational-wave background (SGWB) is formed from the superposition of many events or processes that are too weak and/or too numerous to be resolved individually. The prime objective of the SGWB group is to measure this background, which can arise from cosmological sources such as inflation, cosmic strings, and pre-Big-Bang models or from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars. The measured rate of binary black hole (BBH) and binary neutron star (BNS) mergers indicates that, at design sensitivity, Advanced LIGO may detect an astrophysical background. This detection will be of great interest as a probe of the evolution of the Universe since the beginning of stellar activity. Meanwhile, the detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The stochastic searches are built on the cross-correlation infrastructure, which was originally designed to carry out searches for an isotropic stochastic background, but has been adapted to also search for directional stochastic backgrounds and transient GW signals.

Although no SGWB was detected during O1 and O2, results from the isotropic search constrain the energy density of the stochastic background to be $\Omega_0 < 6.0 \times 10^{-8}$ at 95% confidence. When the Advanced detectors reach design sensitivity, we expect to be as low as 6×10^{-10}.

The isotropic search has been extended to include a test of General Relativity (GR) by searching for a background of non-tensor polarizations. This extension provides a tool for model selection between a tensor and non-tensor background signal, as well as an estimate of the background energy density from tensor, vector, and scalar polarizations. It is also important to estimate the individual contributions of distinct sources of the background, which may be described by distinct spectral shapes. Independent methods have been developed to consider all physically allowed spectral shapes using either a mixing matrix deconvolution or Bayesian parameter estimation. Bayesian parameter estimation techniques are also used to estimate or constrain the average chirp mass and merger rate of the binary black hole population. Significant model development will be necessary for understanding and interpretating the observational results. To support the interpretation of the results, mock data challenges with different sources, such as compact binaries and cosmic strings, will be pursued. Additionally, a fully-Bayesian analysis for an isotropic SGWB is being developed using BayesWave. This analysis is capable of estimating noise power spectra and modeling glitches in the data, allowing a simultaneous estimate of both detector noise and GW background contributions to observed data in a fully-Bayesian manner.

The directional searches provide a method of distinguishing between different stochastic sources using sky maps of gravitational-wave power. The group employs both a radiometer algorithm and a spherical harmonic decomposition to generate sky maps (and strain spectra) that can be used to identify cosmological or local anisotropies as well as point sources. The spherical harmonic decomposition provides an estimate of the energy density of the SGWB from extended sources over the sky. It can also be applied to search for a GW background with parameterized anisotropy, for example anisotropies associated with the compact binary black hole background or cosmic strings. To further study anisotropies in the astrophysical background, GW sky maps can be cross correlated with electromagnetic observables. The broadband radiometer measures the background energy density from point-like sources over the sky, and provides an important tool for GW astronomy when there is significant uncertainty in the phase evolution of a continuous-wave signal. As an application, a narrowband radiometer has been used to search for gravitational waves from Scorpius X-1, the Galactic Center, and SN 1987A. Using a compressed data set folded over a sidereal day, the radiometer can be applied to perform an unmodeled search for persistent sources over all frequencies and sky locations.

Directional searches are performed separately for multiple spectral indices in standard LIGO analyses but it may be possible to deconvolve the skymaps to constrain backgrounds of multiple spectral components. Exploration studies are being performed, initially considering two or three power-law spectral indices. We also investigate models of SGWB anisotropies, such as compact binaries and cosmic strings, which we can test against our results. We will test these models with mock data challenges. Continuous-wave (CW) sources with deterministic but unknown phase evolution, such as a neutron star with unknown spin period, may be detectable either via the stochastic radiometer or via methods being developed in the CW group. The Stochastic group continues to develop these searches, in consultation with the CW Group.

It may be possible for neutron stars to emit transient gravitational waves on time scales lasting hours to weeks. 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. The Stochastic group has developed a cross-correlation pipeline to search for very long-lived gravitational-wave transients on these time scales. Applications of this search include the ability to establish whether an apparently persistent source, e.g., observed in a stochastic background search, exhibits variability in time; and an understanding of the behaviour of detector artefacts on timescales of days to weeks. There is overlap between the very long transient search and searches being carried out in the Burst and Continuous Waves search groups.

The traditional stochastic searches share a common assumption of a Gaussian and stationary background. However, a background from unresolvable binary BH mergers, for example, is likely to be detected first by the Stochastic group even though it will not be stationary and is unlikely to be Gaussian. Non-Gaussian stochastic background signals have been studied using software injections and analyses on mock data. A search for an astrophysical background from unresolved compact binary coalescences is being pursued in conjunction with the CBC group. The joint activity will develop and implement a Bayesian search strategy that is optimally suited to handle the non-stationarity of the expected background from BBH mergers.

The Stochastic group is actively involved in detector characterization efforts, with overlap with the Detector Characterization (DetChar) group. For example, the SGWB group relies on magnetic field measurements to estimate and mitigate contamination due to Schumann resonances. There are also plans to study how intermittent signals from (instrumental, environmental, or astrophysical) transients may bias stochastic analyses using software injections. The group has also developed and maintains a stochastic data-quality monitor to track search sensitivity in real time and to identify problematic sources of noise.

1.4.1 Scientific Operations and O3 Observational results

The Scientific Operations and O3 Observational Results priorities of the Stochastic group are:

1. **Highest priority**
    - **Search for an isotropic background.** Analyze the O3 data for an isotropic stochastic gravitational-wave background, looking as well for evidence of non-GR polarization modes; constrain relevant astrophysical and cosmological models of isotropic gravitational-wave backgrounds; investigate the effect of correlated magnetic noise on the search.
    - **Directional searches for anisotropic backgrounds.** Analyze the O3 data using both the radiometer and spherical harmonic decomposition methods to generate sky maps for both point sources and extended sources of an anisotropic gravitational-wave background; perform an unmodeled search for potentially interesting persistent gravitational-wave sources from specific sky locations; constrain relevant astrophysical and cosmological models of anisotropic backgrounds.

- **Data quality and detector characterization studies.** Investigate the effect of non-stationarity and coherent lines in the O3 data on the stochastic searches, and pursue approaches to mitigate these sources of noise.

2. **High priority**

- **Search for very long transients.** Analyze the O3 data for very-long transient events, thus assessing the temporal distribution of the SGWB. In the case of a BNS or a BHNS detection, the search for a very long duration signal from a merger remnant will be promoted to the rank of highest priority.

- **Folded data set.** Fold the O3 data to a single sidereal day to speed up analyses by a factor of ~ 100. This will facilitate the application of more computationally-expensive stochastic searches like the all-sky all-frequency radiometer and searches for parameterized anisotropy.

1.4.2 Advanced Analysis Methods for Advancing Frontiers

1. **Essential**

- **Stochastic background from compact binary coalescences.** Implement and test an optimal Bayesian search for the nonstationary background produced by individually unresolvable CBC events (e.g., BBH mergers) throughout the universe.

- **Implications and astrophysical modeling.** Develop more accurate theoretical models of astrophysical and cosmological gravitational-wave backgounds; perform mock data challenges to test the recovery of simulated backgrounds corresponding to different theoretical models, using Bayesian model selection or parameter estimation.

- **Component separation.** Implement frequentist or Bayesian component separation methods to determine the individual spectral contributions to an isotropic gravitational-wave background.

- **All-sky all-frequency search for unmodeled persistent sources.** Implement an all-sky, all-frequency extension of the narrow-band radiometer search that can look for unmodeled persistent GW point sources not conforming to the assumptions made by standard template-based searches.

2. **Exploratory**

- **Fully Bayesian search.** Implement a fully Bayesian alternative to the standard cross-correlation statistic search for an isotropic stochastic background; compare the fully Bayesian and standard cross-correlation search to see if any information is lost by ignoring auto-correlated components in the covariance matrices.

- **Component separation using narrowband maps.** Develop and implement component separation methods for anisotropic gravitational-wave backgrounds.

- **Models for anisotropic backgrounds.** Develop theoretical models of astrophysical backgrounds; use the measured SGWB anisotropies to constrain such models; correlate SGWB sky maps with electromagnetic tracers of large-scale structure; and search for parametrized models of anisotropic backgrounds.

- **Dark Photon Search.** Develop the search for the dark photon dark matter. This signal is expected to be narrowband and correlated between GW detectors. Start from the existing analysis pipeline [2], refine it to use theoretical signal template, and apply it to O2 and O3 data.

2 Burst Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the CBC, DetChar, and Stochastic groups in sections 6, 7, and 8, respectively.

Op-2.1 Search for short-duration GW bursts

All-sky searches for short-lived transient astrophysical signals not amenable to template-based methods.

Motivation and methods

A wide range of highly energetic astrophysical phenomena are expected to be accompanied by emission of gravitational-wave transients lasting from milliseconds to several seconds within the instruments' frequency band. For some transient sources, especially compact binary systems made up of neutron stars and/or black holes, their expected gravitational-wave emission is modeled sufficielntly well over most of their parameter space that matched filter techniques using waveform templates can be used to optimally retrieve astrophysical signals from the interferometer data. However, there exists a range of plausible sources of short-duration gravitational-wave emission for which their signal morphologies are poorly modeled or even unknown, and for which no matched filter techniques can be effectively employed. Such sources include core-collapse supernovae, long-duration gamma-ray bursts, soft gamma repeaters and neutron star glitches. The all-sky search for short-duration bursts targets this wide class of sources. For this reason, the all-sky search invokes general transient-finding methods with minimal assumptions on signal morphology. This also provides the opportunity to identify unanticipated sources and signals.

In O1 and O2, the search for unmodeled transients has benefited from independent implementations of burst analysis pipelines [3, 4]. Each analysis uses a measurement basis (Fourier, wavelet or others) in order to identify coherent excess power in the data from multiple detectors (cWB [5], oLIB [6] and BayesWave [7]). These analyses use GW strain data from all available detectors to solve the inverse problem for the impinging gravitational-wave signal by using maximum likelihood and Bayesian statistics approaches. Multi-instrument analysis is essential for the robust detection of unmodeled gravitational-wave transients; fully coherent methods have been shown to perform well at rejecting noise transients while recovering relatively weak signals. We plan to continue using multiple burst pipelines in the foreseeable future. Independent searches for the same science targets present the opportunity for direct comparisons of the analysis, an ability to validate search results, and often leads to search innovation. Multiple, independent searches may also better cover the signal parameter space.

In addition to offline analyses, the all-sky search for transient events are performed in low-latency and successfully produces triggers with as short as a few minutes of time delay to allow for rapid follow-up multi-messenger observations. The ability to quickly identify triggers from generic transient events complements current targeted searches for compact binaries, remaining sensitive to a wider variety of sources.

We note that because of the generic waveforms targeted by these searches, there is sometimes significant overlap with results from other, more narrowly focused search methods.

Major deliverables and critical tasks for O3

ACTIVITY Op-2.1-A: OPERATION IN LOW-LATENCY

TASK Op-2.1-A(i): TESTING AND REVIEW

FTE-months: 6.0

Pipelines (cWB, oLIB and BW) designated for operation in low-latency will be tested, reviewed, and approved prior to the start of the observing run. The low-latency searches are analyzing the LIGO and Virgo data.

TASK Op-2.1-A(ii): TENDING TO THE ONLINE PROCESSES

FTE-months: 10.0

Personnel will be assigned to oversee the online pipelines' state and results, keep current on changing detector conditions, and be on call to consider detection candidates.

TASK Op-2.1-A(iii): FOLLOWING-UP DETECTION CANDIDATES

FTE-months: 8.0

Use codes designed to evaluate GW candidate significances. Employ models to test significance of candidates as astrophysical versus "glitch" (detector artifact) models.

ACTIVITY Op-2.1-B: OFFLINE SEARCH

TASK Op-2.1-B(i): PIPELINE IMPROVEMENTS

FTE-months: 4.0

Complete testing and review of any pipeline improvements in a timely manner, including computation optimization.

TASK Op-2.1-B(ii): DEVELOPMENT AND IMPLEMENTATION OF SIGNAL INJECTIONS

FTE-months: 4.0

Develop the classes of signal types to use for injection studies. Develop the methodology for implementing the injections.

TASK Op-2.1-B(iii): FOLLOWING-UP DETECTION CANDIDATES

FTE-months: 5.0

Use codes designed to evaluate GW candidate significances. Employ models to test significance of candidates as astrophysical versus "glitch" (detector artifact) models. As needed, employ techniques to remove glitches from the data near a GW candidate – to be used by parameter estimation or other follow-up analyses.

TASK Op-2.1-B(iv): REPORTING RESULTS AND REVIEW

FTE-months: 4.0

Report intermediate results in a timely manner as data becomes available during the observing run. Report final results. Reporting should be made within working groups and periodically to the Burst group.

TASK Op-2.1-B(v): PUBLISHING RESULTS

FTE-months: 8.0

Publish a collaboration paper reporting any signals found by the short-duration search, and place limits on some classes of sources.

ACTIVITY Op-2.1-C: DATA QUALITY

GW transient searches benefit from data quality information provided by detector experts. That especially includes the findings of the LSC and Virgo detector characterization groups to identify and understand the origin of the non-stationary noise sources. Safe data quality vetoes are used by burst searches to remove a large fraction of noise outliers. This activity is relevant for all Burst searches.

TASK Op-2.1-C(i): DATA QUALITY PRODUCTS

FTE-months: 6.0

Provide a regularly updated and customized list of data quality flags and vetoes for each familly of Burst searches.

TASK Op-2.1-C(ii): REPORTING

FTE-months: 3.0

Provide regularly feedback to the Burst and detector characterization groups. It is expected that Burst search pipelines will produce and provide triggers as needed for the purpose of detector characterization studies.

ACTIVITY Op-2.1-D: SUBGROUP ADMINISTRATION

Management of the short-duration GW burst subgroup.

TASK Op-2.1-D(i): SUBGROUP LEADERSHIP

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.1 Search for short-duration GW bursts R&D (Long Term)

ACTIVITY LT-2.1-A: ALTERNATIVES TO GENERAL RELATIVITY

In addition to searching for generic transient gravitational-wave events, we also plan to search for gravitational-wave bursts with alternative polarizations. While Einstein's general theory of relativity (GR) predicts that gravitational waves will have a tensor polarization, some alternative theories of gravity predict gravitational waves with other polarizations (namely scalar and vector polarizations). Searching for these alternative polarizations using only the LIGO detectors is unfeasible as the two detectors are nearly co-aligned. The addition of data from the Virgo detector makes it possible to distinguish between polarizations of a gravitational-wave signal. We plan to use one or more burst pipeline to search for gravitational-wave signals with non-GR polarizations, and to quantify the consistency between recovered signals and GR polarizations.

ACTIVITY LT-2.1-B: TOWARDS A 4-DETECTOR NETWORK

Analyze KAGRA data by the existing pipelines, both in low-latency and offline.

ACTIVITY LT-2.1-C: PIPELINE IMPROVEMENTS

Continue to investigate improvements to pipelines. For example, machine learning tools can be used at the post-processing stage to try to overcome the issue of the non-Gaussian transients hampering the search.

Op-2.2 Search for long-duration GW bursts

All-sky searches for 10 – 1000 s long transient astrophysical signals not amenable to template-based methods.

Motivation and methods

Unmodeled long-lived gravitational-wave transients (lasting $\gtrsim$ 10–1,000 s) are an exciting class of signals for Advanced detectors. Such long-lived transients have been predicted to originate at 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, type I bursts from accreting pulsars, and eccentric binary systems. Searches [8, 9] for these sources use minimal assumptions about the signal waveform, so unpredicted sources are detectable as well. The burst group long-duration transient search, carried out by the cWB [5], stampas [10] and X-SphRad [11] pipelines, focuses on signals that last up to 100 s while other searches (see Op-5.3 and Op-4.9) target signals lasting up to several weeks.

Major deliverables and critical tasks for O3

ACTIVITY Op-2.2-A: SEARCH FOR LONG-DURATION GW TRANSIENT SIGNALS IN LIGO AND VIRGO DATA

TASK Op-2.2-A(i): OFFLINE SEARCH

FTE-months: 15.0

Search for GW signals in LIGO and Virgo data with cWB, stampas and X-SphRad. Estimate the significance of the most promising GW candidates and estimate the search sensitivity.

TASK Op-2.2-A(ii): WAVEFORM CATALOG DEVELOPMENT

FTE-months: 6.0

Continue to enhance the long-duration transient waveforms catalogue with astrophysically motivated waveforms. A selection of the most interesting waveforms will be done for the O3 search results publication.

TASK Op-2.2-A(iii): FOLLOWING-UP DETECTOR CANDIDATES

FTE-months: 3.0

Develop the tools to evaluate the significance of a GW candidate against the hypothesis of a noise event. It includes both studies about data quality and the GW signal properties (sky localization etc). It also includes the use of a Bayesian parameter estimation algorithm that tests signal waveform models like magnetars.

TASK Op-2.2-A(iv): REPORTING RESULTS AND REVIEW

FTE-months: 4.0

Report intermediate results in a timely manner as data becomes available during the observing run. Report final results.

TASK Op-2.2-A(v): PUBLISHING RESULTS

FTE-months: 8.0

Publish a collaboration paper reporting any signals found by the long-duration search, and place limits on some classes of sources.

ACTIVITY Op-2.2-B: SUBGROUP ADMINISTRATION

Management of the long-duration GW burst subgroup.

TASK Op-2.2-B(i): SUBGROUP LEADERSHIP

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.2 Search for long-duration GW bursts R&D (Long Term)

ACTIVITY LT-2.2-A: PIPELINE IMPROVEMENTS

TASK LT-2.2-A(i): CWB

Investigate options to improve the cWB sensitivity to long-duration burst signals. One of the options is to use the Wavegraph clustering algorithm, and develop the time-frequency graphs for the signal models specified in this proposal [12].

TASK LT-2.2-A(ii): STAMPAS

Rewrite the stampas pipeline in python to speed it up and improve the performance of the code. These changes will especially allow to reconstruct more accurately the source position in the sky.

TASK LT-2.2-A(iii): X-SPHRAD

Minimal rewrite of functions used pre- & post- processing of X-pipeline in python and integrate image processing core (X-Pyxel). A veto against short-duration glitch using X-SphRad is also under development.

ACTIVITY LT-2.2-B: PARAMETER ESTIMATION

TASK LT-2.2-B(i): SOURCE RECONSTRUCTION

Investigate modeled and unmodeled source reconstruction methods for long transients. It includes to adapt and test the Bayesian parameter estimation code for long-duration signal with the different models of long-duration GW transient sources.

Op-2.3 Search without templates for GWs from binary stellar mass black holes

All-sky Burst searches applied to BBH systems.

Note that the searches for high-mass IMBBH systems are described in Section Op-7.2.

Motivation and methods

The binary black hole (BBH) systems detected in observing runs O1 and O2 have been efficiently found with the matched filter searches using quasi-circular CBC templates. However, other hypothetical types of CBC systems covering a larger range of component masses, spins and eccentricities should also be considered. Detection of such systems would provide information regarding the viability of several proposed binary formation mechanisms and would help discriminate among different formation models. Targeting this wider parameter space of CBC sources with a burst analysis method, which does not rely on templates, creates a search which is robust to a variety of features including high mass ratios, higher order modes, misaligned spins, eccentric orbits, or deviations from general relativity. These may create mismatch between the observed signal and CBC matched-filter search templates. In addition, for BBH systems of increasing mass, the detectable waveforms shorten, so that eventually the templated searches do not hold a distinct advantage over the Burst searches. Recognizing this, a joint Burst-CBC effort was organized for searches of the IMBBH systems, where the total mass exceeds roughly 100 $M_{\odot}$. This is discussed in Section Op-7.2.

Given these considerations, the all-sky Burst searches represent a viable detection method for BBH systems over a wide range of their potential parameter space. A particularly interesting case is that of eccentric systems. 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 significant eccentricity will persist when the binaries evolve into the LIGO/Virgo detection band. Current CBC searches using quasi-circular waveforms from stellar-mass binaries will not efficiently detect these systems for eccentricities $e >\sim 0.05$ [13], therefore dedicated burst searches for these potential sources represent a viable alternative [14].

Note that the EBBH analysis is using the results of the generic binary stellar mass black hole search carried out with cWB pipeline [5].

Major deliverables and critical tasks for O3

ACTIVITY Op-2.3-A: STELLAR MASS BBH SEARCH

TASK Op-2.3-A(i): SEARCH OPTIMIZATION

FTE-months: 1.0

Optimize the all-sky search for (non-eccentric) BBH systems.

Task Op-2.3-A(ii): Offline Search

FTE-months: 6.0

Run the search pipeline(s). Report results in a timely manner.

Task Op-2.3-A(iii): Following-up Detection Candidates

FTE-months: 2.0

Use codes designed to evaluate GW candidate significances. Employ models to test significance of candidates as astrophysical versus "glitch" (detector artifact) models. As needed, employ techniques to remove glitches from the data near a GW candidate – to be used by parameter estimation or other follow-up analyses.

Task Op-2.3-A(iv): Evaluation of Sensitive Parameter Space

FTE-months: 1.0

Use injections to evaluate the sensitivity of the search for ranges of BBH system parameters, including mass ratio, spin, precession, higher-order modes, etc. Compare with the CBC templated searches.

Task Op-2.3-A(v): Reporting Results and Review

FTE-months: 2.0

Report intermediate results in a timely manner as data becomes available during the observing run. Report final results. Reporting should be made within working groups and periodically to the Burst group.

Task Op-2.3-A(vi): Contribute to GW Catalog and Paper

FTE-months: 2.0

GW detections with significances similar to, or greater than, those from the CBC templated search, would be candidates to appear in the GWTC for O3a or O3b and to the corresponding catalog papers.

Activity Op-2.3-B: Eccentric BBH (EBBH) Search

Task Op-2.3-B(i): Search optimization

FTE-months: 2.0

Optimize the EBBH search relative to that presented in the O1-O2 paper.

Task Op-2.3-B(ii): Eccentric Waveforms

FTE-months: 2.0

Evaluate the availability of eccentric BBH waveforms relative to the O1-O2 analysis.

Task Op-2.3-B(iii): Reporting Results and Review

FTE-months: 3.0

Report intermediate results in a timely manner as data becomes available during the observing run. Report final results. Reporting should be made within working groups and periodically to the Burst group.

Task Op-2.3-B(iv): Publishing Results

FTE-months: 4.0

Publish a collaboration paper reporting any signals found by the EBBH search, and place limits on eccentricity.

Activity Op-2.3-C: Subgroup Administration

Management of the BBH burst subgroup.

Task Op-2.3-C(i): Subgroup Leadership

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.3 Search without templates for GWs from binary stellar mass black holes R&D (Long Term)

ACTIVITY LT-2.3-A: DEVELOPMENT OF ECCENTRIC WAVEFORMS

TASK LT-2.3-A(i): WAVEFORM DEVELOPMENT

Continue to monitor the development of waveform models for EBBH systems. Evaluate their impact.

ACTIVITY LT-2.3-B: IMPROVEMENT OF SEARCH SENSITIVITY

TASK LT-2.3-B(i): METHODS FOR IMPROVING THE SEARCH SENSITIVITY

Investigate options to improve the burst search sensitivity to eccentric black hole signals by using different clustering algorithms and time-frequency graphs obtained from relevant signal models.

TASK LT-2.3-B(ii): METHODS FOR LOW-MASS CHIRP SYSTEMS.

Investigate methods for improving the Burst BBH search sensitivity for systems with chirp mass less than 10 $M_\odot$.

TASK LT-2.3-B(iii): ECCENTRICITY RECONSTRUCTION

FTE-months: 3.0

Investigate methods for reconstructing the eccentricity of BBH mergers for any eccentricity.

Op-2.4 GW burst signal characterization

Waveform reconstruction and interpretation.

Motivation and methods

One of the exciting features of gravitational-wave astrophysics is the observation of signals directly tied to the flow of energy and momentum within a source [15]. This signal can be extremely rich in the information it contains. For compact object mergers, it encodes the source masses, spins, distance, and orientation. An observed gravitational-wave signature from a galactic supernova would probe the stellar core, and would give valuable clues to the supernova explosion mechanism, angular momentum, and other dynamic variables. The gravitational waveform from an oscillating neutron star would constrain the neutron star equation of state. For new classes of signals, the waveform will provide a unique path towards understanding the astrophysical source. Even without an astrophysical model, it may be possible to constrain some source parameters based on time-scale and energy arguments.

Reconstructing the waveform of a detected signal is a non-trivial process, involving data from multiple detectors, knowledge of detector positions and responses, and a statistical framework for evaluating a best-fit waveform and properties of the detector noise [7, 16, 17]. Quantifying the uncertainty on reconstructed waveforms is also critical to allow comparisons between measured signals and proposed source models. During O1 and O2, reconstructed waveforms were seen to agree with models for expected signals from binary compact objects coalescences [18, 19]. In addition, burst searches provide a measurement of the polarization state for detected gravitational-wave events [17]. Meaningful polarization measurements are possible with three or more detectors in the network.

Closely related to the best-fit waveform is an estimate of the source's direction [20, 21, 22]. The angular position reconstruction of a gravitational wave source, or "skymap", enables searches for coincident emission by a wide range of electromagnetic and particle observatories. This includes both searches of archival data from all-sky instruments or serendipitous observations, and attempts to rapidly respond to low-latency GW triggers by slewing radio, optical, and X-ray instruments.

Major deliverables and critical tasks for O3

ACTIVITY Op-2.4-A: WAVEFORM RECONSTRUCTION

TASK Op-2.4-A(i): PERFORM WAVEFORM RECONSTRUCTIONS

Deliver waveform reconstructions, with uncertainty, for all detected signals.

FTE-months: 2.0

TASK Op-2.4-A(ii): DEVELOPMENT OF A WAVEFORM COMPARISON METHOD

Develop method to quantitatively compare waveform reconstructions with best templates used in CBC search. Is the detected signal consistent with the best template?

FTE-months: 6.0

TASK Op-2.4-A(iii): CONTRIBUTE TO GW CATALOG AND PAPER

Deliver waveform reconstructions and waveform matching results to the GWTC for O3a and O3b, and to the corresponding catalog papers. Maintain a close working relationship with the catalog paper editorial teams (PET).

FTE-months: 7.0

TASK Op-2.4-A(iv): PRODUCTION OF SKYMAPS

Deliver position reconstruction skymaps for all detected sources, including low-latency skymaps.

FTE-months: 2.0

TASK Op-2.4-A(v): POLARIZATION STUDIES

Provide measurement and interpretation of the polarization patterns for GW events detected with the LIGO-Virgo network.

FTE-months: 3.0

TASK Op-2.4-A(vi): REPORTING RESULTS AND REVIEW

Report progress and results in a timely manner as data becomes available during the observing run. Report final results. Reporting should be made within working groups and periodically to the Burst group.

FTE-months: 4.0

ACTIVITY Op-2.4-B: SUBGROUP ADMINISTRATION

Management of the GW burst signal characterization burst subgroup.

TASK Op-2.4-B(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 2.0

LT-2.4 GW burst signal characterization R&D (Long Term)

ACTIVITY LT-2.4-A: DEVELOPMENT OF NEW AND IMPROVED METHODS

TASK LT-2.4-A(i): IMPROVING WAVEFORMS AND SKY LOCALIZATION

Continue development of improved methods for waveform reconstruction, waveform comparisons, and sky localization.

Op-2.5 Search for GW transients from isolated neutron stars

Motivation and methods

Violent phenomena associated with NSs, such as flaring activity in magnetars [23, 24, 25] and pulsar glitches, may result in the excitation of various oscillatory modes which leads to transient gravitational wave emission. The energetics involved with phenomena such as magnetar flares or pulsar glitches makes detection of an associated gravitational wave burst rather speculative with current detectors. The science pay-off, however, would be tremendous; the detection and characterization of GWs associated with NS oscillations holds the potential for GW neutron star asteroseismology, whereby NS oscillation mode identification and characterization leads to constraints on the equation of state. Our goals for science deliverables are, therefore, focused towards the development of novel searches and techniques, and the deployment of morphology-independent searches, waveform reconstructions, and parameter estimation follow-ups to *extraordinary* events. Past searches targeting such events include [26, 27, 28, 29, 30]. The methods employed overlap with the long-duration burst searches (Section Op-2.2) and the GRB group (Section Op-7.3).

Major deliverables and critical tasks for O3

ACTIVITY Op-2.5-A: MAGNETAR FLARES

TASK Op-2.5-A(i): MONITOR FLARES DATA

Monitor the reported x-ray flare activity reported by external groups such as Swift or Fermi.

FTE-months: 1.0

TASK Op-2.5-A(ii): RUN TRIGGERED SEARCHES

Repeat an O2-like search for galactic flares or any giant flares. The search should include both short duration (less than about 1 s) and long duration algorithms.

FTE-months: 6.0

TASK Op-2.5-A(iii): REPORTING RESULTS AND REVIEW

Report progress and the results of these searches in a timely manner during the observing run. Report final results. Reporting should be made within the GRB group and periodically to the Burst group.

FTE-months: 3.0

TASK Op-2.5-A(iv): PUBLISHING RESULTS

If there is an extraordinary event – e.g. a giant galactic flare or a very nearby ($\sim$ 1 kpc) normal flare – publish a collaboration paper reporting any signals found by the search.

FTE-months: 2.0

LT-2.5 Search for GW transients from isolated neutron stars R&D (Long Term)

ACTIVITY LT-2.5-A: DEVELOPMENT OF NEW AND IMPROVED METHODS

TASK LT-2.5-A(i): METHODS AND MODELING STUDIES

Continue to develop improved search methods. Develop parameter estimation techniques. Progress may require new developments in theoretical modeling or new NS observations.

Op-2.6 Search for GWs from core-collapse supernova

Motivation and methods

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 shock wave is promptly formed from the proto-neutron star and plows through the stellar mantle. If it breaks out of the star's surface, it lights up the star in a supernova explosion. The neutrinos and/or EM radiation herald a core-collapse supernova, and can be used to trigger a search for GW bursts. GWs are produced by bulk aspherical accelerated motion of matter; in the core-collapse supernova (CCSN) context they are a direct probe of the uncertain degree of asymmetry of the supernova engine.

GW signals from CCSN are typically much weaker than signals from binary mergers. Numerical simulations have shown that CCSN signals can span frequencies up to few kHz and durations up to a few seconds, making them hard to detect because their energy is spread over a large area in the time-frequency domain. The current burst searches are not designed to detect such signals and can miss a Galactic CCSN with signal-to-noise ratio below 30. Thus pipeline developments are needed to improve the detection efficiency of CCSN searches.

The strategies for these searches can vary according to detection of different messengers. It may happen that GW are produced while no electromagnetic or neutrino counterpart is detected, in which case the all-sky burst searches (Op-2.1) would be the best search strategy. In case we observe only light from a nearby supernova an optically-triggered search is performed, as was performed for O1-O2 [31]. In case we observe low-significance neutrinos, then a sub-threshold neutrino search may be performed. But special attention is placed when an SNEWS alert reports the detection by neutrinos of a galactic or nearby extragalactic supernova, like supernova SN1987A.

Major deliverables and critical tasks for O3

ACTIVITY Op-2.6-A: OPTICALLY TRIGGERED SEARCH

TASK Op-2.6-A(i): COLLECT TRIGGERS

FTE-months: 2.0

Identify candidate CCSN within roughly 20 Mpc from electromagnetic observations. Work with external groups (DLT40 and AS-SSN) to determine the best estimates for the time of core collapse and nature of the progenitor.

TASK Op-2.6-A(ii): RUN THE GW SEARCH

FTE-months: 3.0

Perform the search for GWs associated with the CCSN time and sky position, similarly to the O1-O2 search, using cWB dedicated pipeline [5].

TASK Op-2.6-A(iii): DEVELOP A PLAN FOR AN EXTRAORDINARY DETECTION

FTE-months: 1.0

Develop a plan to respond to a near-galactic CCSN, including searches triggered by neutrino and/or electromagnetic observations.

TASK Op-2.6-A(iv): REPORTING RESULTS AND REVIEW

FTE-months: 3.0

Report progress and the results of these searches in a timely manner during the observing run. Report final results. Reporting should be made within the working groups and periodically to the Burst group.

TASK Op-2.6-A(v): PUBLISHING RESULTS (UPPER LIMITS)

FTE-months: 4.0

Publish a collaboration paper reporting any upper limits found by the CCSN search targeting sources within 20 Mpc maximum.

ACTIVITY Op-2.6-B: CCSN EXTRAORDINARY EVENT

TASK Op-2.6-B(i): RUN THE SEARCH

FTE-months: 3.0

Run all search pipelines (including cWB dedicated pipeline described in Op-2.6-A(ii)) associated to the external trigger and determine its significance.

TASK Op-2.6-B(ii): PARAMETER ESTIMATION

FTE-months: 3.0

Employ parameter estimation methods to determine the CCSN parameters and possible explosion mechanism.

TASK Op-2.6-B(iii): REPORTING RESULTS AND REVIEW

FTE-months: 3.0

Report progress and the results of the search in a timely manner. Report final results. Reporting should be made within the CCSN group and to the Burst group.

TASK Op-2.6-B(iv): PUBLISHING RESULTS

FTE-months: 3.0

Publish a collaboration paper reporting any signals found by the search.

ACTIVITY Op-2.6-C: SUBGROUP ADMINISTRATION

Management of the CCSN subgroup.

TASK Op-2.6-C(i): SUBGROUP LEADERSHIP

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.6 Search for GWs from core-collapse supernova R&D (long term)

ACTIVITY LT-2.6-A: DEVELOPMENT ACTIVITIES

The following are continuing developments.

TASK LT-2.6-A(i): CCSN WAVEFORM DEVELOPMENT

Continue to procure and catalog CCSN waveforms and use them to develop waveform reconstruction and parameter estimation techniques.

TASK LT-2.6-A(ii): WAVEFORM RECONSTRUCTION AND PARAMETER ESTIMATION

Develop techniques to infer the properties of the supernova dynamics, for example parameters of the proto-neutron star.

TASK LT-2.6-A(iii): SUB-THRESHOLD NEUTRINO-GW COINCIDENT SEARCH

Develop a joint sub-threshold neutrino/GW search.

TASK LT-2.6-A(iv): STATISTICAL SIGNIFICANCE OF COINCIDENT GW-CCSN TRIGGERS

Develop a method for assessing statistical significance of GW triggers associated with one or more supernovae.

TASK LT-2.6-A(v): SINGLE-INTERFEROMETER DETECTION

Develop a method for detecting GWs in coincidence with a CCSN using data from one GW detector.

TASK LT-2.6-A(vi): NOISE REDUCTION METHODS

Develop noise reduction techniques for CCSN searches.

3 CBC Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst, DetChar, and Stochastic groups in sections 6, 7, and 9, respectively.

Op-3.1 CBC Parameter Estimation R&D (Short Term)

Development of tools for characterizing CBC sources in terms of their parameters (short term).

Motivation and methods

The primary task of the parameter estimation (PE) group is to develop, improve, and maintain the techniques and tools necessary for characterizing compact binaries. For each detected event the PE group delivers posterior estimates for the physical characteristics of each binary, using the most sophisticated models possible for both signal and noise. To this end, the PE group's primary research tasks are focused on developing the tools and techniques necessary to take advantage of new signal models that account for more physical effects (e.g., eccentricity, matter effects) as they become available. The group also maintains infrastructure to support tests of general relativity. The group is also working on improved noise models that will relax assumptions made about the stationarity of the detectors' noise. Finally, the group assesses the improvement in parameter inference from such models, guides gravitational-wave model developments and science cases for future gravitational-wave measurements, and informs instrument design.

Major aspects and methods for this activity

ACTIVITY Op-3.1-A: DEVELOPMENT OF PARAMETER ESTIMATION CODE

Incremental improvements of the parameter estimation code will be made during O3 to improve parameter estimation accuracy and performance.

TASK Op-3.1-A(i): MARGINALIZATION OVER FREQUENCY-DEPENDENT DETECTOR CALIBRATION ERRORS AND PSD UNCERTAINTIES

FTE-months: 1.0

During O1 and O2, frequency-dependent but instrument-agnostic models for calibration errors were used for the purposes of marginalization, and point estimates of the noise PSD computed from on-source data were used for each analysis. We plan to move toward physically motivated models for calibration errors, and to marginalize over possible noise PSDs.

TASK Op-3.1-A(ii): FASTER CONVERGENCE WITH IMPROVED SAMPLING ALGORITHMS

FTE-months: 1.0

The group goals related to low latency analyses will require (in part) improvements to our sampling algorithms.

TASK Op-3.1-A(iii): IMPROVEMENTS TO POST-PROCESSING

FTE-months: 1.0

The outputs of the post-processing routines from the PE group are now used by many scientists in and outside of the LIGO and Virgo collaborations. These tools are in need of 1) improvements to the presentation of critical results, 2) additional statistical tests, 3) better usability by other CBC subgroups (e.g., numerical relativity follow-ups, rates and population), 4) adaptation to the open-data era and public releases.

TASK Op-3.1-A(iv): IMPROVEMENTS TO LIBRARY INFRASTRUCTURE

FTE-months: 12.0

To better facilitate the goals outlined above, the LALInference code base and `rapid_pe` are in need of infrastructural updates. This includes the continued migration of the library from C to Python to become more development-friendly, and the tighter integration of `rapid_pe` and LALInference.

TASK Op-3.1-A(v): HYBRIDIZATION AND SURROGATES

FTE-months: 3.0

Working closely with the CBC waveform models R&D group (Sec. Op-3.3) as needed for hybridization and/or surrogates, and simulation groups for targeted follow-up, we will enhance readiness for O3 for direct comparison of GWs from massive BBHs with generic numerical relativity simulations

ACTIVITY Op-3.1-B: EVALUATION OF PARAMETER ESTIMATION METHODS

The PE methods will be evaluated to understand potential biases.

TASK Op-3.1-B(i): USING MORE ACCURATE WAVEFORMS

FTE-months: 2.0

As more faithful waveform models and more numerical relativity simulations become available (see Sec. Op-3.3) which include and explore more physical effects (e.g., multi-modal effects, amplitude corrections), studies will be required to determine the impacts of the inclusion of such physical effects on PE.

TASK Op-3.1-B(ii): BETTER MEASUREMENT OF WAVEFORM SYSTEMATIC ERRORS

FTE-months: 2.0

Thus far the variance between posterior estimates obtained using multiple approximants (e.g., SEOBNRv3 and IMRPhenomPv2) have been used as a proxy for quantifying systematic uncertainties in parameter estimates. Coordinating closely with waveform group efforts to quantify systematic errors in the waveform basis, we must develop more robust and meaningful ways to quantify the impact of systematic errors associated with the use of our approximate waveforms on parameter inferences. Coordinating with applications groups (the Tests of General Relativity R&D group [Sec. Op-3.2], the Binary coalescence rates and population R&D group [Sec. Op-3.4], and the Studies of extreme matter with pre-merger and post-merger GWs R&D group [Sec. Op-7.1]), the group will develop metrics to assess the extent to which systematics propagate into their science deliverables, such as population parameters or identification of non-GR parameters, or otherwise impair the ability to identify potentially highly-informative parameters at all (e.g., eccentricity, tides).

TASK Op-3.1-B(iii): STUDY THE BIASES TO PE CAUSED BY NON-STATIONARY NOISE

FTE-months: 2.0

Current PE analyses assume the detector noise to be stationary over intermediate timescales, 1 to 100's times the length of a detected signal. We know the noise is not always stationary on these timescales, thus we must characterize the biases introduced in parameter estimates due to this false assumption.

ACTIVITY Op-3.1-C: DEPLOYMENT OF PARAMETER ESTIMATION CODE

Parameter estimation libraries will be maintained and deployed for both online and offline usage during O3.

TASK Op-3.1-C(i): DEPLOYMENT OF ONLINE PARAMETER ESTIMATION CODE

FTE-months: 3.0

The parameter estimation pipeline and configuration will be deployed and integrated into the low-latency infrastructure during O3.

TASK Op-3.1-C(ii): DEPLOYMENT OF OFFLINE PARAMETER ESTIMATION CODE

FTE-months: 3.0

The parameter estimation libraries will be maintained and deployed on collaboration computational clusters for use during O3.

ACTIVITY Op-3.1-D: PE WITH MATTER EFFECTS

LIGO/Virgo made the first detection of a binary neutron star (BNS) merger in 2017. In O3, it is possible that LIGO/Virgo may detect ten or more BNS mergers, and also one or more neutron star-black hole (NSBH) mergers. The detected GWs allow for novel measurements of matter effects in the binary mergers, including the neutron star equation of state. Developing good techniques for measuring these effects is an active area of research, and the most recent developments of this work need to be implemented in LIGO's Parameter Estimation code libraries.

TASK Op-3.1-D(i): PARAMETERIZED EQUATION OF STATE ESTIMATION

FTE-months: 3.0

Implement new matter equation of state parameterizations, for example, spectral parameterizations, and incorporate them into the parameter estimation engines.

TASK Op-3.1-D(ii): NON-PARAMETRIC EQUATION OF STATE ESTIMATION

FTE-months: 3.0

Implement non-parametric methods for equation of state estimation into the parameter estimation engines.

TASK Op-3.1-D(iii): PARAMETER ESTIMATION ON MULTIPLE EVENTS

FTE-months: 3.0

Since the equation of state is believed to be universal, it can be better constrained by analyzing multiple events together. Implement methods to do a multiple event equation of state estimation.

ACTIVITY Op-3.1-E: GRAVITATIONALLY LENSED EVENTS

A non-negligible fraction of BBH merger events to be observed by LIGO can undergo strong gravitational lensing. The strong lensing can produce multiple triggers of the same event with time delays varying from weeks to months. Identification of such events can help us to study the properties of gravitational lenses.

TASK Op-3.1-E(i): DETECTING LENSED GRAVITATIONAL WAVES THROUGH MULTIPLE EVENTS

FTE-months: 3.0

Develop methods to perform parameter estimation on pairs of events to detect potential lensed pairs of event arising from the same (lensed) source.

TASK Op-3.1-E(ii): DETECTING LENSED GRAVITATIONAL WAVES THROUGH WAVE OPTICS EFFECTS

FTE-months: 3.0

Gravitational waves lensed by a lensing source of similar size to the gravitational wavelength will exhibit distortions due to wave optics effects. Develop methods to perform parameter estimation to detect such distortions.

ACTIVITY Op-3.1-F: PARAMETER ESTIMATION REVIEW

Review of changes to parameter estimation code and deployment configuration.

TASK Op-3.1-F(i): PARAMETER ESTIMATION CODE REVIEW

FTE-months: 1.0

Review modifications to parameter estimation code.

TASK Op-3.1-F(ii): PARAMETER ESTIMATION ONLINE PIPELINE REVIEW

FTE-months: 1.0

Review of deployment, configuration, and integration of the online parameter estimation engine.

ACTIVITY Op-3.1-G: SUBGROUP ADMINISTRATION

Management of the Parameter Estimation subgroup.

TASK Op-3.1-G(i): SUBGROUP LEADERSHIP

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.1 CBC Parameter Estimation R&D (Long Term)

Development of tools for characterizing CBC sources in terms of their parameters (long term).

Major aspects and methods for this activity

ACTIVITY LT-3.1-A: FASTER PE (UP TO LOW-LATENCY)

Results from stochastic samplers can often take hours to days to obtain, with the lowest-latency analyses making simplifying assumptions (e.g., spins aligned with the orbital angular momentum). We aim to reduce latency, particularly for the more physically accurate models (e.g., including precession effects), and pursue the direct use of waveforms produced by numerical relativity simulations.

ACTIVITY LT-3.1-B: ANALYZING BACKGROUND EVENTS

Though not an official task of the PE group, as the most rigorous stage of signal characterization, PE is often looked to for verification of a trigger's status as signal vs. noise. To better inform the collaboration on such matters, we must conduct complete studies of PE analyses of background events to better understand the behavior of posteriors and detection-related statistics (e.g., coherent vs. incoherent Bayes factor) on foreground and background. This work is coordinated with the CBC detection and search R&D group (Sec. Op-3.6).

ACTIVITY LT-3.1-C: ANALYZING POPULATIONS OF SUB-THRESHOLD EVENTS

For many sources of GWs we expect a stochastic background, which need not be persistent or Gaussian. The use of LALInference to detect a population of sub-threshold events could lead to the detection of such a stochastic background. This work is coordinated with the Binary coalescence rates and population R&D group (Sec. Op-3.4) and the Stochastic group (Sec. 9).

ACTIVITY LT-3.1-D: USE OF BAYES FACTORS IN LOW LATENCY TO HELP INFORM DETECTIONS

The production of Bayes factors, which can be useful as detection statistics, currently takes too long to be useful for decisions made in low latency. The fact that such analyses can include physical effects not accounted for in searches (e.g., precession) means that obtaining such statistics on shorter timescales could allow PE to provide crucial new information at the time of detection. This work is coordinated with the CBC detection and search R&D group (Sec. Op-3.6).

ACTIVITY LT-3.1-E: RECOVER BINARY PROPERTIES AT THE TIME OF FORMATION

Parameter estimates obtained for events thus far correspond to the binaries' properties at some reference frequency, typically when the signal enters the sensitive frequency band of the detectors. To better understand formation scenarios for these binaries, we will need methods to evolve such constraints backward to earlier times.

ACTIVITY LT-3.1-F: RESEARCH AND DEVELOPMENT OF NEW TECHNIQUES

We will continue to investigate the use of new algorithms or hardware-specific optimization (e.g., GPUs) for CBC parameter estimation, to support the desire to lower overall latency until final results are obtained, but also to allow codes to scale to increasing numbers of parameters and/or complex signal models.

Op-3.2 Tests of General Relativity R&D (Short Term)

Short-term research and development on tests of general relativity using compact binary coalescences.

Motivation and methods

The Testing General Relativity group is primarily responsible for testing the consistency of the observed GW signals by LIGO and Virgo with predictions of GR, and for developing the associated data analysis infrastructure. Due to the lack of reliable waveform models in alternative theories, currently the group's primary focus is on "null" tests, which aim to put constraints on deviations from GR predictions without assuming specific alternative theories. Several other aspects of strong gravity, such as the true nature of black holes and the possible existence of exotic compact objects, are also pursued within the group.

Major aspects and methods for this activity

ACTIVITY Op-3.2-A: TESTS OF GR USING QUASI-NORMAL MODES

Sufficiently loud signals from massive BBHs should provide additional evidence of quasi-normal modes. Measurement of multiple quasi-normal modes will allow us to constrain the Kerr nature of the merger remnant.

TASK Op-3.2-A(i): TESTS OF THE NATURE OF THE MERGER REMNANT

Test the nature of merger remnant through measurements of parametrized deviations from GR predictions on complex frequencies and cross-comparison of various modes.

FTE-months: 30.0

ACTIVITY Op-3.2-B: SEARCH FOR LATE TIME ECHOS OF BBH MERGER SIGNALS

Some of the quantum gravity inspired alternatives to black hole horizons predict late-time echoes of GW signals in BBH mergers. These can be constrained, or detected, using upcoming BBH observations.

TASK Op-3.2-B(i): ECHO SEARCHES

Develop and improve echo searches using template-based and model-independent approaches

FTE-months: 6.0

ACTIVITY Op-3.2-C: SUBGROUP ADMINISTRATION

Management of the Testing General Relativity subgroup.

TASK Op-3.2-C(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 2.0

LT-3.2 Tests of General Relativity R&D (Long Term)

Long-term research and development on tests of general relativity using compact binary coalescences.

Major aspects and methods for this activity

We will develop methods to perform the following tests of general relativity and assessment of systematics.

ACTIVITY LT-3.2-A: CONSTRAINING THE PARAMETER SPACE OF VARIOUS BLACK HOLE MIMICKERS

There are theoretical proposals of exotic alternatives to black holes, which can be massive and compact enough to be confused with black holes. We will be able to constrain the parameter space of some of these models based on constraints on the tidal deformability, spin-induced quadrupole moment, etc.

ACTIVITY LT-3.2-B: CHARACTERIZATION OF WAVEFORM SYSTEMATICS

Missing physics, including eccentricity, higher-order modes, spin precession, black-hole charge and non-vacuum environments have the ability to mimic deviations of GR. A systematic exploration of the impact of inaccuracies and missing physics in waveform templates on various tests of GR will be conducted.

ACTIVITY LT-3.2-C: BEYOND-GR EFFECTS ON THE GW WAVEFORM AND TESTS OF GR

Effects beyond GR will manifest themselves in all stages of the gravitational waveform, including the inspiral, merger, ringdown and possible echoes. Different tests of GR will respond differently to different classes of effects. We will explore beyond-GR effects on the GW waveform and tests of GR.

ACTIVITY LT-3.2-D: SEARCHES FOR NON-TENSORIAL POLARIZATIONS

Emission of beyond-GR GWs with scalar or vector polarizations can occur with arbitrary phases evolutions and polarization mixtures. We will develop model agnostic and theory-specific analyses.

Op-3.3 CBC Waveform Models R&D (Short Term)

Development of waveforms to faithfully model physics in binary coalescence for searches, parameter estimation and tests of General Relativity (short term).

Motivation and methods

The waveforms group aims to provide the collaboration with waveform models for template-based analyses of gravitational wave events, most importantly for compact binary coalescence events. Our long-term vision foresees waveform models which include all physical effects that may influence our GW analyses, and which can be evaluated sufficiently quickly for all GW-analysis purposes. Furthermore, we strive to quantify errors that arise from model approximations and from neglected physical effects. These goals require a combination of analytical and numerical modeling of CBC waveforms, as well as acceleration techniques to speed up evaluation of waveform models.

Major aspects and methods for this activity

The following activities are critical for generating O3 results.

ACTIVITY Op-3.3-A: NEW WAVEFORM MODELS

Improve / add waveform models expanding parameter ranges or introducing new physics.

TASK Op-3.3-A(i): PRECESSING BBH WAVEFORM MODELS

FTE-months: 36.0

Improve precessing BBH waveform models by extensively tuning/testing against precessing numerical relativity (NR) simulations.

TASK Op-3.3-A(ii): INCLUDE ECCENTRICITY IN BBH WAVEFORM MODELS

FTE-months: 36.0

Eccentric waveform models are required to quantify search sensitivity, and to estimate or bound the eccentricity of observed CBC events. We aim to develop models for moderate eccentricity that cover non-spinning and subsequently aligned-spin binaries. Specifically, we aim to have a non-spinning eccentric IMR model implemented in LAL and reviewed by the end of O3.

TASK Op-3.3-A(iii): TIDAL & SPIN EFFECTS FTE-months: 36.0

Improve inspiral waveforms for NS-NS and BH-NS systems that include NS-tides and NS-spin effects.

TASK Op-3.3-A(iv): IMPROVE MODELING OF SUB-DOMINANT MODES FTE-months: 36.0

To allow for improved parameter estimation, we aim to improve our waveform models of spinning, non-precessing BBH systems, and to include sub-dominant modes in precessing IMR waveform models. Sub-dominant modes will also be implemented for waveform models of tidally interacting binaries.

TASK Op-3.3-A(v): IMPROVED NR-CALIBRATED FITS FOR SPECIFIC BBH PROPERTIES FTE-months: 12.0

In addition to full waveform models, there is continued need in parameter estimation and testing-GR applications for more accurate and general NR-calibrated fits for BBH properties such as final mass, final spin, radiated energy, kicks, peak luminosity and frequency. New developments can include both conventional fits and surrogate models, with a particular focus on the full precessing parameter space.

TASK Op-3.3-A(vi): NR-CALIBRATED FITS FOR SPECIFIC BH-NS AND NS-NS PROPERTIES FTE-months: 12.0

Implement in LAL accurate NR-calibrated fits for binaries including the remnant black hole mass and spin, radiated energy, peak luminosity and postmerger frequencies fits.

TASK Op-3.3-A(vii): EXPAND THE NR WAVEFORM CATALOG AS BASELINE DATA FOR A VARIETY OF WAVEFORM/PE/TESTINGGR/BURST PROJECTS FTE-months: 12.0

For BBH: Convert to LVC-NR format and add to the LVC-NR repository additional BBH waveforms. Of particular priority are NR waveforms with validated sub-dominant modes of sufficient accuracy even at high SNR; eccentric simulations; simulations at sparsely explored regions of high mass-ratio, high spin or both; long simulations to validate transition to analytical inspiral waveforms; and detailed coverage of merger/ringdown for high-mass systems. We also plan to expand simulation coverage supporting comparisons of GW measurements directly to the NR waveform catalog, without the need for an intermediary model.

For BH-NS, NS-NS systems: Convert to LVC-NR format and add to the LVC-NR repository waveforms for BH-NS and NS-NS systems which are either publicly available, or contributed by NR groups.

ACTIVITY Op-3.3-B: EVALUATION OF WAVEFORM MODELS

Waveform models will be evaluated in the following ways.

TASK Op-3.3-B(i): CROSS-VALIDATION BETWEEN DIFFERENT NR CODES FOR CBC SYSTEMS FTE-months: 12.0

Cross-validation between different NR codes for CBC systems to assess the accuracy and reliability of NR waveforms to confirm NR waveforms are of sufficient quality for their use in studies as varied as search-efficiency, parameter recovery bias, and waveform model development. Of particular priority are: precessing BBH; a comparison of sub-dominant modes; and NS-NS simulations.

TASK Op-3.3-B(ii): CONTINUE PER-EVENT NR FOLLOW-UP AS NEEDED FTE-months: 2.0

Improve the accuracy of observational statements and/or test systematic biases using NR simulations in response to suitable detection candidates.

Task Op-3.3-B(iii): Improve Understanding of Waveform Model Errors and Attendant Systematics

FTE-months: 6.0

Improve understanding of waveform model errors and attendant systematics by cross-comparisons between different waveform models or parameterized models. In particular at significantly unequal mass-ratios and/or high spins, and also paying attention to sub-dominant modes.

Activity Op-3.3-C: Algorithmic and Computational Improvements to Waveform Models

Task Op-3.3-C(i): Evaluation Speed of Important Waveform Models

FTE-months: 6.0

Improve evaluation speed of important waveform models for faster turn-around of parameter estimation, most notably tidal NS-NS waveforms and EOB models.

Task Op-3.3-C(ii): Investigate Application of New Mathematical Tools to Waveform Modeling

FTE-months: 6.0

Such tools may lead to the development of models that include more physical effects (e.g., surrogate models, deep learning or Gaussian process regression), or that may significantly speed up existing waveform models (e.g., reduced-order models).

Activity Op-3.3-D: Waveform Review

Task Op-3.3-D(i): Reviews of Waveform Code

FTE-months: 36.0

Review of implementation of waveform models, including code review, correctness of results across domain of applicability, and conformance to waveform conventions.

Activity Op-3.3-E: Code Maintenance and Infrastructure Improvement

Task Op-3.3-E(i): LALSimulation code maintenance

FTE-months: 6.0

Rapid response to LALSimulation bug fixes, code changes and feature requests that are required to carry out the Collaboration's science tasks.

Task Op-3.3-E(ii): Develop Review Package for Standard Tests

FTE-months: 3.0

Task Op-3.3-E(iii): Standardize Waveform Conventions Across Models

FTE-months: 3.0

Task Op-3.3-E(iv): Numerical Relativity Injection Infrastructure

FTE-months: 4.0

Extend the Numerical Relativity Injection Infrastructure to handle eccentric waveforms, for which the orbital frequency is not monotonic.

Activity Op-3.3-F: Subgroup Administration

Management of the Waveforms subgroup.

Task Op-3.3-F(i): Subgroup Leadership

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.3 CBC Waveform Models R&D (Long Term)

Development of waveforms to faithfully model physics in binary coalescence for searches, parameter estimation and tests of General Relativity (long term).

Motivation and methods

Our ultimate goal is a plurality of waveform models for systems which may include precession, eccentricity and matter effects all together. Specific aspects toward this ultimate goal are articulated in the major aspects for this activity (below).

Major aspects and methods for this activity

ACTIVITY LT-3.3-A: PRECESSING AND ECCENTRIC IMR WAVEFORM MODELS

Development of precessing and eccentric IMR waveform models.

ACTIVITY LT-3.3-B: ACCURATE NS-BH AND BH-BH WAVEFORM MODELS FOR PRECESSING SYSTEMS INCLUDING EQUATION-OF-STATE EFFECTS AND SUB-DOMINANT MODES

Develop accurate NS-BH and BH-BH waveform models for precessing systems including equation-of-state effects and sub-dominant modes.

ACTIVITY LT-3.3-C: BH-NS WAVEFORM MODELS THAT INCLUDE MERGER/DISRUPTION OF THE NS

Develop BH-NS waveform models that include merger/disruption of the NS.

ACTIVITY LT-3.3-D: WAVEFORM MODELS FOR BINARIES ON UNBOUND ORBITS

Develop waveform models for hyperbolic and parabolic encounters.

ACTIVITY LT-3.3-E: LONG EVOLUTION OF WAVEFORMS

Compute NR waveforms for all types of CBC systems with sufficient accuracy and length to quantify waveform modeling errors at sensitivities of future GW detectors.

Op-3.4 Binary Coalescence Rates and Population R&D (Short Term)

Provide the means to estimate the astrophysical rate of various classes of compact binary coalescences, estimate model-driven distributions of their properties, and leverage that modelling to improve understanding of astrophysical processes and environments.

Motivation and methods

The primary charge of the Rates and Population (Rates/Pop.) subgroup is to infer the properties of astrophysical populations of merging binaries through statistical and phenomenological modelling. These properties include the mass, spin, intrinsic merger rate, and spatial distributions. This modelling is then fed back into schemes which process the outputs of CBC searches and of parameter estimation algorithms to categorize and establish the significance of new events as they arise.

Possible binary merger events are considered in four categories: the binary black hole (BBH) and binary neutron star (BNS) categories are currently observed with a non-zero event rate (expected number of mergers per time per unit of comoving volume), while for the neutron star black hole binary (NSBH) and intermediate mass black hole binary (IMBHB) categories we establish upper limits on rate. This categorization is ad-hoc, but the implied boundaries correspond to possible divisions in the occurrence and outcomes of astrophysical processes, e.g. core collapse supernovae or binary mass transfer. The distributions of events within each category are influenced by a rich set of astrophysical phenomena which we wish to explore. With the initial set of 10 BBH and 1 BNS obtained in O1 and O2, we have begun to observe broad features in the mass, spin, and redshift evolution space.

The need for a more fine-grained approach to event categorization and rate measurement led to an extension to the rates and significance infrastructure — a mixture model of foreground and background fit empirically to search distributions. This procedure was employed to self-consistently categorize and obtain merger rates of the aforementioned categories for the events in the O1/O2 catalog. However, the population distribution and inferred rate/categorization schemes are strongly coupled — additional developments to unify the two branches of research are underway.

As the binary merger census expands in number and cosmological reach, additional features of their population will become measurable. Furthermore, we should be able to resolve subpopulations. With a few hundred events in hand, we are likely able to determine details about the origin of the components, as well as probe correlations between mass and spin distributions. Thus, we expect that collection of more events will allow us to develop a more refined and comprehensive picture of the properties of the *population*, e.g., their formation channels and properties in aggregate. It is expected that the infrastructure developed in the context of BBH is flexible enough to encompass and connect more event categories as they are discovered. In addition to the interface with CBC searches, we also expect work here to influence both the structure and data products exposed in future catalogs of compact binaries.

This group is also committed to interfacing with other communities which develop astrophysical simulations (binary population synthesis for example) in a variety of contexts, as well as opportunistic projects and/or synergies which can leverage our modelling to infer or measure specific processes or properties of astrophysical or cosmological significance which are otherwise inaccessible.

Major aspects and methods for this activity

ACTIVITY Op-3.4-A: MONITORING AND UPDATING POPULATION INFERENCE

As an ongoing activity, the R&P group will monitor updates to the mass, spin, and redshift distributions for known categories of binaries. This will enable us to identify exceptional events, and significant updates to distribution morphology, as well as enable preliminary explorations of astrophysical implications.

TASK Op-3.4-A(i): UPDATING MODEL CONSTRAINTS

FTE-months: 2.0

On a roughly bi-weekly cadence (or the cadence that is commensurate to the current detection rate), will provide updates to baseline parameter distributions such as mass, spin, and rates.

ACTIVITY Op-3.4-B: COMMON CODE AND DATA PRODUCT DEVELOPMENT

To support the ongoing and future activities of the R&P group, we will continue to develop a common set of codes and data product formats. Its primary purpose is to allow comparison of baseline inference codes and to easily disseminate the results of studies. Several of these codes will also benefit from a single source of information needed by inference codes, such as event sample ingestion and preparation and computation of detection selection effects and surveyed volume. Longer term goals involve integration of codebases to facilitate internally consistent mode parameter, rates, and detection significance/categorization into a single pipeline as well as common model definitions.

TASK Op-3.4-B(i): RAPID SOURCE CLASSIFICATION AND P-ASTRO CALCULATION OF LOW-LATENCY TRIGGERS

FTE-months: 1.0

Consuming the outputs of low latency CBC searches to calculate the astrophysical significance of each event candidate as it is produced. This will interface with the LVAlert and gracedb event brokers.

In addition to this, examine using the outputs of event parameter estimation to update and refine source classification.

TASK Op-3.4-B(ii): METHODS TO MEASURE PIPELINE SPACETIME SENSITIVITY

FTE-months: 6.0

Develop methods to efficiently measure the spacetime sensitivity of a network of interferometers delineated by source parameters and redshift, integrating this characterization with population inference codes, and ensuring they achieve the accuracy needed for our science goals. Publishing this infrastructure and associated data product is essential for both internal and external science.

ACTIVITY Op-3.4-C: POPULATION INFERENCE PLATFORM DEVELOPMENT

The O1 and O2 populations were inferred by a suite of tools designed to explore various features of the binary merger parameter space. Here we describe the efforts to expand and merge these platforms for inference.

TASK Op-3.4-C(i): EMPIRICAL DISTRIBUTIONS — BINNED MASS DISTRIBUTIONS

FTE-months: 6.0

Investigate the component mass distribution using a regularized Gaussian process fit to a binned mass distribution. This expands on the current parameterized power law primary mass hierarchical inference.

TASK Op-3.4-C(ii): EMPIRICAL DISTRIBUTIONS II — GMMS AND MCMCS FOR MASS AND SPIN DISTRIBUTIONS

FTE-months: 6.0

Determine parameter dependent event rates using both parameteric and nonparametric methods. Planned for low latency operation, and as needed in the short term for LSC publications.

TASK Op-3.4-C(iii): HIERARCHICAL INFERENCE ENGINE WITH THE `RAPID_PE` TOOLKIT

FTE-months: 6.0

The `rapid_pe` pipeline allows for non-Markovian evaluation of the GW event likelihood function. This is specially suited to hierarchical inference since it avoids some of the complications of priors required to evaluate the hierarchical likelihood.

ACTIVITY Op-3.4-D: POPULATION ASTROPHYSICS

As more fine-grained features of the population become measurable, we intend to make more detailed studies of their potential origins in astrophysical processes. Also, we will investigate the origin of correlations within the distributions, while further constraining potential physical mechanisms.

TASK Op-3.4-D(i): REDSHIFT EVOLUTION OF RATES AND MASS DISTRIBUTIONS

FTE-months: 6.0

This project will extend the infrastructure needed to infer rate and mass spectrum dependence on redshift.

TASK Op-3.4-D(ii): EVALUATION OF MASS AND SPIN DISTRIBUTIONS BY THE USE OF PHENOMENOLOGICAL AND/OR PARAMETERIZED MODELS

FTE-months: 6.0

Develop phenomenological and/or parameterized models to best extract astrophysics from the population.

TASK Op-3.4-D(iii): IDENTIFICATION AND EXPLOITATION OF BBH MASS SCALES FOR COSMOLOGY

FTE-months: 6.0

Identify and calibrate mass scales in the BBH mass distribution as an independent measure of merger redshifts and explore cosmological constraints that can be obtained from the BBH population.

TASK Op-3.4-D(iv): DISTINGUISHING FORMATION SCENARIOS USING SPINS FTE-months: 3.0

Applying the results of spin measurements from GW observations to distinguish BBH fornation scenarios.

TASK Op-3.4-D(v): INFERENCE ON ASTROPHYSICALLY MOTIVATED FEATURES IN POPULATIONS FTE-months: 3.0

Identify features in mass / spin / redshift dependent rate distributions which arise from astrophysical processes. Interpretation and inference on these within the physical constraints imposed by phenomenological and physically motivated models in the literature.

ACTIVITY Op-3.4-E: INTEGRATION AND FEEDBACK WITH OTHER R&D GROUPS

The tools and results produced by the R&P group is both dependent on and can influence the research direction of other groups and projects. We list projects within the scope of R&P which also have significant impact and expertise drawn from other R&D groups and their charges.

TASK Op-3.4-E(i): POPULATION-BASED TEMPLATE WEIGHTING METHODS TO EVALUATE CBC RATES FTE-months: 3.0

Binary merger search pipelines can be optimized for detecting a population of events with a known parameter distribution, by incorporating a template-dependent weighting in their ranking statistics. The resulting ranking statistic maps to the ratio of density of signal events from the given population to noise events, which is then directly applicable to the mixture model approach for estimating rates in the presence of noise events. Mass weighting for fixed (known) population distributions is already implemented in some form in the offline search pipelines, either simply via hard cuts in parameter space or by more sophisticated methods allowing for potentially overlapping signal populations. There is thus room for significant upgrades concerning detail and accuracy of modelling, flexibility and computational cost.

TASK Op-3.4-E(ii): AUTOMATED SIMULATION-BASED SENSITIVITY ESTIMATION FTE-months: 2.0

In order to accurately survey the search sensitivity to a continuous spectrum of possible binary populations, a computationally intensive 'broad range' simulation campaign will be designed and carried out. The outcome of these simulations (injections) will be processed via importance sampling to model any given population. We will explore how to reuse the results of injection campaigns to most effectively cover the parameter space, yielding an automated population sensitivity estimate.

TASK Op-3.4-E(iii): IMPACT OF WAVEFORM SYSTEMATICS ON INFERENCE FTE-months: 6.0

Coordinating with the waveform and parameter estimation groups, when warranted we will assess the impact of model systematics on population inference. As in O2, in the short term we will begin this analysis by repeating our inferences with multiple waveform inputs.'

TASK Op-3.4-E(iv): EOS MEASUREMENTS IN POPULATIONS OF NEUTRON STARS FTE-months: 6.0

Coordinating with the parameter estimation and extreme matter groups, population studies with neutron star components will incorporate and contribute to understanding of the equation of state of neutron star matter.

TASK Op-3.4-E(v): REEXAMINING EVENTS WITH POPULATION CONSTRAINTS FTE-months: 2.0

Coordinating with the parameter estimation and extreme matter group, individual events should be reexamined with priors corresponding to constraints implied by the current knowledge of the population (e.g. mass and spin reweighting). This will impact our understanding of their properties in the context of the population itself.

TASK Op-3.4-E(vi): BRIDGING POPULATIONS WITH COSMOLOGY AND TESTING GR

FTE-months: 6.0

Coordinating with the cosmology and TGR group, we should strive to disseminate and apply consistently our best knowledge of population distributions. As our measurements become more refined, cross-correlations between our inferred mass, spin, and redshift distributions will strongly influence the conclusions drawn by other groups. This calls for methodological studies and stronger dialog between groups.

ACTIVITY Op-3.4-F: RATES AND POPULATIONS METHODS AND CODE REVIEW

TASK Op-3.4-F(i): REVIEW OF PARTICULAR METHOD

FTE-months: 6.0

Integrated method and code review for particular method.

ACTIVITY Op-3.4-G: SUBGROUP ADMINISTRATION

Management of the Rates and Populations subgroup.

TASK Op-3.4-G(i): SUBGROUP LEADERSHIP

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.4 Binary Coalescence Rates and Population R&D (Long Term)

Long term development of interpretative superstructure to infer astrophysics which is sensitive to the distribution of their properties.

Major aspects and methods for this activity

ACTIVITY LT-3.4-A: COMMON CODE AND DATA PRODUCT DEVELOPMENT

To support the ongoing and future activities of the R&P group, we will continue to develop a common set of codes and data product formats. Its primary purpose is to allow comparison of baseline inference codes and to easily disseminate the results of studies. Several of these codes will also benefit from a single source of information needed by inference codes, such as event sample ingestion and preparation and computation of detection selection effects and surveyed volume. Longer term goals involve integration of codebases to facilitate internally consistent mode parameter, rates, and detection significance/categorization into a single pipeline as well as common model definitions.

TASK LT-3.4-A(i): MIXTURE MODEL FOR SIGNAL AND NOISE POPULATIONS

FTE-months: 6.0

Develop a fully self-consistent mixture model analysis that can simultaneously infer the population and rate of both foreground (astrophysical) and background (noise) events without further interpretation from searches. This will allow for distinguishing terrestrial noise events without biasing our inferences by assuming all candidate events above an arbitrary threshold to be real.

TASK LT-3.4-A(ii): RATES AND POPULATION TOOLKIT DEVELOPMENT

FTE-months: 6.0

Develop a set of search-independent and flexible tools to facilitate population rates and inference. `https://git.ligo.org/RatesAndPopulations/lvc-rates-and-pop/`

ACTIVITY LT-3.4-B: POPULATION INFERENCE PLATFORM DEVELOPMENT

The O1 and O2 populations were inferred by a suite of tools designed to explore various features of the binary merger parameter space. Here we describe the efforts to expand and merge these platforms for inference.

TASK LT-3.4-B(i): EMPIRICAL DISTRIBUTIONS — FUTURE DEVELOPMENT

FTE-months: 12.0

Explore, implement, and assess the need/use cases for more flexible population inference models, in offline and potentially low-latency use.

ACTIVITY LT-3.4-C: POPULATION ASTROPHYSICS

As more fine-grained features of the population become measurable, we intend to make more detailed studies of their potential origins in astrophysical processes. Also, we will investigate the origin of correlations within the distributions, while further constraining potential physical mechanisms.

TASK LT-3.4-C(i): DISTINGUISHING FORMATION SCENARIOS USING SPINS

FTE-months: 6.0

Applying the results of spin measurements from GW observations to distinguish BBH fornation scenarios.

Op-3.5 CBC Cosmology R&D (Short Term)

Develop methods to estimate cosmological parameters using GW observations, and explore other aspects of CBCs as standard distance indicators (short term).

Motivation and methods

The cosmology group is responsible for obtaining estimates of cosmological parameters such as the Hubble parameter H_0 from GW signals detected by LIGO-Virgo. The methods involved include identification of a set of possible hosts using an observed EM counterpart to the GW event and statistical cross-correlation of the GW distance estimate with catalogues of potential host galaxies in the absence of a counterpart. Since a precise estimate requires combining information from multiple events, correcting for any systematic bias that is expected to accumulate over observations is crucial. Selection effects are known to play an important role even with only a few observations. Smaller effects like redshift uncertainties and GW calibration uncertainties could become important with an increasing number of observations. A large part of the research and development involves developing methods to understand and account for such effects.

Major aspects and methods for this activity

ACTIVITY Op-3.5-A: COSMOLOGY PIPELINE

A precise measurement of cosmological parameters, such as the Hubble parameter, requires combining information from multiple GW observations, with or without transient electromagnetic counterparts. The fact that gravitational wave interferometers have a finite detection threshold introduces a systematic selection bias. Additionally, for the statistical analysis with galaxy catalogues, the incompleteness of the catalogue is expected to introduce further biases. We have put together a pipeline to estimate cosmological parameters from multiple GW observations, taking into account the above selection effects. The existing pipeline is adequate for H_0 measurements with current data but must be further improved for the future.

TASK Op-3.5-A(i): COSMOLOGY CODE IMPROVEMENTS

FTE-months: 6.0

Add new features to gwcosmo code, including pixelisation and improved selection function estimation.

ACTIVITY Op-3.5-B: COSMOLOGY MOCK DATA CHALLENGE

Validation of current and future versions of the cosmology pipeline on simulated universes via a mock data challenge.

TASK Op-3.5-B(i): MOCK DATA CHALLENGE: CONSTRUCTION OF MOCK DATA SET

FTE-months: 3.0

One or more datasets (complete galaxy catalog, incomplete galaxy catalog, observed events) will be generated that include additional physical population features. MDCs will include both BBH and BNS sources.

TASK Op-3.5-B(ii): MOCK DATA CHALLENGE: VALIDATION OF COSMOLOGY PIPELINE

FTE-months: 6.0

Improvements to the cosmology pipeline will be validated by running on the previously mentioned mock datasets.

ACTIVITY Op-3.5-C: REVIEW OF COSMOLOGY PIPELINE

Continuing method and code review of the cosmology pipeline.

TASK Op-3.5-C(i): REVIEW OF COSMOLOGY PIPELINE METHODS

FTE-months: 1.0

Review of new statistical methods or features adopted in the cosmology pipeline.

TASK Op-3.5-C(ii): REVIEW OF COSMOLOGY PIPELINE CODE

FTE-months: 1.0

Review of the implementation of new statistical methods/features in the cosmology code.

TASK Op-3.5-C(iii): REVIEW OF COSMOLOGY PIPELINE MOCK DATA RESULTS

FTE-months: 1.0

Review of the performance of the cosmology code on the mock data challenge.

ACTIVITY Op-3.5-D: SYNERGIES WITH OTHER COSMOLOGICAL PROBES

Gravitational wave constraints on cosmological parameters are just one of many methods for understanding the large scale structure and evolution of the Universe. It has been frequently demonstrated that different probes can provide orthogonal constraints which, when combined, are much stronger than any one probe in isolation. As gravitational wave constraints improve, the impact on cosmological inference will be greatest when combined with other data sets. The purpose of this project is to understand how GW observations fit into this wider context. We will identify which other types of data are most complementary to the information coming from the GW observations and how constraints can be improved by combining data sets. Other data sets that we will consider will include type Ia supernovae, Baryon Acoustic Oscillations, strong lensing (e.g., HOLICow), surface brightness fluctuation measurements and others.

Another aspect of this project will be to explore how these combined analyses can improve our understanding of other cosmological probes. An example of this is to use GW measurements to improve calibration of type IA supernovae. A binary neutron star coalescence event could be used to validate the distance to a galaxy or a cluster in which a supernova is known to have occurred and hence provide an independent calibration of the supernova luminosity. The GW measurement would be better than other distance estimators if the event was within 100Mpc. We will explore how such measurements might influence measurements of H_0 using supernovae. Using the population of standard sirens, it may also be possible to cross-calibrate other methods such as Type Ia SNe or BAO. This will be particularly useful as a way to look for systematic errors.

TASK Op-3.5-D(i): CATALOGUE CONSTRUCTION FOR SUPERNOVAE CALIBRATION

FTE-months: 3.0

Assemble a catalogue of all nearby (< 1 Gpc) supernovae, focussing especially on clusters and SNe type Ia.

TASK Op-3.5-D(ii): MOCK DATA CHALLENGE FOR SUPERNOVA CALIBRATION

FTE-months: 9.0

Set up a mock data challenge for coincident observation of a binary neutron star event and a SNe Ia.

TASK Op-3.5-D(iii): COMPARISON OF STANDARD SIREN CONSTRAINTS WITH OTHER METHODS

FTE-months: 12.0

Situate standard siren constraints within the landscape of cosmological constraints, focusing especially on Type Ia supernovae and strong lensing time delay constraints.

ACTIVITY Op-3.5-E: SUBGROUP ADMINISTRATION

Management of the Cosmology subgroup.

TASK Op-3.5-E(i): SUBGROUP LEADERSHIP

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.5 CBC Cosmology R&D (Long Term)

Develop methods to estimate cosmological parameters using GW observations, and explore other aspects of CBCs as standard distance indicators (long term).

Major aspects and methods for this activity

ACTIVITY LT-3.5-A: IMPORTANCE OF PECULIAR VELOCITY CORRECTIONS AS A FUNCTION OF DISTANCE

A crucial strength of GW standard sirens is that they provide distances that bypass completely the traditional EM "distance ladder" that combines primary and secondary distance indicators. For sources within the Local Supercluster, however, the peculiar velocity of the siren host galaxy can require significant correction, as was the case for GW170817. While most BBH sirens are likely to be sufficiently distant that these peculiar velocity corrections are not important, we propose to investigate thoroughly the potential impact of systematic errors in the peculiar velocity correction for nearby sources, particularly "golden" NS binaries within 100 Mpc. We will use mock galaxy catalogues derived from n-body simulations to study this, with particular focus on systematics arising from possible non-Gaussian peculiar velocity residuals.

ACTIVITY LT-3.5-B: DEVELOP A COMPLETE UNDERSTANDING OF SYSTEMATIC EFFECTS IN MEASUREMENT OF COSMOLOGICAL PARAMETERS

Since a precise estimate of cosmological parameters requires combining information from multiple events, even small systematic effects can lead to biases in measurements. In addition to the impact of selection effects already discussed above, systematic biases can be present in redshift estimates in galaxy catalogues, which can be significant if photometric catalogues are being used. Incorrect assumptions about the astrophysical population of sirens and the evoluaiton of the merger rate with redshift can also lead to biases in the measured cosmological parameters. Moreover GW calibration effects and GW waveform uncertainties are also expected to become important as the precision of measurement becomes tighter with an increasing number of observations. Other effects such as galaxy clustering or correlations between BNS mergers and the properties of their host galaxies might also lead to systematic biases if ignored, but could also be exploited to improve the power of the statistical method. We plan to investigate and attempt to understand these effects thoroughly and compute the requirements (on both statistical uncertainties and systematic biases) necessary to achieve any given specified accuracy in the estimation of cosmological parameters.

ACTIVITY LT-3.5-C: COMBINING COSMOLOGICAL AND POPULATION INFERENCE

Cosmological constraints rely on models of the astrophysical population of sirens being used in the analysis. At present, the cosmological inference uses a handful of population models consistent with the results of rates and populations analysis. However, this neglects correlations between inferred population parameters and does not reflect the uncertainties. In addition, the rates and populations analysis assumes a fixed cosmology, and so there is an inconsistency when using those results to subsequently infer cosmological parameters. In the long term, inference should be on cosmological and population parameters simultaneously, with one set of parameters marginalised over when inferring the other and vice versa. In the short term, improvements will come from using the posterior distributions of one analysis in the other rather than point estimates. Briging these analyses together will require methodological studies and close links with other groups, in particular Rates and Populations.

Op-3.6 CBC All Sky Search R&D (Short Term)

Short term development and tuning of search pipelines for online/offline running; generate template banks; assess data quality issues relevant to CBC detection.

Motivation and methods

The online and offline detection and search technical development groups work to develop sensitive and computationally efficient pipelines to identify compact binary merger signals in strain data, and manage the generation of search results via running the pipelines on LIGO-Virgo data. These pipelines generally operate in “all-sky” mode, i.e., searching all available data after non-analyzable times have been identified and removed, as distinct from “externally triggered” searches for GWs from reported astrophysical events such as GRBs.

Offline searches run with a latency of order a few days to weeks on a stable and carefully selected data set, to provide reproducible results for publication including precise evaluation of the significance of candidate events and the sensitivity of the search to populations of realistic binary merger signals. Online / low-latency searches run primarily to generate triggers for follow-up including initial evaluation of trigger significance, mass and spin values and extrinsic parameters relevant to sky localization. Development of methods for low latency data selection and estimation of search sensitivity is motivated by the desirability of convergence of results between online and offline searches if possible.

Major aspects and methods for this activity

ACTIVITY Op-3.6-A: O3 PIPELINE DEVELOPMENT

As the detector sensitivity curves change, and as the network of gravitational wave detectors grow, it is necessary to update aspects of the search pipelines to optimize search efficiency.

Changes to template banks are needed in order to respond to changes in detector sensitivity curves as well as changes to the parameter space of signals being targeted.

By the end of O2, Virgo had joined the two LIGO detectors in the network of gravitational wave observatories. GW170814 was the first joint LIGO-Virgo detection. The GstLAL pipeline analyzed the end of O2 data with a pipeline that included 3 detectors in it detection statistic. PyCBC is upgrading its detection statistic to handle more than two detectors for O3. The KAGRA detector will potentially join LIGO and Virgo during O3b. If sufficiently sensitive, it could have a positive impact on detection efficiency.

TASK Op-3.6-A(i): CONSTRUCTION OF A TEMPLATE BANK FOR GSTLAL FTE-months: 12.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes. Tune and test the template bank's performance in simulations and real data.

TASK Op-3.6-A(ii): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR GSTLAL FTE-months: 12.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK Op-3.6-A(iii): CONTINUE OPTIMIZING THE GSTLAL SEARCH SENSITIVITY DURING O3 FTE-months: 12.0

Incremental improvements to the GstLAL pipeline's search sensitivity during the O3 run.

TASK Op-3.6-A(iv): CONTINUE OPTIMIZING THE GSTLAL COMPUTATIONAL PERFORMANCE DURING O3 FTE-months: 12.0

Incremental improvements to the GstLAL pipeline's computational performance during the O3 run.

TASK Op-3.6-A(v): CONTINUE OPTIMIZING THE GSTLAL ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE FTE-months: 24.0

Improvements to GstLAL online analysis that reduce latency of alerts and allow for BNS alerts $\sim$ 30 seconds before merger.

TASK Op-3.6-A(vi): CONSTRUCTION OF A TEMPLATE BANK FOR MBTA FTE-months: 2.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK Op-3.6-A(vii): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR MBTA FTE-months: 6.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK Op-3.6-A(viii): CONTINUE OPTIMIZING THE MBTA SEARCH SENSITIVITY DURING O3 FTE-months: 8.0

Incremental improvements to the MBTA pipeline's search sensitivity during the O3 run.

TASK Op-3.6-A(ix): CONTINUE OPTIMIZING THE MBTA COMPUTATIONAL PERFORMANCE DURING O3 FTE-months: 3.0

Incremental improvements to the MBTA pipeline's computational performance during the O3 run.

TASK Op-3.6-A(x): CONSTRUCTION OF A TEMPLATE BANK FOR SPIIR FTE-months: 2.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK Op-3.6-A(xi): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR SPIIR FTE-months: 6.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK Op-3.6-A(xii): CONTINUE OPTIMIZING THE SPIIR SEARCH SENSITIVITY DURING O3 FTE-months: 8.0

Incremental improvements to the SPIIR pipeline's search sensitivity during the O3 run.

TASK Op-3.6-A(xiii): CONTINUE OPTIMIZING THE SPIIR COMPUTATIONAL PERFORMANCE DURING O3 FTE-months: 3.0

Incremental improvements to the SPIIR pipeline's computational performance during the O3 run.

TASK Op-3.6-A(xiv): CONSTRUCTION OF A TEMPLATE BANK FOR PYCBC FTE-months: 2.0

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK Op-3.6-A(xv): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR PYCBC FTE-months: 12.0

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK Op-3.6-A(xvi): CONTINUE OPTIMIZING THE PYCBC SEARCH SENSITIVITY DURING O3 FTE-months: 12.0

Incremental improvements to the PyCBC pipeline's search sensitivity during the O3 run.

TASK Op-3.6-A(xvii): CONTINUE OPTIMIZING THE PYCBC COMPUTATIONAL PERFORMANCE DURING O3 FTE-months: 4.0

Incremental improvements to the PyCBC pipeline's computational performance during the O3 run.

TASK Op-3.6-A(xviii): GENERATION OF INJECTION SETS FOR OFFLINE RUNS FTE-months: 3.0

Generation of injection sets to be used to estimate spacetime volume sensitivity of the various pipelines over parameter space.

ACTIVITY Op-3.6-B: O3 PIPELINE DEPLOYMENT

Search pipelines must be deployed and maintained on collaboration computer clusters for both online and offline analyses.

TASK Op-3.6-B(i): DEPLOYMENT OF GSTLAL PIPELINE FOR ONLINE RUNNING FTE-months: 24.0

Deploy, monitor, and maintain the GstLAL online pipeline for low-latency trigger generation.

TASK Op-3.6-B(ii): DEPLOYMENT OF GSTLAL PIPELINE FOR OFFLINE RUNNING FTE-months: 24.0

Deploy and maintain the GstLAL pipeline for deeper offline searches.

TASK Op-3.6-B(iii): DEPLOYMENT OF MBTA PIPELINE FOR ONLINE RUNNING FTE-months: 6.0

Deploy, monitor, and maintain the MBTA online pipeline for low-latency trigger generation.

TASK Op-3.6-B(iv): DEPLOYMENT OF PYCBC PIPELINE FOR ONLINE RUNNING FTE-months: 6.0

Deploy, monitor, and maintain the PyCBC online pipeline for low-latency trigger generation.

TASK Op-3.6-B(v): DEPLOYMENT OF PYCBC PIPELINE FOR OFFLINE RUNNING FTE-months: 8.0

Deploy and maintain the PyCBC pipeline for deeper offline searches.

TASK Op-3.6-B(vi): DEPLOYMENT OF SPIIR PIPELINE FOR ONLINE RUNNING FTE-months: 6.0

Deploy, monitor, and maintain the SPIIR online pipeline for low-latency trigger generation.

ACTIVITY Op-3.6-C: O3 PIPELINE REVIEW

Review of changes to O3 pipelines and to configuration changes.

TASK Op-3.6-C(i): REVIEW OF GSTLAL PIPELINE

FTE-months: 2.0

Review of changes to the GstLAL online and offline pipelines. Both changes to code and to configurations will be reviewed.

TASK Op-3.6-C(ii): REVIEW OF MBTA PIPELINE

FTE-months: 2.0

Review of changes to the MBTA online pipelines. Both changes to code and to configurations will be reviewed.

TASK Op-3.6-C(iii): REVIEW OF SPIIR PIPELINE

FTE-months: 2.0

Review of changes to the SPIIR online pipelines. Both changes to code and to configurations will be reviewed.

TASK Op-3.6-C(iv): REVIEW OF PYCBC PIPELINE

FTE-months: 2.0

Review of changes to the PyCBC online and offline pipelines. Both changes to code and to configurations will be reviewed.

ACTIVITY Op-3.6-D: SOURCE-DEPENDENT RESULTS FOR RATE CALCULATIONS

To infer the rates of sources which inhabit only a subset of the broad CBC search space (e.g. BNS, NSBH) it is desirable to produce results which are weighted or otherwise restricted to promote events originating from specific source types and downrank/exclude others. The timescale to implement improvements to the method adopted in O2 is the end of O3, and it intersects with Rates/Pop. work, Sec. Op-3.4.

TASK Op-3.6-D(i): IMPLEMENTATION OF MULTI-COMPONENT FGMC FOR GSTLAL PIPELINE

FTE-months: 12.0

Improve the source classification of the online and offline GstLAL pipelines throughout O3. For example, per-template weights must be updated whenever the template bank is updated, and possible analytic methods could be introduced to improve the fidelity of the method.

TASK Op-3.6-D(ii): IMPLEMENT P-ASTRO CALCULATION FOR PYCBC PIPELINE

FTE-months: 5.0

Include p-astro calculations within the PyCBC online/offline pipeline, including source classification in online and parameter space reweighting to better pick out signals where we already know details of the population.

ACTIVITY Op-3.6-E: CBC-RELATED DETECTOR CHARACTERIZATION TASKS

Development and maintenance of tools to characterize the impact of detector state on CBC searches and identify possible veto times was ongoing since O2 and will continue through O3 to adapt to new detector characterization challenges encountered.

TASK Op-3.6-E(i): DETCHAR FOLLOWUP OF GSTLAL TRIGGERS

FTE-months: 2.0

Investigate gstlal single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

TASK Op-3.6-E(ii): DETCHAR FOLLOWUP OF PYCBC TRIGGERS

FTE-months: 2.0

Investigate PyCBC single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

ACTIVITY Op-3.6-F: SUBGROUP ADMINISTRATION

Management of the all-sky pipelines subgroup.

TASK Op-3.6-F(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 2.0

LT-3.6 CBC All Sky Search R&D (Long Term)

Long term development and tuning of search pipelines for online/offline running.

Motivation and methods

As well as continuing to run online and offline searches in O3, we must start to consider the problems that future improvements to the detector, and the inclusion of additional detectors, will bring (All with next to no personpower). We specifically want to consider expanding the search parameter space to include "exotic" sources, which our current searches are not sensitive to. We want to consider how to efficiently search a network of detectors, and we want to start to consider how we will address the computational challenges that 3G-networks will pose.

Major aspects and methods for this activity

ACTIVITY LT-3.6-A: SEARCHING FOR NOVEL OR "EXOTIC" SOURCE TYPES

Current search techniques necessarily make assumptions about the signal model to reduce the computational cost. These assumptions lead to certain types of rare, but astrophysically very rewarding, systems potentially being missed. This includes systems exhibiting strong precessional dynamics, systems where subdominant modes have a significant contribution, systems on significantly eccentric orbits and signals emitted from compact objects whose behaviour significantly deviates from GR predictions. New methods have been proposed to search for some of these sources, but significant work on implementation and tuning of a search will be required to obtain results.

ACTIVITY LT-3.6-B: COHERENT ALL-SKY SEARCH WITH 3+ DETECTORS

CBC searches currently look for coincident triggers, with the exception of the coherent GRB analysis. In the long term, a network of 3+ detectors of comparable sensitivity will motivate the development of fully coherent search algorithms. Considerable work remains to be done in optimisation to extend the methods pioneered in the coherent GRB analysis to cover the all-sky, all-time parameter space in a computationally efficient manner. This research will continue throughout the O3 timeframe, with the aim of reaching maturity in time for design sensitivity detector networks.

ACTIVITY LT-3.6-C: NOVEL SEARCH OPTIMIZATION TECHNIQUES

To address the computational challenge that the 3G era, and to a lesser extent, a 5-detector 2G network at design sensitivity, will pose, we must consider how to reduce the computational cost of our searches. A number of methods have been proposed for this, including reducing the template count by using a reduced basis, using multi-banding to acheive a similar affect and computational optimization of existing codes. Additionally it has been proposed that convolutional neural networks might acheive similar sensitivity to traditional matched-filtering searches. Given the wide range of methods and the requirements of this activity is expected to be an area of research for some time to come, with the implementation and review of practical methods likely to be during O4 or beyond.

ACTIVITY LT-3.6-D: NOVEL SEARCH SENSITIVITY IMPROVEMENTS

As we learn more about the search parameter space, we should continue to think about how we can most effectively find the compact binary merger signals buried in our data. This broad item covers a number of techniques that might be considered to improve search sensitivity. This ranges from using improved signal-based classifiers to better separate noise from signal, using better glitch identification techniques to remove non-Gaussianities from the data that can particularly harm the search to including better knowledge of the types of compact binary in the Universe to better identify "sub-threshold" events.

ACTIVITY LT-3.6-E: SUBTHRESHOLD SEARCHES FOR GRAVITATIONALLY LENSED COUNTERPARTS

Subthreshold searches with reduced template banks based on both GstLAL or PyCBC are under development to look for gravitationally lensed counterparts of higher-significance events. Together with parameter estimation for (potential) lensed pairs and microlensing effects (see Op-3.1), such searches can be used to constrain lensing rates, rule out exotic models, and break degeneracies in hierarchical population studies.

Op-3.7 O3a Catalog of Compact Binaries

Produce a catalog of compact binary coalescence candidate signals observed during O3a along with parameter estimates and rate estimates. The catalog would include a binary merger found by a burst search, with template-based parameter estimation.

Motivation and goals

The Catalog represents the list of definitive and marginal compact binary coalescences identified by the LIGO/Virgo Collaboration along with search results, data quality statements, source classification, parameter estimates, and summary statements on tests of general relativity, equation of state inference, and rates and population inference.

At the end of O2, compact binary coalescences from ten binary black hole systems and one binary neutron star had been definitively observed [1]. With O3's improved sensitivity, a higher rate of observed events is expected. This will provide a population of signals that will allow improved estimates of astrophysical rates and distributions of compact binary coalescences; further tests of general relativity; and possibly detections of new categories of compact binaries such as neutron star + black hole systems or systems with components in putative astrophysical mass gaps. With the commissioning break separating the run into O3a and O3b, it is a natural choice to produce a catalog after each of these sub-runs, so as to disseminate our results in a timely way.

Major aspects and methods for this activity

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 O3 and release a detailed description of all detected systems, covering their detection and physical parameters, inferred using the best available waveform models.

In O3a data 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. Two independent search codes, pycbc and gstlal, will be run on the data. In addition, the cWB burst search will be run, which is capable of detecting higher-mass binary black hole systems.

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, including the statistical errors. We will also provide an estimate of the systematic error by 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 O3a, using latest versions of data quality and calibration. In coordination with the Gravitational Wave Open Science Center we will produce an electronic data release to go alongside the publication.

ACTIVITY Op-3.7-A: OFFLINE SEARCHES

Perform searches of gravitational wave data for compact binary coalescences using multiple search pipelines.

Note: requires calibrated data and detector characterization.

TASK Op-3.7-A(i): GSTLAL PIPELINE OPERATION

FTE-months: 12.0

Offline running of the GstLAL search over O3a data chunks.

TASK Op-3.7-A(ii): PYCBC PIPELINE OPERATION

FTE-months: 6.0

Offline running of the PyCBC search over O3a data chunks.

TASK Op-3.7-A(iii): CWB PIPELINE OPERATION

FTE-months: 7.0

Offline running of the cWB search over O3a data chunks.

ACTIVITY Op-3.7-B: DATA QUALITY

Obtain data quality statements for each detection candidate identified by the offline searches.

TASK Op-3.7-B(i): DETECTOR CHARACTERIZATION ROTA

FTE-months: 2.0

Produce a data quality report for each candidate event. This task is identical to task O.C.2.1 in the LSC-Virgo Operations White Paper.

ACTIVITY Op-3.7-C: OFFLINE PARAMETER ESTIMATION

Perform parameter estimation on detection candidates identified by the offline searches.

Note: requires calibrated data at times of events.

TASK Op-3.7-C(i): PARAMETER ESTIMATION EVENT ROTA

FTE-months: 12.0

Run parameter estimation pipeline on each candidate event. There are 2 parameter estimation rota takers at any one time, and, including training and write-up, this task amounts to about 50% time when on rota.

TASK Op-3.7-C(ii): PARAMETER ESTIMATION EXPERT ROTA

FTE-months: 12.0

Supervise parameter estimation event rota efforts. There are 2 parameter estimation expert rota takers at any one time (approximately 50% time when on-shift), plus the effort to train rota members.

Certify validity of sample chains.

FTE-months: 1.0 (Reviewer / experts)

TASK Op-3.7-C(iii): POSTERIOR SAMPLE CURATION

Collect preferred posterior sample chains from event rota runs for each candidate event. Make available as part of the electronic catalog.

FTE-months: 2.0

TASK Op-3.7-C(iv): WAVEFORM RECONSTRUCTION

Perform waveform reconstruction estimation.

FTE-months: 1.0

ACTIVITY Op-3.7-D: RATE ESTIMATION

Provide high-level rate and population statements on different source categories (BNS, NSBH, BBH, etc.).

TASK Op-3.7-D(i): MULTI-COMPONENT FGMC CLASSIFICATION

Apply multi-component FGMC method on event lists from CBC pipelines to obtain astrophysical probabilities for each source categories (Terrestrial, BNS, NSBH, BBH, etc.).

FTE-months: 6.0

TASK Op-3.7-D(ii): SUMMARY CATEGORICAL RATE ESTIMATION

Obtain high-level rate estimations based on the multi-component FGMC method results and the surveyed spacetime volumes measured using the injection sets.

FTE-months: 6.0

ACTIVITY Op-3.7-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.7-E(i): PROJECT MANAGEMENT

FTE-months: 3.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.7-E(ii): PAPER WRITING COORDINATION

FTE-months: 6.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.7-E(iii): FIGURE PREPARATION

FTE-months: 3.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.7-E(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 12.0

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.7-F: TECHNICAL REVIEW

TASK Op-3.7-F(i): REVIEW OF GSTLAL PIPELINE SEARCH RESULTS

Review of GstLAL search results: candidate lists, background estimation, sensitivity.

FTE-months: 1.0

TASK Op-3.7-F(ii): REVIEW OF PYCBC PIPELINE SEARCH RESULTS

FTE-months: 1.0

Review of PyCBC search results: candidate lists, background estimation, sensitivity.

TASK Op-3.7-F(iii): REVIEW OF CWB PIPELINE SEARCH RESULTS

FTE-months: 1.0

Review of cWB search results: candidate lists, background estimation, sensitivity.

TASK Op-3.7-F(iv): REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES

FTE-months: 1.0

Review of Parameter Estimation posterior sample chains.

ACTIVITY Op-3.7-G: PAPER REVIEW

TASK Op-3.7-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK Op-3.7-G(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

Expected products and/or outcomes

- Catalog publication of events in O3a: April, 2020 (submit to arXiv and journal).
- Strain data release surrounding catalog events in O3a: April, 2020 (GWOSC).
- Posterior samples for catalog events in O3a: April, 2020 (GWOSC).
- Data behind the figures appearing in O3a Catalog: April, 2020 (DCC).

Op-3.8 O3b Catalog of Compact Binaries

Produce a catalog of compact binary coalescence candidate signals observed during O3b along with parameter estimates and rate estimates. The catalog would include a binary merger found by a burst search, with template-based parameter estimation.

Motivation and goals

Continuation of activity Op-3.7 during O3b epoch.

Major aspects and methods for this activity

Similar to Op-3.7 for searches over data from O3b epoch.

ACTIVITY Op-3.8-A: OFFLINE SEARCHES

Perform searches of gravitational wave data for compact binary coalescences using multiple search pipelines.

Note: requires calibrated data and detector characterization.

TASK Op-3.8-A(i): GSTLAL PIPELINE OPERATION

FTE-months: 12.0

Offline running of the GstLAL search over O3b data chunks.

TASK Op-3.8-A(ii): PYCBC PIPELINE OPERATION

FTE-months: 6.0

Offline running of the PyCBC search over O3b data chunks.

TASK Op-3.8-A(iii): CWB PIPELINE OPERATION

FTE-months: 7.0

Offline running of the cWB search over O3b data chunks.

ACTIVITY Op-3.8-B: DATA QUALITY

Obtain data quality statements for each detection candidate identified by the offline searches.

TASK Op-3.8-B(i): DETECTOR CHARACTERIZATION ROTA

FTE-months: 2.0

Produce a data quality report for each candidate event. This task is identical to task O.C.2.1 in the LSC-Virgo Operations White Paper.

ACTIVITY Op-3.8-C: OFFLINE PARAMETER ESTIMATION

Perform parameter estimation on detection candidates identified by the offline searches.

Note: requires calibrated data at times of events.

TASK Op-3.8-C(i): PARAMETER ESTIMATION EVENT ROTA

FTE-months: 12.0

Run parameter estimation pipeline on each candidate event.

TASK Op-3.8-C(ii): PARAMETER ESTIMATION EXPERT ROTA

FTE-months: 6.0

Supervise parameter estimation event rota efforts.

Certify validity of sample chains.

TASK Op-3.8-C(iii): POSTERIOR SAMPLE CURATION

FTE-months: 2.0

Collect preferred posterior sample chains from event rota runs for each candidate event.

TASK Op-3.8-C(iv): WAVEFORM RECONSTRUCTION

FTE-months: 1.0

Perform waveform reconstruction estimation.

ACTIVITY Op-3.8-D: RATE ESTIMATION

Provide high-level rate and population statements on different source categories (BNS, NSBH, BBH, etc.).

TASK Op-3.8-D(i): MULTI-COMPONENT FGMC CLASSIFICATION

FTE-months: 6.0

Apply multi-component FGMC method on event lists from CBC pipelines to obtain astrophysical probabilities for each source categories (Terrestrial, BNS, NSBH, BBH, etc.).

TASK Op-3.8-D(ii): SUMMARY CATEGORICAL RATE ESTIMATION

FTE-months: 6.0

Obtain high-level rate estimations based on the the multi-component FGMC method results and the surveyed spacetime volumes measured using the injection sets.

ACTIVITY Op-3.8-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.8-E(i): PROJECT MANAGEMENT

FTE-months: 3.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.8-E(ii): PAPER WRITING COORDINATION

FTE-months: 6.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.8-E(iii): FIGURE PREPARATION

FTE-months: 3.0

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.8-E(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 12.0

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.8-F: TECHNICAL REVIEW

TASK Op-3.8-F(i): REVIEW OF GSTLAL PIPELINE SEARCH RESULTS

FTE-months: 1.0

Review of GstLAL search results: candidate lists, background estimation, sensitivity.

TASK Op-3.8-F(ii): REVIEW OF PYCBC PIPELINE SEARCH RESULTS

FTE-months: 1.0

Review of PyCBC search results: candidate lists, background estimation, sensitivity.

TASK Op-3.8-F(iii): REVIEW OF CWB PIPELINE SEARCH RESULTS

FTE-months: 1.0

Review of cWB search results: candidate lists, background estimation, sensitivity.

TASK Op-3.8-F(iv): REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES

FTE-months: 1.0

Review of Parameter Estimation posterior sample chains.

ACTIVITY Op-3.8-G: PAPER REVIEW

TASK Op-3.8-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK Op-3.8-G(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

Expected products and/or outcomes

- Catalog publication of events in O3b: October, 2020 (submit to arXiv and journal).
- Strain data release surrounding catalog events in O3b: October, 2020 (GWOSC).
- Posterior samples for catalog events in O3b: October, 2020 (GWOSC).
- Data behind the figures appearing in O3b Catalog: October, 2020 (DCC).

Op-3.9 O3a Astrophysical Distribution of Compact Binaries

Determine the astrophysical mass and spin distributions of compact binary systems, and rate estimates for O3a.

Motivation and goals

The detection of GW150914 and GW151226 firmly established the existence of stellar-mass binary black holes (BBH), with a coalescence rate of 12-213 Gpc^{-3} yr^{-1}, high enough to make them a primary source for future observing runs. In the O2 run we have collected three additional BBH events (GW170104, GW170608, and GW170814) and expect a few additional such events (excluding sub-threshold "LVT" designated candidates), 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 their natal environments.

The collaboration has published the results of a hierarchical analysis which infers the exponent of a power law governing the distribution of the primary mass of BBH systems. While this may be an incomplete description of a more complicated distribution, the current bound of $\alpha = -2.35$ is useful in ruling out models with flatter or steeper distributions in mass. Features such as a minimum or maximum black hole mass (e.g., the edges of "mass gaps") have been probed with more sophisticated models, and their early results show promise for independent methods to explore these topics. However, additional confident detections are needed to place more detailed constraints on the distribution of binary physical parameters, such as the spin magnitude and orientation of the component objects. As additional detections are collected, this information can be used to measure relative contributions from different formation channels as well as measure finer details about the models that represent the formation channels. This has immeasurable value to the astrophysics community, since those models can often have many free parameters which are not constrained well by other observations.

Major aspects and methods for this activity

ACTIVITY Op-3.9-A: BINARY NEUTRON STAR POPULATION INFERENCE

Inference on the binary neutron star rate.

TASK Op-3.9-A(i): PARAMETRIC BNS MERGER RATE ESTIMATE

FTE-months: 2.0

Estimate the rate of BNS mergers using FGMC with a parametric mass model.

TASK Op-3.9-A(ii): NON-PARAMETRIC BNS MERGER RATE ESTIMATE

FTE-months: 2.0

Estimate the rate of BNS mergers using FGMC-KKL method based on the distinct observed categories.

ACTIVITY Op-3.9-B: BLACK HOLE MASS DISTRIBUTION

Inference on the mass distribution of binary black holes observed.

TASK Op-3.9-B(i): PARAMETRIC HIERARCHICAL INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS

FTE-months: 2.0

Perform parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3a Catalog.

TASK Op-3.9-B(ii): NON-PARAMETRIC HIERARCHICAL INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS

FTE-months: 2.0

Perform non-parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3a Catalog.

ACTIVITY Op-3.9-C: BLACK HOLE MERGER RATES WITH REDSHIFT EVOLUTION

Estimate the merger rate of binary black holes.

TASK Op-3.9-C(i): NON-EVOLVING RATE ESTIMATION

FTE-months: 2.0

Perform FGMC style rate estimation for models A, B, and C, with no redshift evolution.

TASK Op-3.9-C(ii): INFERENCE ON REDSHIFT EVOLUTION

FTE-months: 1.0

Obtain merger rate as a function of redshift.

ACTIVITY Op-3.9-D: BLACK HOLE SPIN DISTRIBUTION

Inference on the spin distributions of binary black holes observed.

TASK Op-3.9-D(i): PARAMETRIC HIERARCHICAL INFERENCE OF SPIN MAGNITUDE AND TILTS FROM OBSERVED BBH EVENTS

FTE-months: 2.0

Perform parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3a Catalog.

TASK Op-3.9-D(ii): NON-PARAMETRIC INFERENCE OF SPIN MAGNITUDE AND TILTS FROM OBSERVED BBH EVENTS

FTE-months: 2.0

Perform non-parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3a Catalog.

ACTIVITY Op-3.9-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.9-E(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.9-E(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.9-E(iii): FIGURE PREPARATION

FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.9-E(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 0.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.9-F: TECHNICAL REVIEW

TASK Op-3.9-F(i): REVIEW OF PARAMETRIC BNS MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.9-F(ii): REVIEW OF NON-PARAMETRIC BNS MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.9-F(iii): REVIEW OF PARAMETRIC BBH MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.9-F(iv): REVIEW OF NON-PARAMETRIC BBH MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.9-F(v): REVIEW OF PARAMETRIC BBH SPIN DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric spin distribution results, including posterior sample chains.

TASK Op-3.9-F(vi): REVIEW OF NON-PARAMETRIC BBH SPIN DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric spin distribution results, including posterior sample chains.

TASK Op-3.9-F(vii): REVIEW OF NON-EVOLVING BBH RATE ESTIMATION RESULTS

FTE-months: 0.5

Review of the non-evolving BBH rate estimation, including posterior sample chains.

TASK Op-3.9-F(viii): REVIEW OF BBH REDSHIFT EVOLUTION RESULTS

FTE-months: 0.5

Review of the BBH redshift evolution results, including posterior sample chains.

ACTIVITY Op-3.9-G: PAPER REVIEW

TASK Op-3.9-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 0.5

Publications & Presentations review of scientific content in Astrophysical Distributions paper.

TASK Op-3.9-G(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in Astrophysical Distributions paper.

Expected products and/or outcomes

- O3a Astrophysical Distributions companion paper: April, 2020 (submit to arXiv and journal).
- Posterior samples from posterior distributions: April, 2020 (GWOSC).
- Data products describing the detector sensitivity that can be used for independent population analyses: April 2020 (GWOSC).
- Data behind the figures appearing in the O3a Astrophysical Distributions paper: April, 2020 (DCC).

Op-3.10 O3b Astrophysical Distribution of Compact Binaries

Determine the astrophysical mass and spin distributions of compact binary systems, and rate estimates for O3b.

Major aspects and methods for this activity

ACTIVITY Op-3.10-A: BINARY NEUTRON STAR POPULATION INFERENCE

Inference on the binary neutron star rate.

TASK Op-3.10-A(i): PARAMETRIC BNS MERGER RATE ESTIMATE

Estimate the rate of BNS mergers using FGMC with a parametric mass model.

FTE-months: 2.0

TASK Op-3.10-A(ii): NON-PARAMETRIC BNS MERGER RATE ESTIMATE

Estimate the rate of BNS mergers using FGMC-KKL method based on the distinct observed categories.

FTE-months: 2.0

ACTIVITY Op-3.10-B: BLACK HOLE MASS DISTRIBUTION

Inference on the mass distribution of binary black holes observed.

TASK Op-3.10-B(i): PARAMETRIC HIERARCHICAL INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS

Perform parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3b Catalog.

FTE-months: 2.0

TASK Op-3.10-B(ii): NON-PARAMETRIC HIERARCHICAL INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS

Perform non-parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3b Catalog.

FTE-months: 2.0

ACTIVITY Op-3.10-C: BLACK HOLE MERGER RATES WITH REDSHIFT EVOLUTION

Estimate the merger rate of binary black holes.

TASK Op-3.10-C(i): NON-EVOLVING RATE ESTIMATION

Perform FGMC style rate estimation for models A, B, and C, with no redshift evolution.

FTE-months: 2.0

TASK Op-3.10-C(ii): INFERENCE ON REDSHIFT EVOLUTION

Obtain merger rate as a function of redshift.

FTE-months: 1.0

ACTIVITY Op-3.10-D: BLACK HOLE SPIN DISTRIBUTION

Inference on the spin distributions of binary black holes observed.

TASK Op-3.10-D(i): PARAMETRIC HIERARCHICAL INFERENCE OF SPIN MAGNITUDE AND TILTS FROM OBSERVED BBH EVENTS

Perform parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3b Catalog.

FTE-months: 2.0

TASK Op-3.10-D(ii): NON-PARAMETRIC INFERENCE OF SPIN MAGNITUDE AND TILTS FROM OBSERVED BBH EVENTS

FTE-months: 2.0

Perform non-parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3b Catalog.

ACTIVITY Op-3.10-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.10-E(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.10-E(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.10-E(iii): FIGURE PREPARATION

FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.10-E(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 0.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.10-F: TECHNICAL REVIEW

TASK Op-3.10-F(i): REVIEW OF PARAMETRIC BNS MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.10-F(ii): REVIEW OF NON-PARAMETRIC BNS MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.10-F(iii): REVIEW OF PARAMETRIC BBH MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.10-F(iv): REVIEW OF NON-PARAMETRIC BBH MASS DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric mass distribution results, including posterior sample chains.

TASK Op-3.10-F(v): REVIEW OF PARAMETRIC BBH SPIN DISTRIBUTION RESULTS

FTE-months: 0.5

Review of the parametric spin distribution results, including posterior sample chains.

TASK Op-3.10-F(vi): REVIEW OF NON-PARAMETRIC BBH SPIN DISTRIBUTION RESULTS FTE-months: 0.5

Review of the parametric spin distribution results, including posterior sample chains.

TASK Op-3.10-F(vii): REVIEW OF NON-EVOLVING BBH RATE ESTIMATION RESULTS FTE-months: 0.5

Review of the non-evolving BBH rate estimation, including posterior sample chains.

TASK Op-3.10-F(viii): REVIEW OF BBH REDSHIFT EVOLUTION RESULTS FTE-months: 0.5

Review of the BBH redshift evolution results, including posterior sample chains.

ACTIVITY Op-3.10-G: PAPER REVIEW

TASK Op-3.10-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 0.5

Publications & Presentations review of scientific content in Astrophysical Distributions paper.

TASK Op-3.10-G(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in Astrophysical Distributions paper.

Expected products and/or outcomes

- O3b Astrophysical Distributions companion paper: October, 2020 (submit to arXiv and journal).
- Posterior samples from posterior distributions: October, 2020 (GWOSC).
- Data products describing the detector sensitivity that can be used for independent population analyses: October 2020 (GWOSC).
- Data behind the figures appearing in the O3b Astrophysical Distributions paper: October, 2020 (DCC).

Op-3.11 O3a Strong-Field Tests of General Relativity

Subject GR to a battery of tests based on observed CBC signals, ranging from tests of strong field dynamics to tests of the nature of gravitational waves, using events in the O3a catalog.

Motivation and goals

LIGO's first crop of binary black hole mergers has allowed us, for the first time, to test the predictions of general relativity in the highly relativistic, strong-field regime [32, 33]. Using these events we set limits on the deviation from the post-Newtonian (PN) description of the inspiral phase, mass of the graviton and dispersion relationship for GWs. Moreover, we have shown that the final remnant's mass and spin are mutually consistent, that data following the peak are consistent with the least-damped quasi-normal mode of the remnant black hole. Most of these constraints were further improved by combining detections [33, 19, 34].

In addition, the first detection of a binary neutron star merger, GW170817, had a long inspiral phase from which we were be able to conduct a phenomenological test for dipole radiation [35]. GW170817 was also detected in conjunction with electromagnetic information, which has given us information beyond what can be measured with just a gravitational-wave signal, such as the redshift of the source and the time difference between the gravitational-wave and electromagnetic signal. These additional pieces of information have given us the ability to put constraints on the specific alternative theories of gravity that predict large deviations between the gravitational-wave and electromagnetic signal, and insight into the polarisation modes of gravitational waves [36].

In O3, we expect new detections of BBHs and BNSs, and anticipate detections of BHNS systems, which will further tighten the existing constraints. Due to the lack of waveform models arising from alternative theories of gravity, in the near future our phenomenological tests will continue to follow the “top-down" methodology which will allow us to detect deviations from GR, but not necessarily to identify the underlying alternative theory. Below we list the priority science results anticipated from GW observations in the O3 observing run and beyond.

Major aspects and methods for this activity

ACTIVITY Op-3.11-A: CONSISTENCY TESTS OF GR

Look for inconsistency between observed results and GR predictions for the events in O3a Catalog.

TASK Op-3.11-A(i): RESIDUALS TEST

FTE-months: 2.0

Subtract best fit waveforms from data surrounding each event and look for excess residuals. Apply this test to all confident detections in the O3a catalog.

TASK Op-3.11-A(ii): INSPIRAL-MERGER-RINGDOWN CONSISTENCY TEST

FTE-months: 2.0

Compare predicted final mass and spin of each event, as determined from the inspiral, with the values inferred from the post-inspiral stages, according to GR. Apply this test to all confident BBH events in the O3a catalog.

ACTIVITY Op-3.11-B: PARAMETERIZED TESTS OF GR

Perform parameter estimation including a set of parameters that allows for deviations from GR parameters in various PN coefficients.

TASK Op-3.11-B(i): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN INSPIRAL

FTE-months: 2.0

Perform parameter estimation for each event while including a parameterized set of deviations from GR in inspiral.

TASK Op-3.11-B(ii): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN POST-INSPIRAL

FTE-months: 2.0

Perform parameter estimation for each event while including a parameterized set of deviations from GR in post-inspiral.

ACTIVITY Op-3.11-C: PARAMETERIZED TESTS GRAVITATIONAL WAVE PROPAGATION

Investigate various dispersion models to determine if there are Lorentz-invariance violations.

TASK Op-3.11-C(i): TEST FOR LORENTZ-INVARIANCE VIOLATIONS

FTE-months: 2.0

Perform parameter estimation on all events in the O3a Catalog while allowing for dephasing potentially caused by violation of Lorentz invariance.

ACTIVITY Op-3.11-D: POLARIZATION TESTS

Seek alternative polarization content (vector or scalar polarizations) in well-localized events in the O3a Catalog.

TASK Op-3.11-D(i): TEST FOR NON-TENSOR POLARIZATIONS

FTE-months: 2.0

Perform parameter estimation allowing for non-tensor polarization content (either pure-vector or pure-scalar) on events that are well localized by detection in three detectors.

ACTIVITY Op-3.11-E: QUASI-NORMAL MODES TESTS

Measure multiple quasi-normal modes from black-hole mergers in O3a to constrain the nature of the merger remnant.

TASK Op-3.11-E(i): TESTS OF THE NATURE OF THE MERGER REMNANT

FTE-months: 6.0

Test the nature of merger remnant nature through measurements of parametrized deviations from GR predictions on complex frequencies and cross-comparison of various modes.

ACTIVITY Op-3.11-F: SEARCH FOR LATE TIME ECHOES

Constrain, or detected, late-time echoes of GW signals using black-hole mergers in O3a.

TASK Op-3.11-F(i): ECHO SEARCHES

FTE-months: 2.0

Search for late-time echoes using template-based and model-independent approaches

ACTIVITY Op-3.11-G: COMPARE GRAVITATIONAL WAVES WITH ELECTROMAGNETIC WAVES

Compare the properties of gravitational waves with electromagnetic waves using multi-messenger detections in O3a.

TASK Op-3.11-G(i): SPEED OF GRAVITY

FTE-months: 1.0

Compare the arrival times of the counterpart with gravitational waves to constrain the speed of gravity.

TASK Op-3.11-G(ii): EXTRA DIMENSIONS

FTE-months: 1.0

Constrain effects of large extra dimensions on the gravitational-wave propagation behaviour.

ACTIVITY Op-3.11-H: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.11-H(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.11-H(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.11-H(iii): FIGURE PREPARATION

FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.11-H(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 0.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.11-I: TECHNICAL REVIEW

TASK Op-3.11-I(i): REVIEW OF RESIDUALS TEST

FTE-months: 0.5

Review of the residuals consistency test results.

TASK Op-3.11-I(ii): REVIEW OF IMR TEST

FTE-months: 0.5

Review of the IMR consistency test results.

TASK Op-3.11-I(iii): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE GENERATION

FTE-months: 0.5

Review of the parameterized test of gravitational wave generation results.

TASK Op-3.11-I(iv): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE PROPAGATION

FTE-months: 0.5

Review of the Lorentz-invariance violation test results.

TASK Op-3.11-I(v): REVIEW OF POLARIZATION TEST

FTE-months: 0.5

Review of the polarization test results.

TASK Op-3.11-I(vi): REVIEW OF QUASI-NORMAL MODES TESTS

FTE-months: 0.5

Review of the quasi-normal modes tests results.

TASK Op-3.11-I(vii): REVIEW OF SEARCH FOR LATE TIME ECHOES

FTE-months: 0.5

Review of the search for late time echoes results.

TASK Op-3.11-I(viii): REVIEW OF COMPARE GRAVITATIONAL WAVES WITH ELECTROMAGNETIC WAVES

FTE-months: 0.5

Review of the comparison of gravitational waves with electromagnetic waves.

TASK Op-3.11-I(ix): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE

FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY Op-3.11-J: PAPER REVIEW

TASK Op-3.11-J(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 0.5

Publications & Presentations review of scientific content in O3a Testing GR paper.

TASK Op-3.11-J(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in O3a Testing GR paper.

Expected products and/or outcomes

- O3a Testing GR companion paper: April, 2020 (submit to arXiv and journal).
- Posterior samples from posterior distributions: April, 2020 (GWOSC).
- Data behind the figures appearing in O3a Testing GR paper: April, 2020 (DCC).

Op-3.12 O3b Strong-Field Tests of General Relativity

Subject GR to a battery of tests based on observed CBC signals, ranging from tests of strong field dynamics to tests of the nature of gravitational waves, using events in the O3b catalog.

Major aspects and methods for this activity

ACTIVITY Op-3.12-A: CONSISTENCY TESTS OF GR

Look for inconsistency between observed results and GR predictions for the events in O3b Catalog.

TASK Op-3.12-A(i): RESIDUALS TEST FTE-months: 2.0

Subtract best fit waveforms from data surrounding each event and look for excess residuals. Apply this test to all confident detections in the O3b catalog.

TASK Op-3.12-A(ii): INSPIRAL-MERGER-RINGDOWN CONSISTENCY TEST FTE-months: 2.0

Compare predicted final mass and spin of each event, as determined from the inspiral, with the values inferred from the post-inspiral stages, according to GR. Apply this test to all confident BBH events in the O3b catalog.

ACTIVITY Op-3.12-B: PARAMETERIZED TESTS OF GR

Perform parameter estimation including a set of parameters that allows for deviations from GR parameters in various PN coefficients.

TASK Op-3.12-B(i): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN INSPIRAL FTE-months: 2.0

Perform parameter estimation for each event while including a parameterized set of deviations from GR in inspiral.

TASK Op-3.12-B(ii): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN POST-INSPIRAL FTE-months: 2.0

Perform parameter estimation for each event while including a parameterized set of deviations from GR in post-inspiral.

ACTIVITY Op-3.12-C: PARAMETERIZED TESTS GRAVITATIONAL WAVE PROPAGATION

Investigate various dispersion models to determine if there are Lorentz-invariance violations.

TASK Op-3.12-C(i): TEST FOR LORENTZ-INVARIANCE VIOLATIONS FTE-months: 2.0

Perform parameter estimation on all events in the O3b Catalog while allowing for dephasing potentially caused by violation of Lorentz invariance.

ACTIVITY Op-3.12-D: POLARIZATION TESTS

Seek alternative polarization content (vector or scalar polarizations) in well-localized events in the O3b Catalog.

TASK Op-3.12-D(i): TEST FOR NON-TENSOR POLARIZATIONS

FTE-months: 2.0

Perform parameter estimation allowing for non-tensor polarization content (either pure-vector or pure-scalar) on events that are well localized by detection in three detectors.

ACTIVITY Op-3.12-E: QUASI-NORMAL MODES TESTS

Measure multiple quasi-normal modes from black-hole mergers in O3b to constrain the nature of the merger remnant.

TASK Op-3.12-E(i): TESTS OF THE NATURE OF THE MERGER REMNANT

FTE-months: 6.0

Test the nature of the merger remnant through measurements and cross-comparison of various modes.

ACTIVITY Op-3.12-F: SEARCH FOR LATE TIME ECHOES

Constrain, or detected, late-time echoes of GW signals using black-hole mergers in O3b.

TASK Op-3.12-F(i): ECHO SEARCHES

FTE-months: 2.0

Search for late-time echoes using template-based and model-independent approaches

ACTIVITY Op-3.12-G: COMPARE GRAVITATIONAL WAVES WITH ELECTROMAGNETIC WAVES

Compare the properties of gravitational waves with electromagnetic waves using multi-messenger detections in O3b.

TASK Op-3.12-G(i): SPEED OF GRAVITY

FTE-months: 1.0

Compare the arrival times of the counterpart with gravitational waves to constrain the speed of gravity.

TASK Op-3.12-G(ii): EXTRA DIMENSIONS

FTE-months: 1.0

Constrain effects of large extra dimensions on the gravitational-wave propagation behaviour.

ACTIVITY Op-3.12-H: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.12-H(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.12-H(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.12-H(iii): FIGURE PREPARATION

FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.12-H(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 0.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.12-I: TECHNICAL REVIEW

TASK Op-3.12-I(i): REVIEW OF RESIDUALS TEST

FTE-months: 0.5

Review of the residuals consistency test results.

TASK Op-3.12-I(ii): REVIEW OF IMR TEST

FTE-months: 0.5

Review of the IMR consistency test results.

TASK Op-3.12-I(iii): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE GENERATION

FTE-months: 0.5

Review of the parameterized test of gravitational wave generation results.

TASK Op-3.12-I(iv): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE PROPAGATION

FTE-months: 0.5

Review of the Lorentz-invariance violation test results.

TASK Op-3.12-I(v): REVIEW OF POLARIZATION TEST

FTE-months: 0.5

Review of the polarization test results.

TASK Op-3.12-I(vi): REVIEW OF QUASI-NORMAL MODES TESTS

FTE-months: 0.5

Review of the quasi-normal modes tests results.

TASK Op-3.12-I(vii): REVIEW OF SEARCH FOR LATE TIME ECHOES

FTE-months: 0.5

Review of the search for late time echoes results.

TASK Op-3.12-I(viii): REVIEW OF COMPARE GRAVITATIONAL WAVES WITH ELECTROMAGNETIC WAVES

FTE-months: 0.5

Review of the comparison of gravitational waves with electromagnetic waves.

TASK Op-3.12-I(ix): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE

FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY Op-3.12-J: PAPER REVIEW

TASK Op-3.12-J(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 0.5

Publications & Presentations review of scientific content in O3b Testing GR paper.

TASK Op-3.12-J(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in O3b Testing GR paper.

Expected products and/or outcomes

- O3b Testing GR companion paper: October, 2020 (submit to arXiv and journal).
- Posterior samples from posterior distributions: October, 2020 (GWOSC).
- Data behind the figures appearing in O3b Testing GR paper: October, 2020 (DCC).

Op-3.13 O3a Hubble Constant Measurements

Measure the Hubble constant using both EM associations and statistical associations with a galaxy catalog using events up to and including O3a catalog events.

Motivation and goals

Gravitational waves from the binary neutron star merger GW170817 along with its uniquely identified host galaxy led to a first "standard siren" measurement of the Hubble parameter independent of the cosmological distance ladder. The identification of the host galaxy was possible because of the coincident optical counterpart to GW170817. Similar observations in O3 of binaries involving a neutron star with identified electromagnetic counterparts will improve the precision of the measurement. Additionally, the statistical method of cross correlation of gravitational-wave distance estimates with catalogues of potential host galaxies, can be used in the absence of a uniquely identified counterpart. In particular it will be possible to do this for well-localized binary black hole mergers, a good number of which are expected in O3. Intermediate between these two is the case where an electromagnetic counterpart is observed but it cannot be associated to a unique host galaxy. Such events can also be used to improve cosmological constraints.

Major aspects and methods for this activity

ACTIVITY Op-3.13-A: MEASUREMENT OF HUBBLE CONSTANT

Obtain a combined H_0 estimate from binary neutron stars with identified electromagnetic counterparts, and other binary coalescences (neutron stars or black holes) without uniquely identified counterparts.

TASK Op-3.13-A(i): COUNTERPART ONLY MEASUREMENT OF H_0 FTE-months: 15.0

Analyze events with electromagnetic counterparts to obtain a joint measurement on the Hubble constant.

TASK Op-3.13-A(ii): STATISTICAL ONLY MEASUREMENT OF H_0 FTE-months: 15.0

Analyze events without electromagnetic counterparts to obtain a joint statistical measurement on the Hubble constant.

TASK Op-3.13-A(iii): COMBINED MEASUREMENT OF H_0 FTE-months: 6.0

Combine both counterpart and statistical measurements of the Hubble constant to obtain a full posterior.

TASK Op-3.13-A(iv): ASSESSMENT OF SYSTEMATIC UNCERTAINTIES FTE-months: 12.0

Investigate the effect of potential systematic uncertainties by varying parameters such as the luminosity cutoff, the underlying mass distribution used in the selection function, the galaxy catalog completeness, etc.

ACTIVITY Op-3.13-B: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.13-B(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.13-B(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.13-B(iii): FIGURE PREPARATION

FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.13-B(iv): SCIENCE SUMMARY AND DATA RELEASE

FTE-months: 0.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.13-C: TECHNICAL REVIEW

TASK Op-3.13-C(i): REVIEW OF COUNTERPART ONLY MEASUREMENT OF H_0

FTE-months: 0.5

Review of the counterpart only Hubble constant measurement results.

TASK Op-3.13-C(ii): REVIEW OF STATISTICAL ONLY MEASUREMENT OF H_0

FTE-months: 0.5

Review of the statistical only Hubble constant measurement results.

TASK Op-3.13-C(iii): REVIEW OF COMBINED MEASUREMENT OF H_0

FTE-months: 0.5

Review of the combined Hubble constant measurement results.

TASK Op-3.13-C(iv): REVIEW OF ASSESSMENT OF SYSTEMATIC UNCERTAINTIES

FTE-months: 0.5

Review of the systematic uncertainty study results.

TASK Op-3.13-C(v): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE

FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY Op-3.13-D: PAPER REVIEW

TASK Op-3.13-D(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 0.5

Publications & Presentations review of scientific content in H_0 paper.

TASK Op-3.13-D(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in H_0 paper.

Expected products and/or outcomes

- O3a H_0 companion paper: April, 2020 (submit to arXiv and journal).
- Posterior samples from posterior distributions: April, 2020 (GWOSC).
- Data behind the figures appearing in the O3a H_0 paper: April, 2020 (DCC).

Op-3.14 O3b Hubble Constant Measurements

Measure the Hubble constant using both EM associations and statistical associations with a galaxy catalog using events up to and including O3b catalog events.

Major aspects and methods for this activity

ACTIVITY Op-3.14-A: MEASUREMENT OF HUBBLE CONSTANT

Obtain a combined H_0 estimate from binary neutron stars with identified electromagnetic counterparts, and other binary coalescences (neutron stars or black holes) without uniquely identified counterparts.

TASK Op-3.14-A(i): COUNTERPART ONLY MEASUREMENT OF H_0

FTE-months: 1.0

Analyze events with electromagnetic counterparts to obtain a joint measurement on the Hubble constant.

TASK Op-3.14-A(ii): STATISTICAL ONLY MEASUREMENT OF H_0

FTE-months: 1.0

Analyze events without electromagnetic counterparts to obtain a joint statistical measurement on the Hubble constant.

TASK Op-3.14-A(iii): COMBINED MEASUREMENT OF H_0

FTE-months: 1.0

Combine both counterpart and statistical measurements of the Hubble constant to obtain a full posterior.

TASK Op-3.14-A(iv): ASSESSMENT OF SYSTEMATIC UNCERTAINTIES

FTE-months: 1.0

Investigate the effect of potential systematic uncertainties by varying parameters such as the luminosity cutoff, the underlying mass distribution used in the selection function, the galaxy catalog completeness, etc.

ACTIVITY Op-3.14-B: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.14-B(i): PROJECT MANAGEMENT

FTE-months: 2.0

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK Op-3.14-B(ii): PAPER WRITING COORDINATION

FTE-months: 2.0

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK Op-3.14-B(iii): FIGURE PREPARATION FTE-months: 0.5

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK Op-3.14-B(iv): SCIENCE SUMMARY AND DATA RELEASE FTE-months: 0.5

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY Op-3.14-C: TECHNICAL REVIEW

TASK Op-3.14-C(i): REVIEW OF COUNTERPART ONLY MEASUREMENT OF H_0 FTE-months: 0.5

Review of the counterpart only Hubble constant measurement results.

TASK Op-3.14-C(ii): REVIEW OF STATISTICAL ONLY MEASUREMENT OF H_0 FTE-months: 0.5

Review of the statistical only Hubble constant measurement results.

TASK Op-3.14-C(iii): REVIEW OF COMBINED MEASUREMENT OF H_0 FTE-months: 0.5

Review of the combined Hubble constant measurement results.

TASK Op-3.14-C(iv): REVIEW OF ASSESSMENT OF SYSTEMATIC UNCERTAINTIES FTE-months: 0.5

Review of the systematic uncertainty study results.

TASK Op-3.14-C(v): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY Op-3.14-D: PAPER REVIEW

TASK Op-3.14-D(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 0.5

Publications & Presentations review of scientific content in H_0 paper.

TASK Op-3.14-D(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in H_0 paper.

Expected products and/or outcomes

- O3b H_0 companion paper: October, 2020 (submit to arXiv and journal).
- Posterior samples from posterior distributions: October, 2020 (GWOSC).
- Data behind the figures appearing in the O3b H_0 paper: October, 2020 (DCC).

Op-3.15 Search for sub-solar-mass compact binary coalescences

Search for compact binary coalescences with a component having mass below a solar mass

Motivation and goals

Compact objects with masses below $\sim 1\ M_\odot$ are not expected to be generated as endpoints of stellar evolution. The lowest mass neutron stars are expected to have masses above the Chandrasekhar mass [37] less the gravitational binding energy. Current models and observations place the minimum neutron star mass near $\sim 1.15\ M_\odot$ [38, 39, 40]. The lightest black holes are constrained by the maximum non-rotating neutron star mass, which is currently believed to be $\sim 2\ M_\odot$ [41].

There are several models that predict the formation of sub-solar mass black holes. One class posits that sub-solar mass primordial black holes could have formed via the prompt collapse of large overdensities in the early universe [42]. The size and abundance of primordial black holes is closely related to the early universe equation of state and the scale of the primoridal perturbations [43, 44, 45, 46]. Another class of models links sub-solar mass black holes to particulate dark matter, either via a complex particle spectrum [47] or nuclear interactions with neutron stars [48, 49, 50, 51, 52, 53, 54].

O3 deliverables

- Carry out a thorough search for sub-solar mass compact binary mergers in O3 data

ACTIVITY Op-3.15-A: O3 SEARCH FOR SUB-SOLAR MASS COMPACT BINARY MERGERS

TASK Op-3.15-A(i): DETERMINE SEARCH PARAMETERS

FTE-months: 1.0

Design, generate, and test coverage of a bank of template waveforms for sub-solar mass compact binaries.

TASK Op-3.15-A(ii): RUN SEARCH PIPELINE

FTE-months: 5.0

Carry out a matched filter based search using the template bank designed to recover sub-solar mass compact binaries.

ACTIVITY Op-3.15-B: PUBLICATION

TASK Op-3.15-B(i): RESULTS INTERPRETATION

FTE-months: 4.0

In the event of a detection, we will perform parameter estimation. For a null result, we will provide rate upper limits and discuss other ways to meaningfully present constraints on the abundance of sub-solar mass compact objects/binaries.

TASK Op-3.15-B(ii): PAPER WRITING

FTE-months: 1.0

Op-3.16 Characterizing exceptional CBC events

Prepare / write a paper to discuss in detail any compact binary coalescence that is deemed to be of particular relevance and meriting its own publication. This complements the catalog concept. (This paper could include Burst content if found by a burst search.)

Motivation and goals

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 black hole + neutron star binary, systems with definitive spin precession, etc. Such systems will warrant specific attention to be determined only once confirmed.

Some examples of exceptional events would be one that yields:

- the first detection of a neutron star + black hole binary, a binary with a sub-solar-mass component, or an intermediate-mass black-hole binary;
- measurement of the highest/lowest neutron star mass, or the highest stellar-mass black hole mass;
- clear statement on neutron star equation of state;
- clear evidence of a black hole in a predicted mass gap;
- clear evidence of unequal mass ratio;
- clear evidence of spin-induced precession;
- measurement of a high-spin system;
- measurement of black hole quasi-normal modes;
- measurement of higher-order gravitational wave emission modes;
- clear evidence of orbital eccentricity;
- a multi-messenger counterpart (externally-triggered or in electromagnetic/neutrino follow-up searches);
- substantial improvement in the measurement of the Hubble constant;
- clear evidence of deviation from general relativity;
- clear indication of a particular formation channel.

Major aspects and methods for this activity

Activities and tasks will come into scope upon the identification of an exceptional event. Here we give a generic placeholder for future accounting purposes.

ACTIVITY Op-3.16-A: AD HOC ACTIVITY

Placeholder for an ad hoc activity. Activities will be defined upon the occurrence of an exceptional event.

TASK Op-3.16-A(i): AD HOC TASK

Placeholder for an ad hoc task. Tasks will be defined upon the occurrence of an exceptional event.

FTE-months: 48.0 (12 months per exceptional event paper times 4 exeptional events)

Expected products and/or outcomes

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

4 CW Group Activity Plans

Op-4.1 Targeted searches for known pulsars

Motivation

Rapidly spinning neutron stars in our galaxy may emit gravitational waves if they are not perfectly symmetric about their spin axis. Our searches target a subset of sources for which pulsations are observed in radio, X-ray, or other electromagnetic radiation bands. Pulsar timing through electromagnetic observations can tell us precise sky positions, frequencies, frequency evolution, and binary orbital parameters (if applicable) of these objects, so that targeted analyses need search only a small parameter space (sometimes only a single phase template) and are not computationally limited. Electromagnetic observations also set an upper limit on the gravitational-wave strain we could see from a known pulsar, by assuming that all of its observed spindown is due to gravitational-wave emission (see Equation 5 of [55]).

The searches assume gravitational-wave emission from a triaxial neutron star, with the electromagnetic and gravitational-wave components rotating as one unit. This would lead to gravitational-wave emission at twice the rotation frequency ($2f$) of the star. 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. Emission from other mechanisms is possible and can lead, for example, to a signal at a star's rotation frequency, f [56]. Detecting signals at either f, or both f and $2f$, would give further insight into the coupling between the crust and core of a neutron star.

Methods

Three mature analysis pipelines for targeted searches are the time-domain Bayesian pipeline [57], the 5-vector method [58], and the time-domain $\mathcal{F}/\mathcal{G}$-statistic method [55]. All three pipelines will be used for high-value targets for which the spin-down limit has, or could nearly be, surpassed. The remaining sources will be searched for with the time-domain Bayesian pipeline. Searches will target emission at both f and $2f$.

Activities for O3

ACTIVITY Op-4.1-A: EARLY O3 TARGETED PULSAR PAPER

It is expected that the first few months of data from the O3 run the will be sensitive enough that the spin-down limit will be surpassed for a handful of recycled millisecond pulsars. Previously spin-down limits have only been surpassed for so-called "young" pulsars [59, 60]. Two millisecond pulsars that are particularly promising are J0437−4715 and J0711−6830. We will produce a paper, aimed at a high profile journal, describing a search for signals from these few millisecond pulsars. The paper will also provide an update on the searches for the high profile targets, the Crab and Vela pulsars. The analysis will use LIGO and Virgo data from the start of the O3 run until the September observing break.

TASK Op-4.1-A(i): OBTAIN PULSAR EPHEMERIDES — FTE-months: 3.0

Obtain timing ephemerides from electromagnetic observers for the selected pulsars that are coherent over O3.

TASK Op-4.1-A(ii): RUN TIME-DOMAIN BAYESIAN PIPELINE — FTE-months: 3.0

Run the time-domain Bayesian pipeline on the selected targets, searching at the two harmonics of the pulsar spin frequency: f and $2f$.

Task Op-4.1-A(iii): Run the time-domain $\mathcal{F}/\mathcal{G}$-statistic pipeline

FTE-months: 3.0

Search for gravitational waves from the selected pulsars analyzing data from network of three detectors (LIGO and Virgo). Search at two harmonics of the pulsar spin frequency: f and $2f$.

Task Op-4.1-A(iv): Run the 5-vector pipeline

FTE-months: 3.0

Search for gravitational waves from the selected pulsars. Independent searches at f and $2f$. Some code review needed in view of recent changes.

Task Op-4.1-A(v): Write paper

FTE-months: 3.0

Write a paper describing the results of the search, with an emphasis on the astrophysical significance of surpassing the spin-down limit for millisecond pulsars.

Activity Op-4.1-B: Full O3 targeted pulsar paper

As with previous runs (e.g. [61]), we will perform a search for all pulsars with rotation frequencies greater than 10 Hz for which we have a reliable timing ephemeris spanning the O3 run. The search will target emission at either, or both, once and twice the stellar rotation frequency. From the results we will make inferences on the underlying ellipticity distributions of populations of pulsars.

Task Op-4.1-B(i): Obtain pulsar ephemerides

FTE-months: 3.0

Obtain timing ephemerides from electromagnetic observers for pulsars with rotation frequencies greater than 10 Hz that are coherent over O3.

Task Op-4.1-B(ii): Run time-domain Bayesian pipeline

FTE-months: 3.0

Run the time-domain Bayesian pipeline on the all targets.

Task Op-4.1-B(iii): Run the 5-vector pipeline

FTE-months: 3.0

Search for gravitational waves from all the pulsars for which updated ephemerides will be available. Independent searches at f and $2f$.

Task Op-4.1-B(iv): Run the time-domain $\mathcal{F}/\mathcal{G}$-statistic pipeline

FTE-months: 3.0

Search for gravitational waves from around 30 known pulsars for which spin down limit can be surpassed or nearly surpassed. Analyze data from network of three detectors (LIGO and Virgo). Search at two harmonics of the pulsar spin frequency.

Task Op-4.1-B(v): Population inference code development and review

FTE-months: 3.0

Review the code to be used to perform the population inference on the pulsar ellipticity distributions.

Task Op-4.1-B(vi): Population inference

FTE-months: 3.0

Perform population inference on the ellipticity distribution of pulsars, splitting the population between "young" and millisecond pulsars.

Task Op-4.1-B(vii): Write paper

FTE-months: 3.0

Write a paper describing the results of the search.

Op-4.2 Narrow-band searches for known pulsars

Motivation

These searches are an extension of targeted searches for known pulsars (Section Op-4.1) in which the position of the source is assumed to be accurately known while the rotational parameters are slightly uncertain [62]. This type of search is generally computationally heavier with respect to targeted searches. In general, narrow-band searches allow one to take into account a possible mismatch between the gravitational wave rotational parameters and those inferred from electromagnetic observations. For instance, the gravitational wave could be emitted by the core of the neutron star which may have a slightly different rotational frequency with respect to the magnetosphere.

Methods

Two pipelines, one based on the 5-vector method [63] used in target searches, and one based on the $\mathcal{F}$-statistic [59], can be used for narrow-band searches. The basic idea is to explore a range of frequency and spin-down values around the electromagnetic-derived values by properly applying barycentric and spin-down corrections to the data in such a way that a signal would appear as monochromatic apart from the sidereal modulation. Of the order of 10^7 points in the parameter space are typically explored in a narrow-band search.

Activities for O3

ACTIVITY Op-4.2-A: EARLY O3 SEARCHES

Using 4 months and then 8 months of data, we will search for CWs from known pulsars for which we expect to surpass or approach the spindown limit. If no updated ephemeris will be available, we will use the ones of O2.

TASK Op-4.2-A(i): RUN SEARCHES

FTE-months: 3.0

Run the search using the 5-vector method and the $\mathcal{F}$-statistic method and produce and check for the presence of interesting outliers.

TASK Op-4.2-A(ii): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

FTE-months: 3.0

Check for the presence of noise lines close to each outlier taking into account the modulation due to the Earth motion. Compare the outliers with the Early searches outliers.

TASK Op-4.2-A(iii): OUTLIERS FOLLOWUP – TARGETED SEARCHES

FTE-months: 3.0

Check the nature of the outlier by performing several targeted searches using more and more data for each outlier. A persistent GW signal is expected to be always present. Compare these results with software injections if necessary. Follow up from potential more sensitive searches should also be performed (see Section Op-4.12).

TASK Op-4.2-A(iv): SENSITITVITY STUDIES

FTE-months: 3.0

We will compute upper-limits on CW emission from a subset of the pulsars in different frequency bands, in order to check our sensitivity.

ACTIVITY Op-4.2-B: FULL O3 NARROW-BAND SEARCH

We will search for continuous GWs from ∼40 known pulsars for which we expect to surpass or approach the spindown limit using the entire O3 data. If no interesting outlier is present, we will set upper-limits on the GWs emission. We expect to surpass the spindown limit for additional 4-5 pulsars at frequencies lower than 100 Hz and improve our previous constraints in [64].

TASK Op-4.2-B(i): RUN SEARCHES

FTE-months: 3.0

Run the search using the 5-vector method and the $\mathcal{F}$-statistic method and produce and check for the presence of interesting outliers.

TASK Op-4.2-B(ii): OUTLIERS FOLLOWUP – DATA QUALITY STUDIES

FTE-months: 3.0

Check for the presence of noise lines close to each outlier taking into account the modulation due to the Earth motion. Compare the outliers with the Early searches outliers.

TASK Op-4.2-B(iii): OUTLIERS FOLLOWUP – TARGETED SEARCHES

FTE-months: 3.0

Check the nature of the outlier by performing several targeted searches using more and more data for each outlier. A persistent GW signal is expected to be always present. Compare these results with software injections if necessary.

TASK Op-4.2-B(iv): SET UPPER LIMITS

FTE-months: 3.0

In the event of no detection, we will put upper limits on the GWs emission.

TASK Op-4.2-B(v): REVIEW SEARCH RESULTS

FTE-months: 3.0

Review of any updated part of the codes and the search results.

TASK Op-4.2-B(vi): PUBLICATION

FTE-months: 3.0

Produce a publication with the results of each pipeline.

Op-4.3 Targeted searches for non-tensorial emission from known pulsars

Motivation

Traditional searches for CWs targeted at known pulsars (Sections Op-4.1, Op-4.2), assume that sources emit the tensorial plus and cross gravitational-wave polarizations predicted by the general theory of relativity. It is conceivable, however, that due to a departure from general relativity neutron stars may generate scalar and vector polarizations, on top or instead of tensor ones. If so, power in those extra modes would have been largely missed by standard targeted searches. In contrast, a search for non-tensorial continuous signals from known pulsars would be capable of detecting and classifying those alternative modes in a theory-independent way [65, 66].

Generic metric theories of gravity may support up to six gravitational polarizations: two scalar modes (breathing and longitudinal), two vector modes (x and y) and two tensor modes (plus and cross). Because general relativity makes the unambiguous prediction that only the two tensor modes may exist, the presence of any of the tensorial modes, no matter how weak, would be fatal for the theory. Although it is not possible to use the current LIGO-Virgo network to carry out this important test of general relativity with transient signals, this can be done with long-lived CWs.

Methods

The search for non-tensorial CWs from known pulsars expands the time-domain Bayesian targeted analysis [57] to be sensitive to signals of any polarization content at a given frequency, without assuming any specific theory of gravity or emission mechanism. If a signal is detected, rigorous Bayesian methods will allow us to determine whether there is evidence of a departure from general relativity. The search for scalar GW radiation predicted by Brans-Dicke theory adapts the $\mathcal{F}$-statistic to search for this particular GW signal.

Activities for O3

ACTIVITY Op-4.3-A: FULL O3 TARGETED PULSAR PAPER

We will perform a search for CW signals from a selection of known pulsars in which we allow their polarization state to contain non-tensorial modes. This search will be performed on O3 data using the same set of pulsars as for the standard targeted pulsar search (Section Op-4.1). It will expand upon the analysis of O1 data by allowing the signals to have emission at both once and twice the source rotation frequency.

TASK Op-4.3-A(i): CODE UPDATE

FTE-months: 1.0

Update the Bayesian parameter estimation code to allow the inclusion of components of the non-tensorial signal at both f and $2f$.

TASK Op-4.3-A(ii): CODE REVIEW

FTE-months: 1.0

Review the code updates to confirm they perform as expected.

TASK Op-4.3-A(iii): RUN TIME-DOMAIN BAYESIAN PIPELINE

FTE-months: 3.0

Run the time-domain Bayesian pipeline on the all targets, making use of the pulsar ephemerides and heterodyned data products already obtained for the standard known pulsar search.

TASK Op-4.3-A(iv): RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

FTE-months: 3.0

For around 30 known pulsars for which spin down limit can be surpassed or nearly surpassed, search for for scalar radiation predicted by Brans-Dicke theory.

TASK Op-4.3-A(v): WRITE PAPER

FTE-months: 1.0

Add these results to the full O3 targeted search paper (Section Op-4.1).

Op-4.4 Directed searches targeting Cassiopeia A and other Galactic supernova remnants

Motivation

Young neutron stars may be the strongest isolated radiators of gravitational waves. Supernova kicks indicate that neutron stars are born with some asymmetry, and spin-downs of young pulsars are generally more rapid than those of old pulsars, allowing for more gravitational wave emission as a possible part of that spin-down. Mountains may settle on long timescales with no plate tectonics to revive them, and r-modes (long-lived fluid oscillations) eventually succumb to viscosity as the star cools. Many of the youngest neutron stars in the galaxy are known not as pulsars, but as non-pulsing x-ray point sources embedded in young supernova remnants, such as the current record holder Cas A at $\sim$ 300 years old. Extremely young extragalactic sources without an associated electromagnetic point source, e.g., SNR 1987A, also merit consideration.

For these targets the sky direction is known but there is not even an approximate timing solution, so the searches cover wide bands of frequency (hundreds of Hz) and frequency derivatives. The parameter space is still small enough compared to all-sky surveys that time spans of order one to several weeks can be coherently integrated; and semi-coherent techniques can integrate longer time spans.

Methods

Most previous searches have been based on the $\mathcal{F}$-statistic [67], either as fully coherent [68, 69, 70] or semi-coherent [71] methods. Hidden Markov model techniques can also be used to track the unknown signal frequency in a young supernova remnant as it wanders due to secular spin-down and un-modeled stochastic timing noise [72], and are a computationally cheap supplement to other techniques. An extended application of the hidden Markov model technique allows tracking both once and twice the spin frequency of the star, producing better sensitivities in the case that the signal contains two frequency components [73].

Another way of looking for these signals is to use the FrequencyHough transform as already done for all-sky searches. A re-adaptation of the full all-sky Frequency Hough transform to a new directed search pipeline, is done within the Band-Sampled-Data framework [74]. The pipeline is a semi-coherent method where the coherent part is covered by the BSD heterodyned data while the incoherent part is performed through the production of "peakmaps" and Frequency Hough maps.

Activities for O3

ACTIVITY Op-4.4-A: EARLY O3 SUPERNOVA REMNANTS PAPER

We will run a directed search for selected supernova remnants using some of the available pipelines, e.g. Viterbi, BSD-directed.

TASK Op-4.4-A(i): SOURCE SELECTION

Select a list of sources for directed searches.

FTE-months: 3.0

TASK Op-4.4-A(ii): RUN SEARCH AND POST-PROCESSING

Run directed searches using multiple pipelines, identify and follow up candidates, and veto outliers caused by instrumental artifacts.

FTE-months: 3.0

TASK Op-4.4-A(iii): SET UPPER LIMITS

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

FTE-months: 3.0

TASK Op-4.4-A(iv): REVIEW SEARCH RESULTS

Review the search procedure and results.

FTE-months: 3.0

TASK Op-4.4-A(v): PUBLICATION

Produce a publication presenting the results.

FTE-months: 3.0

Op-4.5 Directed searches targeting Scorpius X-1 and other low-mass X-ray binaries

Motivation

Accretion in a binary system leads to recycling, where the neutron star spins up to near-kHz frequencies. In the torque balance scenario, the gravitational radiation reaction torque balances the accretion torque, which is proportional to the X-ray flux, in turn implying a limit on the characteristic wave strain proportional to that flux [75]. Torque balance is one possible explanation for the observed fact that the spin frequencies of low-mass X-ray binaries (LMXBs) are systematically lower than predicted. Directed searches for accreting binaries are a high priority because the sources are relatively powerful if they are emitting near the torque balance limit. A CW detection would shed light on several important astrophysical questions: by combining CW and electromagnetic data, one could tie down the emission mechanism, produce equation-of-state information, and probe the physics of the X-ray emission mechanism and of any differential rotation between the interior and crust.

Methods

A number of largely independent algorithms have been developed which can be used to search for LMXBs: cross-correlation [76, 77, 78], doubly-Fourier transformed data (TwoSpect; [79]), hidden Markov models (Viterbi; [80, 81, 82]), coherent summation of matched-filter sidebands (Sideband; [83]), and a resampling procedure, which is a generalization of the 5-vector method [84]. The central challenge facing these searches is that the spin frequency and orbital parameters are in general unknown. Furthermore the spin frequency is likely to wander stochastically in response to the fluctuating torque [85].

Activities for O3

ACTIVITY Op-4.5-A: FULL O3 SCORPIUS X-1 PAPER

Pending person power and computational resources, we will run a directed search for continuous gravitational waves from Scorpius X-1 using the cross-correlation, Viterbi, and TwoSpect search pipelines. In the event of a detection, we will publish results from all pipelines, as well as detailed follow up; otherwise we will set upper limits.

TASK Op-4.5-A(i): RUN VITERBI SEARCH

FTE-months: 3.0

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK Op-4.5-A(ii): RUN CROSS-CORRELATION SEARCH

FTE-months: 3.0

Run cross-correlation search, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK Op-4.5-A(iii): FOLLOW UP STATISTICAL OUTLIERS – VETOES

FTE-months: 3.0

Follow up statistical outliers from each search using line-lists and tests of the efficacy of each candidate source. This may be done collectively or by each individual search.

TASK Op-4.5-A(iv): FOLLOW UP STATISTICAL OUTLIERS – PARAMETER ESTIMATION

FTE-months: 3.0

Statistical outliers that pass vetoes in the above task should be analyzed with a denser set of matched-filter templates if possible and followed up using more-sensitive, but computationally intensive search methods like that used for the targeted known pulsar search.

TASK Op-4.5-A(v): SET UPPER LIMITS

FTE-months: 3.0

In the event of no detection, each pipeline sets upper limits on gravitational-wave emission from Scorpius X-1.

TASK Op-4.5-A(vi): PUBLICATION

FTE-months: 3.0

Produce a single publication either presenting the detection of continuous gravitational-waves from Scorpius X-1 or comparing upper limits from the search pipelines that were used.

ACTIVITY Op-4.5-B: FULL O3 OTHER LMXBS / AMSPS PAPER

Pending person power and computational resources, we will run a directed search for a selection of low mass X-ray binary (LMXB) targets for which there are electromagnetic constraints on the neutron star rotation frequencies. Accreting millisecond pulsars (AMSPs) will be our prime targets in this search due to their well constrained rotation frequencies. We will use the Viterbi search pipeline initially, however other search pipelines could also be used if person and computational resources allow.

TASK Op-4.5-B(i): TARGET LIST

FTE-months: 3.0

Identify a list of LMXBs / AMSPs targets.

TASK Op-4.5-B(ii): RUN VITERBI SEARCH

FTE-months: 3.0

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK Op-4.5-B(iii): FOLLOW UP STATISTICAL OUTLIERS – VETOS

FTE-months: 3.0

We will use the same veto procedure as applied in the Scorpius X-1 search to follow up any statistical outliers.

TASK Op-4.5-B(iv): PUBLICATION

FTE-months: 3.0

Produce publication presenting the LMXBs / AMSPs search results.

Op-4.6 Directed searches targeted the Galactic center

Motivation

All-sky searches for continuous gravitational waves are computationally limited because of the rapid increase in computational cost with coherence time of the search. Hence there is a trade-off between searching the largest sky area at reduced sensitivity, or searching a smaller sky region with increased sensitivity. There are regions in the sky that are thought to host high concentrations of the types of objects that might be emitting detectable continuous GWs; the Galactic center and globular clusters are both regions of interest. Several independent lines of evidence suggest the presence of a large number of NS in the few inner parsecs of the Milky Way and may also explain the EM excess measured by astronomical surveys which are not emitted by resolved sources [86, 87, 88, 89, 90].

Methods

The idea is to explore a wide frequency and spin-down parameter space, limiting–where possible–the computational cost of the search. The BSD-directed search pipeline [91] pointing to the sky position of Sgr A*. The BSDs are complex time series sampled at 0.1 s and divided into frequency bands of 10 Hz [74]. For the search of CW signals the time series is heterodyned, partially removing the Doppler effect. From this time series we build “peakmaps”, which consist in a collection of time-frequency peaks selected from the average spectrum. The peakmap will be the input of the FrequencyHough transform which will map the time-frequency peaks into the intrinsic frequency/spin-down values of the source. Selected candidates, if significant enough, will be followed up with methods similar to those used in all-sky searches.

Activities for O3

ACTIVITY Op-4.6-A: EARLY O3 GALACTIC CENTER PAPER (NOT YET PLANNED)

Pending on person power, we will run a directed search(es) for the Galactic center using some of the available pipelines, e.g. BSD-directed.

TASK Op-4.6-A(i): RUN SEARCH AND POST-PROCESSING

FTE-months: 3.0

Run directed search(es), identify and follow up candidates, and veto outliers caused by instrumental artifacts.

TASK Op-4.6-A(ii): SET UPPER LIMITS

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

FTE-months: 3.0

TASK Op-4.6-A(iii): REVIEW SEARCH RESULTS

Review the search procedure and results.

FTE-months: 3.0

TASK Op-4.6-A(iv): PUBLICATION

Produce a publication presenting the results.

FTE-months: 3.0

Op-4.7 All-sky searches for isolated sources

Motivation

While other CW searches explore regions of potentially high interest, e.g. known pulsars and directed targets, it is prudent to conduct comprehensive searches of the entire parameter space so as not to miss an unexpected source, one for which electromagnetic pulsations have not yet been detected. Theory suggests that fractional deformations or *ellipticities* of neutron stars as high as 10^{-5} could be sustained by neutron star crusts. On the other hand, there are observed neutron stars with ellipticities smaller than 10^{-8}, and it may well be that still smaller ellipticities are common. As our searches struggle to touch ellipticities of 10^{-7} at the top of the explored frequency range, it is likely that the first discovered source would have an unusually high ellipticity.

Methods

There are several pipelines in the CW group that have been optimized for different search scenarios, data quality and analysis speed. PowerFlux [92] can be used to carry out broad all-sky searches over entire frequency space with the aim of producing results as promptly as possible. It is the only pipeline that performs direct estimation of gravitational wave power. The loosely coherent pipeline [93] is capable of improved sensitivity at greater computational cost. FrequencyHough [94] and SkyHough [95] are based on different implementations of the Hough transform algorithm and inherit its resilience to contaminated data. The time-domain $\mathcal{F}$-statistic pipeline [96] is based on a method with a long coherence time. This makes it resilient to many artifacts affecting pipelines with shorter coherence lengths. All pipelines have experience with processing large number of outliers with streamlined follow-up methods and vetoes.

Activities for O3

ACTIVITY Op-4.7-A: FULL O3 ALL-SKY ISOLATED PAPER

TASK Op-4.7-A(i): RUN THE SKYHOUGH SEARCH

Run the SkyHough search code for single and multiple interferometer data, using the data of the two most sensitive detectors, produce a large list of candidate sources and post-process the results, either by checking coincidences among different data sets (among different detector or between first and second half of the O3 run) and/or implementing a number of vetoes.

FTE-months: 3.0

TASK Op-4.7-A(ii): RUN TIME-DOMAIN $\mathcal{F}$-STATISTIC PIPELINE

Run the time domain F-statistic pipeline for network of two LIGO and one Virgo detectors. Search the band of [20 - 750] Hz divided into segments 6 days long and 0.25 Hz wide with the two-step procedure. First search the segments coherently using the $\mathcal{F}$-statistic and then search for coincidences among candidates in each frequency band.

FTE-months: 3.0

TASK Op-4.7-A(iii): RUN THE FREQUENCYHOUGH SEARCH FTE-months: 3.0

Run the FrequencyHough search code for the LIGO-Virgo detector network, produce a large list of candidate sources and post process the results, either by checking coincidences among different data sets (among different detector or between first and second half of the O3 run) and/or implementing a number of vetoes.

TASK Op-4.7-A(iv): RUN THE POWERFLUX SEARCH FTE-months: 3.0

Run the PowerFlux search code on data from the LIGO detectors to set upper limits and search for significant outliers.

TASK Op-4.7-A(v): FOLLOW UP STATISTICAL OUTLIERS FTE-months: 3.0

Follow up statistical outliers from each search using longer coherent integration times. This may be done collectively or by each individual search.

TASK Op-4.7-A(vi): SET UPPER LIMITS FTE-months: 3.0

In the event of no detection, each pipeline sets averaged population based upper limits on the gravitational-wave strain amplitude and derives astrophysical implications.

TASK Op-4.7-A(vii): REVIEW FTE-months: 3.0

Review search set up and results, as well as any recent search method improvements and optimizations (Section LT-4.16).

TASK Op-4.7-A(viii): PUBLICATION FTE-months: 3.0

Produce a single publication either presenting the detection of continuous gravitational-waves from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used on O3 data.

ACTIVITY Op-4.7-B: EARLY O3 ALL-SKY ISOLATED PAPER (NOT YET PLANNED)

TASK Op-4.7-B(i): RUN THE SKYHOUGH SEARCH FTE-months: 3.0

Define the parameter space of the search depending on computational resources. Estimate the depth of the search by means of software injected simulated signals in the data. Run the SkyHough search code for single and multiple interferometer data, using the first 6 months of O3 data from the two most sensitive detectors, and post process the results by checking coincidences and implementing a number of vetoes. Produce a list of candidate sources. Depending on the achieved sensitivity, results will be presented or not for publication.

TASK Op-4.7-B(ii): RUN THE POWERFLUX SEARCH FTE-months: 3.0

Run the PowerFlux search code on data from the LIGO detectors to set upper limits and search for significant outliers.

TASK Op-4.7-B(iii): REVIEW FTE-months: 3.0

Review search set up and results.

TASK Op-4.7-B(iv): PUBLICATION FTE-months: 3.0

Produce a single publication either presenting the detection of continuous gravitational-waves from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used on early O3 data.

Op-4.8 All-sky searches for unknown sources in binaries

Motivation

CW emission from neutron stars in binary systems (see also Section Op-4.5) are of particular interest because of recycling, where a companion star accretes matter onto the neutron star, imparting angular momentum to it and speeding it up. Most observed millisecond pulsars observed in radio, X-rays and/or γ rays reside in or once resided in systems where the accretion has stopped, but where the neutron stars retain a high angular velocity. Accretion can provide a natural mechanism to impart asymmetries in the neutron star moment of inertia, thus causing the star to emit continuous gravitational waves, even after accretion has subsided.

Neutron stars in unknown binary systems present an extreme challenge for CWs 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, and adding the unknown binary orbital modulations makes the problem all the more difficult.

Methods

The TwoSpect method [97], which relies on doubly-Fourier transformed data, is to date the only method that has been applied to LIGO and Virgo data to perform an all-sky search for unknown sources in binaries [98]. TwoSpect allows for a broad range of parameter space to covered while maintaining computational efficiency.

The BinarySkyHough is a new pipeline [99] developed from the SkyHough method, one of the semi-coherent pipelines able to perform all-sky searches for continuous wave signals with a low computational cost. BinarySkyHough is an extension of this method, which allows to search for signals from neutron stars in binary systems, which have an extra Doppler modulation. Due to the highly increased computational cost, BinarySkyHough requires GPUs in order to have a feasible computational cost. A test run using this pipeline is currently underway using O2 open data.

Activities for O3

ACTIVITY Op-4.8-A: EARLY/FULL O3 ALL-SKY BINARY PAPER (NOT YET PLANNED)

Contingent on availability of GPU resources, run the existing BinarySkyHough code for a broad frequency band all-sky search using the two stage approach with the same detection statistics (weighted Hough and weighed powers).

TASK Op-4.8-A(i): APPLICATION FOR COMPUTING TIME

FTE-months: 3.0

Application for computing time to obtain external LVC resources.

TASK Op-4.8-A(ii): RUN BINARYSKYHOUGH CODE

FTE-months: 3.0

Run BinarySkyHough code for unknown CW signals using early O3 data. Parameter space to be determined upon computational resources (zero spin-down and three binary parameters).

TASK Op-4.8-A(iii): POST-PROCESSING AND VETOES

FTE-months: 3.0

Production of top-list of candidates, selection of clusters, application of lines veto, multi-detector significance veto, binary modulation "DMOff" veto, and χ^2 veto.

TASK Op-4.8-A(iv): FOLLOW-UP CANDIDATES

FTE-months: 3.0

Follow-up candidates with an adaptation of MCMC Follow-up F-statistic method.

TASK Op-4.8-A(v): REVIEW

FTE-months: 3.0

This will include code review as well as reviewing search results.

TASK Op-4.8-A(vi): PUBLICATION

FTE-months: 3.0

A paper on these results will be written and submitted for publication.

ACTIVITY Op-4.8-B: INVESTIGATE FEASIBILITY OF A TWOSPECT SEARCH USING O3 DATA

FTE-months: 3.0

Pending availability of person power and computing resources, investigate the feasibility of an O3 search using the mature TwoSpect algorithm. This would require running the search, resuming and concluding review efforts, and publication of results.

Op-4.9 Searches for long-transient emission from a post-merger neutron star

Motivation

With the first observed binary neutron star (BNS) merger GW170817 [35] happening relatively close to Earth at $\sim$ 40 Mpc, interest has arisen in using CW-derived analysis methods to search for a long-lived neutron star remnant from any similar events detected in the future. While shorter remnant signals on the order of milliseconds to hundreds of seconds can be effectively searched for with methods derived from burst and stochastic searches [100], longer signals associated with the rapid spindown of a young massive neutron star are well suited for CW-derived methods [101]. These remnant searches can play a crucial role in constraining the nature of the remnant and thus the nuclear physics properties of the involved objects [102, 103].

Methods

The parameter space [104, 105], signal morphology and data quality requirements are still quite different from other CW searches. Available methods include adaptations of the hidden-Markov-model Viterbi tracking algorithm [106, 107] and the two semi-coherent Hough algorithms [95, 108, 109, 110] to the rapid-spindown waveform model from [111]. It is also possible to combine some of these methods, with a cheaper, more generic method as a first-stage search and a semicoherent modelled algorithm as a follow-up stage.

Selection of worthwhile BNS candidates for long-duration post-merger searches depends on the rate of increase in detector sensitivity, on the distances at which such events are found, and on how well they are localized.

Activities for O3

ACTIVITY Op-4.9-A: ONGOING COORDINATION WITH OTHER WORKING GROUPS

FTE-months: 3.0

During O3, CW post-merger experts will be on standby to, in the event of an interesting nearby BNS detection, coordinate with other working groups and the observatory heads/operators about search plans and required stand-down times in detector interventions to maximize science opportunities. Nominal thresholds for this have been agreed, but continued coordination will be beneficial.

ACTIVITY Op-4.9-B: OPPORTUNISTIC O3 LONG POST-MERGER PAPER (ON STANDBY)

Pending on person power and event rates, we will run a directed search for the remnant of any sufficiently nearby and well localized BNS merger using some of the available pipelines: Viterbi, adaptive transient Hough, and/or generalized frequency-Hough transform.

TASK Op-4.9-B(i): COORDINATION WITH SHORT-DURATION PUBLICATION PLANS FTE-months: 3.0

The planning of these searches and the eventual publication will require coordination with members of the CBC, burst and stochastic groups to ensure full exploitation of all post-merger science opportunities, proper folding-in of prior information from the inspiral phase, efficient data quality studies, and a streamlined publication schedule.

TASK Op-4.9-B(ii): RUN SEARCHES FTE-months: 3.0

Run different existing search pipelines, post-process results, and in the event of statistical outliers produce a list of candidate signals.

TASK Op-4.9-B(iii): FOLLOW UP STATISTICAL OUTLIERS – VETOES FTE-months: 3.0

Follow up statistical outliers from each search, either collectively or by each individual search.

TASK Op-4.9-B(iv): DATA QUALITY STUDIES FTE-months: 3.0

Data around and after the merger needs to be studied for gaps, nonstationarities, transient line features etc; both in advance to determine optimal search setups, and in more detail if outliers are found.

TASK Op-4.9-B(v): SET UPPER LIMITS FTE-months: 3.0

In the event of no detection, each pipeline sets upper limits through injection of simulated signals.

TASK Op-4.9-B(vi): REVIEW SEARCH RESULTS FTE-months: 3.0

This will include code review of any updated parts of the search pipelines, as well as reviewing their search configurations and results.

TASK Op-4.9-B(vii): PUBLICATION FTE-months: 3.0

Either produce a single stand-alone publication presenting results of the different search pipelines and/or incorporate the results as a brief summary in a more general CBC paper on the BNS event.

Op-4.10 Searches for long-lived transient emission following a pulsar glitch

Motivation

The CW group is primarily focused on searching for truly *continuous* gravitational waves: periodic signals lasting at least as long as an observation run. However, electromagnetic observations of transient neutron star phenomena, such as pulsar glitches, raise the possibility that neutron stars also emit gravitational wave signals on time scales of hours–weeks due to short-lived deformations [112]. The mechanisms behind pulsar glitches are still poorly understood [113] and post-glitch GW observations (including upper limits) could yield valuable insights complementary to radio and other EM observations.

Methods

Many CW search algorithms can be adapted to search for long-duration transients by studying their intermediate, time-dependent data products or running separate analyses on shorter time intervals. For quasi-monochromatic transients during the post-glitch relaxation phase, the transient $\mathcal{F}$-statistic [112, 114] is an efficient method with demonstrated performance on real data [115]. A simple search based on the transient $\mathcal{F}$-statistic method and a setup similar to [115] can be cheaply run for several such targets, with additional development and/or the use of GPUs [114] allowing for either deeper or more searches. The PyFstat package [116] can also search for transient emission using the $\mathcal{F}$-statistic. For shorter signals with frequency evolution, more immediately associated with the glitch event itself, methods similar to those for post-merger searches [106, 107, 108, 110] or from the burst and stochastic domains [7, 117] could also be employed.

Similar to post-merger searches, post-glitch searches face unique data quality and candidate validation challenges. For example, periods of no or degraded data due to environmental effects degrade transient search performance more strongly than for full-run CW searches, and transient lines that would be too weak to affect a year-long analysis can produce strong spurious candidates in a transient search. Once statistical outliers are found in a search, the standard approach of increasing coherence time is not always helpful for transients, and follow-up must instead rely on data quality studies, varying the time steps used in the analysis, generalizing the signal model, and grid-less MCMC methods [118].

Activities for O3

ACTIVITY Op-4.10-A: OPPORTUNISTIC O3 GLITCH PAPER (ON STANDBY)

The case for an O3 paper targeting transients from pulsar glitches depends on the number of such events observed in EM timing of nearby pulsars with frequencies matching the detectors' sensitivity band (assuming the usual factor of 2 for the dominant GW emission frequency).

TASK Op-4.10-A(i): MONITOR AND SELECT TARGETS

FTE-months: 3.0

Data on promising glitches in nearby pulsars needs to be collected and prioritised as search targets. This will be based on the work of EM observers under the MoUs already in place for targeted CW searches (Section Op-4.1) and public literature and databases.

TASK Op-4.10-A(ii): CODE REVIEW

FTE-months: 3.0

The transient $\mathcal{F}$-statistic code in LALSuite and PyFstat packages has not been used in LVC publications before and will require code review. It is based on a simple re-use of intermediate data products from the reviewed CW $\mathcal{F}$-statistic code.

TASK Op-4.10-A(iii): SEARCH

FTE-months: 3.0

For each glitch target, a search of several months of data covering a small frequency band (similar to the searches in Section Op-4.2) must be performed. The detailed search setup can be chosen based on the number of promising targets and the available person-power and computing budget.

TASK Op-4.10-A(iv): CANDIDATE FOLLOW-UP

FTE-months: 3.0

Statistical outliers will be first subjected to data quality scrutiny and anything that cannot be attributed to instrumental lines must be followed up with variations in the search setup and through MCMC methods.

TASK Op-4.10-A(v): DATA QUALITY STUDIES

FTE-months: 3.0

The total time interval covered by each search depends on the pattern of usable science quality data segments, strong transient instrumental lines need to be identified in advance and cleaned from the data, and statistical outliers need to be subjected to deeper checks.

TASK Op-4.10-A(vi): SET UPPER LIMITS

FTE-months: 3.0

If no promising detection candidates survive, upper limits can be set through injections of simulated signals. For large glitches (e.g. from Vela) during O3, beating the indirect energy upper limit can be expected.

TASK Op-4.10-A(vii): REVIEW SEARCH RESULTS

FTE-months: 3.0

In addition to the main search code review, the target list, search configurations and results will require review.

TASK Op-4.10-A(viii): PUBLICATION

FTE-months: 3.0

A single paper can describe the search results for any number of glitches targeted during O3. Coordination with short-duration transient searches for the same targets will be beneficial.

Op-4.11 Searches for continuous emission from axion clouds around black holes

Motivation

Axion clouds forming around BH are expected to emit CW signals over long times. According to theoretical predictions, which are based on several approximations, the emitted signal is exactly monochromatic. We do not want to rely on this strong assumption and aim at developing a robust method for CW signals with zero or very small spin-down (-up) and a finite unknown coherence time. While we have in mind BH/axion cloud systems as a reference source, the method can be used to search for other signals with similar characteristics.

Methods

A simple semi-coherent procedure, in which data are analyzed using various collections of FFTs of durations from hundreds to thousand seconds, has been developed. The procedure is computationally relatively cheap and is suited to an all-sky search [119]. Another method is a semi-coherent directed search for such systems based on hidden Markov model tracking, which is robust against potentially slow frequency variations of the signals due to the expected intrinsic evolutions and astrophysical interactions [120].

Activities for O3

ACTIVITY Op-4.11-A: FULL O3 AXION CLOUD DIRECTED SEARCH PAPER (NOT YET PLANNED)

Pending on person power, we will run a directed search for selected sources including well localized CBC mergers and/or nearby BHs in X-ray binaries using the Viterbi pipeline.

TASK Op-4.11-A(i): SOURCE SELECTION

FTE-months: 3.0

Select sources for directed searches, including closer, well localized, more massive CBC merger remnants and/or known BHs in X-ray binaries with well measured parameters.

TASK Op-4.11-A(ii): RUN SEARCH AND POST-PROCESSING

FTE-months: 3.0

Run directed searches using the existing Viterbi pipeline, identify and follow up candidates, and veto outliers caused by instrumental artifacts.

TASK Op-4.11-A(iii): SET CONSTRAINTS

FTE-months: 3.0

In the event of no detection, interpret results and set constraints on axion mass and other properties.

TASK Op-4.11-A(iv): REVIEW SEARCH RESULTS

FTE-months: 3.0

Review search results. (The pipeline has been reviewed in previous CW analyses.)

TASK Op-4.11-A(v): PUBLICATION

FTE-months: 3.0

Produce a publication presenting the results.

ACTIVITY Op-4.11-B: FULL O3 AXION CLOUD ALL-SKY SEARCH PAPER (NOT YET PLANNED)

Pending on person power, we will run an all-sky search for boson cloud continuous signals, relying on the semi-coherent all-sky pipeline method described above, as well as further developments.

TASK Op-4.11-B(i): RUN SEARCH AND POST-PROCESSING

FTE-months: 3.0

Run the search, identify and follow up candidates, and veto outliers caused by instrumental artifacts.

TASK Op-4.11-B(ii): SET CONSTRAINTS

FTE-months: 3.0

In the event of no detection, interpret results and set constraints on axion mass and other properties.

TASK Op-4.11-B(iii): REVIEW SEARCH RESULTS

FTE-months: 3.0

Review some portions of the analysis pipeline and search results.

TASK Op-4.11-B(iv): PUBLICATION

FTE-months: 3.0

Produce a publication presenting the results.

Op-4.12 Support for continuous wave searches: Follow-up of interesting candidates

Motivation

A candidate for the first detection of continuous gravitational waves will need to be vigorously vetted by many different pipelines. Since many wide-parameter-space searches produce very large numbers of candidates, follow-up pipelines which can efficiently deal with a long list of targets will be necessary.

Methods

Naturally, the pipelines used to search for known pulsars (Sections Op-4.1, Op-4.2) may also be used for candidate follow-up. Follow-up pipelines have also been developed as part of many of the directed (Sections Op-4.4, Op-4.5, Op-4.6) and all-sky (Sections Op-4.7, Op-4.8) search methods. A highly-optimized semi-coherent $\mathcal{F}$-statistic search code [121] was found to be more effective for candidate follow-up compared to other implementations [122]. Other methods have been developed more specifically for candidate follow-up. A general-purpose follow-up tool has been described recently in [118]. A long-transient add-on to semi-coherent analyses is also available for intermediate follow-up steps [123].

The follow-up of outliers from CW searches will generally be accompanied by manual investigation of the detector noise to check for any spectral artifacts that may be responsible for the outliers (Section Op-4.13).

Activities for O3

ACTIVITY Op-4.12-A: FOLLOW-UP OF INTERESTING CONTINUOUS WAVE CANDIDATES

FTE-months: 3.0

As required/requested, use a range of different analysis methods to follow up any interesting candidates found by frontline continuous wave searches, with the goal to confirm or reject their continuous nature.

ACTIVITY Op-4.12-B: FOLLOW-UP OF INTERESTING LONG-TRANSIENT CANDIDATES

FTE-months: 3.0

As required/requested, use a range of different analysis methods to follow up any interesting candidates found by frontline long-transient searches, or to study transient properties of candidates found in CW searches but found in a previous follow-up stage to not follow the expected CW behaviour.

Op-4.13 Support for continuous wave searches: Detector characterization

Motivation

The input data to any continuous gravitational wave analysis pipeline must be carefully characterized and prepared before use. Improperly calibrated data, or data that is otherwise contaminated with excess noise, must be excised from the input data, otherwise analysis results may be affected by large numbers of spurious outliers. Part of this work benefits from a close interaction with the detector characterization working group and the site commissioning staff, as well as informing noise mitigation actions.

Methods

Several tools are used to validate and characterize detector data during observing runs. Volunteers from the detector characterization and CW groups will participate in DetChar Data Quality monitoring shifts, checking to see if new contaminations have appeared that may impact the astrophysical results that the group can deliver. Potentially, if some contamination disappears, this might also indicate a noise coupling source that can be reported back to the site commissioning staff. Experts within the CW group may also investigate further using additional outputs from these tools. Most of the tools employed (which include spectral averaging with fine resolution, spectral line finding, spectral comb finding and data folding on integer-second intervals) are mature, and several of these tools have been integrated into the automated daily summary pages. The results of this data monitoring are reported back to the detector characterization working group. Reports on line contamination identified in search results and/or as part of data preparation is also provided to the detector characterization team.

A small set of data quality flags, produced by the detector characterization working group, are applied to the calibrated detector data so that the most egregious data are discarded. Some data quality flags are only needed for short duration searches, whereas the coherent time interval for most CW searches negates the need for most “glitch” transient flags. The CW group will validate which data quality flags are needed and which can be safely ignored.

Another aspect of detector characterization is detector response validation via "hardware injection" recovery, that is, via the successful reconstruction of signals injected into the interferometer data by radiation pressure actuation on the test masses ("photon calibration"). A set of 15 such signals ranging from 12 Hz to 2991 Hz are monitored daily, weekly and cumulatively during observational runs to validate response and to catch unintended calibration changes. Similar infrastructure can be used to monitor detector sensitivity to known pulsars.

Activities for O3

ACTIVITY Op-4.13-A: DETECTOR CHARACTERIZATION AND SPECTRAL ARTIFACT MITIGATION

TASK Op-4.13-A(i): DATA QUALITY MONITORING

FTE-months: 3.0

Collaborate with Detector Characterization subgroup to participate in monitoring data quality on a weekly basis. Special attention should be paid to spectral noise artifacts and changes thereof.

TASK Op-4.13-A(ii): SPECTRAL ARTIFACT INVESTIGATION AND MITIGATION

FTE-months: 3.0

Investigate artifacts that are problematic for CW/Stochastic searches and work with DetChar and on-site staff to mitigate the most problematic sources of contamination.

TASK Op-4.13-A(iii): GENERATE LIST OF SPECTRAL ARTIFACTS

FTE-months: 3.0

Following the early and full observing run data taking intervals, generate a list of spectral artifacts including whether those artifacts are vetted to be non-astrophysical. Work with GWOSC to publish the lists for public data release.

TASK Op-4.13-A(iv): OUTLIER FOLLOW UP INVESTIGATIONS

FTE-months: 3.0

Outliers from CW search pipelines may need additional, manual investigation to check for any spectral artifacts as part of CW follow up strategies.

ACTIVITY Op-4.13-B: MONITORING OF HARDWARE INJECTIONS

FTE-months: 3.0

Results of automated hardware injection recovery will be monitored, using several different programs of different methodologies: 1) a Bayesian inference method used in targeted-pulsar searches; 2) a frequentist exact-template method in which only amplitude and phase constant vary; and 3) a Fourier-domain F-Statistic search. Any unusual results should be reported to DetChar, Calibration, and hardware injection teams.

ACTIVITY Op-4.13-C: MONITORING OF NARROW FREQUENCY BANDS OF PARTICULAR INTEREST

FTE-months: 3.0

The frequentist method of monitoring hardware injections will also be applied to a handful of "high value" known pulsars (spindown limit accessible) to monitor on a daily basis the sensitivity of the data in those bands and to alert commissioners when sensitivity shows sudden degradation.

Op-4.14 Support for continuous wave searches: Data preparation

Motivation

Since continuous GWs are nearly monochromatic in the Solar System Barycenter reference frame, it is useful for most CW search pipelines to pre-process the $h(t)$ time series into a few common data products ready for analysis by the different pipelines. Common data products include: Short Fourier Transforms (SFTs), Short Fourier Transform Database (SFDB), Band-Sampled Data (BSD), and heterodyned data. Different data products are needed because different analysis pipelines are optimized for knowledge of an putative source (e.g., targeted, directed, or all-sky).

Methods

Data products generated for CW searches generally rely on well known digital data analysis methods, such as the Fast Fourier Transform, heterodyning, or resampling. These algorithms are coded and used within the LALSuite library and the Virgo PSS C code and the Matlab software Snag.

In conjunction with characterising every observing run data set, an appropriate set of data quality flags are used to select time intervals of high-quality $h(t)$ data and used as input for these data products. Once appropriate data is selected, the data is processed and is stored in common computing locations (e.g., distributed to LSC computing clusters via LDR).

The time-domain Bayesian [57] and $\mathcal{F}/\mathcal{G}$-statistic [55] targeted pulsar searches require narrowband time series for each pulsar. The production of these time series makes use of pulsar timing ephemerides that provide a coherent phase solution for each pulsar signal over the course of an observing run. For each pulsar the phase evolution is used to heterodyne the raw $h(t)$, which is subsequently low-pass filtered and downsampled [124]. This gives a complex time series, with a sample rate of one per minute, which can then be used for further analysis.

Activities for O3

ACTIVITY Op-4.14-A: DETERMINE APPROPRIATE TIME SEGMENTS TO ANALYZE

FTE-months: 3.0

Before producing common data products, it is important to identify time segments for which data is reliable. Data quality flags will be chosen in such a way to eliminate truly bad data.

ACTIVITY Op-4.14-B: PRODUCE FOURIER TRANSFORM FILES

TASK Op-4.14-B(i): PRODUCE SFTS

FTE-months: 3.0

SFT files will be produced for a variety of coherence times and at least two windowing choices (Tukey, Hann).

TASK Op-4.14-B(ii): PRODUCE SFDB

FTE-months: 3.0

SFDB files will be produced at the CNAF computing center with four different coherence times: 8192 s, 4096 s, 2048 s, 1024 s for the frequency bands [10 - 128] Hz, [128 - 512] Hz, [10 - 1024] Hz, [10 - 2048] Hz, respectively.

TASK Op-4.14-B(iii): DISTRIBUTE DATA PRODUCTS

FTE-months: 3.0

SFT data products will be distributed to different LSC computing clusters via LDR, and SFDBs will be transferred to other Virgo clusters as well as the Caltech LSC cluster.

ACTIVITY Op-4.14-C: PRODUCE TIME SERIES FILES

TASK Op-4.14-C(i): PRODUCE BSD

FTE-months: 3.0

BSD files will be produced on a monthly base. Each file contains a complex time series covering a 10 Hz frequency band.

TASK Op-4.14-C(ii): PRODUCE NARROWBAND HETERODYNED TIME SERIES

FTE-months: 3.0

The narrowband heterodyned time series will be produced for a range of pulsars with rotation frequencies $\gtrsim 10\,\mathrm{Hz}$ for which ephemerides can be obtained from electromagnetic observers.

Op-4.15 Support for continuous wave searches: Scientific software maintenance

Motivation

The software used and developed by the CW group are maintained in version-controlled repositories in different locations, often in semi-private repositories, and generally are managed by the code authors themselves. One exception is the LALSuite repository [125], which contains important CW core routines and data, such as the antenna patterns as a function of time and sky location and the Sun and Earth ephemeris files. To ensure that this software base is maintained with standard good practice procedures, contributions to the main LALSuite repository [2] are restricted to a merge request model.

Methods

Maintainers from the CW group assist the LALSuite librarian in vetting and approving merge requests to the main repository, to ensure code is well documented and tested, maintains backward compatibility where appropriate, and to reduce the likelihood of introducing new bugs. Issues potentially relevant to the whole group, as well as recently-approved merge requests, are discussed in the weekly teleconferences. Code contributions from external authors (defined as those who are not LVC members) are also supported through an e-mail service desk system.[3]

Activities for O3

ACTIVITY Op-4.15-A: MAINTENANCE OF CW SOFTWARE IN LALSUITE

FTE-months: 3.0

Address issues and approve merge requests to CW software in the LALSuite repository, and keep the CW group informed of any important changes or bugs.

ACTIVITY Op-4.15-B: SUPPORT FOR LALSUITE REPOSITORY MANAGEMENT

FTE-months: 3.0

Work with the LALSuite librarian to ensure the contribution model, code review, continuous integration and other aspects of the repository management continue to evolve and are suitable for the scientific needs of the working group.

LT-4.16 Further improvement and optimization of existing data analysis pipelines

Motivation

The most efficient use of limiting computing resources is essential to the scientific goals of the CW group. Typically, the codes used by the CW group are highly optimized, due to the demanding computational nature of many searches, but further improvements may still be possible. Time spent on optimization will need to be weighed against the potential reduction in run time of the analysis in question, as well as the time needed to review the new version of the code.

At the request of the LSC and Virgo computing teams, the CW group may periodically produce optimization reports to ensure responsible use of LVC computing resources. When requested, pipelines that are found to be the highest users of computing resources will produce optimization reports and work with the LSC computing optimization team to reduce the computing load.

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[2] `https://git.ligo.org/lscsoft/lalsuite`

[3] contact+lscsoft-lalsuite-1438-issue-@support.ligo.org

Activities

ACTIVITY LT-4.16-A: ASTROPHYSICALLY-INFORMED PARAMETER SPACE SELECTION

All-sky searches for unknown continuous wave sources are extremely computationally expensive. It is therefore important to find ways of using the available computational and man-power resources most efficiently. This can be achieved through Monte Carlo-type modelling of the Galactic neutron star population, to build an astrophysically-informed picture of where in parameter space detections are most likely to be made. This knowledge could then be used to make decisions as to how to allocate resources, in terms of sky locations and spin-down parameters.

ACTIVITY LT-4.16-B: FURTHER IMPROVEMENT AND OPTIMIZATION OF THE SKYHOUGH CODE FOR ALL-SKY SEARCHES

The SkyHough method is one of the semi-coherent pipelines able to perform all-sky searches for continuous wave signals with a low computational cost. SkyHough has been used to analyzed O1 and O2 data [126, 127, 128]. Possibilities for further improvement and optimization include: modifying the existing SkyHough code to enable the creation of toplists of candidates form both single and multiple interferometer data (or sets of data) without the need to run the code twice on the same data. using of deep neural network and random forest to classify SkyHough cluster candidates for all sky searches. parallelizing SkyHough code, porting to CUDA some routines to reduce computational cost of isolated all-sky CW searches. implementing and test the viability to use of SparsePHMDs routines: a different way to structure the PHMDs which optimize the first stage of the SkyHough code, provided by the LSC computing optimization team. studying the implementation of universal statistics to derive upper limits. Review of all code modifications would be required.

ACTIVITY LT-4.16-C: IMPROVEMENT AND OPTIMIZATION OF TRANSIENT $\mathcal{F}$-STATISTIC SEARCHES

The transient $\mathcal{F}$-statistic method [112, 114] is well suited for quasi-monochromatic long transients after pulsar glitches (Section Op-4.10). It is computationally cheap as long as applied only to narrow frequency bands around twice the pulsar rotation frequency and simple, rectangular transient window functions. However, the search can be made more robust and general with several improvements over the simple type of setup as it was used in [115]. The method itself can easily support generic transient amplitude evolutions [112], e.g. exponential decay, but the LALSuite code [125] is very slow for these. A much faster GPU implementation is available [114, 116] but will require some (limited) amount of additional work to integrate it in the full search pipeline, plus additional review. The easiest way to run a transient $\mathcal{F}$-statistic search is to reuse the standard 1800 s SFTs produced for all-sky CW searches (Section Op-4.7), but extension of the search space to shorter transients and a detailed follow-up with denser coverage of transient parameters can be achieved with generating and analyzing multiple sets of SFTs with different baselines. Better methods in the time and/or frequency domain to find, clean or mitigate instrumental artifacts will improve the robustness of the search and reduce the effort required for follow-up and review of outliers.

ACTIVITY LT-4.16-D: OPTIMIZATION OF THE FREQUENCYHOUGH PIPELINE

The main target is to port on GPU the heaviest parts of the code.The core FrequencyHough routine has been already ported and reviewed. The capability of running a full all-sky search on new LIGO-Virgo data will depend on the availability of enough GPU resources. The porting will be based on the TensorFlow framework. Extensive tests and comparisons with old code will be done in order to verify the new code behaves properly. An exploratory analysis, over a reduced parameter space, will be run using O2 data. A paper describing the new implementation and the pilot analysis will be written. New pieces of the code, not previously reviewed, will be subject to a review.

ACTIVITY LT-4.16-E: OPTIMIZATION OF THE CROSS-CORRELATION PIPELINE

CrossCorr is the most sensitive pipeline to search for Sco X-1 (Section Op-4.5). Since the sensitivity is determined by the coherence time, which is tied to computing cost, the search is computationally limited: anything which allows the code to run faster enables us to run a more sensitive search. Improvements to the O1 pipeline include: use of resampling [129] to speed up the computation at lower frequencies; more efficient template lattices to cover the orbital parameter space; re-optimization of the choice of coherence times as a function of frequency and orbital parameters.

ACTIVITY LT-4.16-F: EXPLORE FURTHER TWOSPECT ANALYSIS IMPROVEMENTS

TwoSpect provides a framework for analysis of CW sources in binary systems, and is especially powerful when the neutron star or binary parameters are unknown. Pending person power, explore new analysis strategies with the goal of improvements in TwoSpect detection capabilities; this would prove very useful for future all-sky searches for unknown neutron stars in binary systems.

ACTIVITY LT-4.16-G: FINISH X-STATISTIC DEVELOPMENT

The X-Statistic program uses the TwoSpect infrastructure to search for known directions on the sky where a binary system is known or suspected to reside, but for which neither spin frequency nor orbital period is known. The method gives deeper sensitivity than the all-sky TwoSpect algorithm (which is limited by its initial hierarchical step of incoherent harmonic summing), but less sensitive than a fully templated TwoSpect directed search that exploits a known orbital period. The X-Statistic program is being run and refined using O2 data, but the long-term plan is to deploy it on O3 and future data.

LT-4.17 Development of model-robust/agnostic data analysis methods

Motivation

Given the limited knowledge of neutron star physics, particularly beyond nuclear densities, it is conceivable that the usual continuous quasi-sinusoidal model of a CW signal may not entirely reflect nature, and that not accounting for such deviations could prevent detection. In general, without knowledge of what for such deviations could take, this is a difficult issue to address. Relaxing the assumption of phase lock between gravitational and electromagnetic emission is a key motivation for the narrow-band pulsar searches (Section LT-4.17). The stochastic wandering of the spin frequency of LMXBs is a key consideration for directed searches (Section Op-4.5), although the timescale of the wandering is difficult to quantify. The lack of knowledge of the behavior of long-transient signals, such as from a post-merger neutron star remnant (Section Op-4.9) or a pulsar glitch (Section Op-4.10) motivates the development of robust pipelines for such sources. Signals which are not truly continuous, but are intermittent on some timescale, present a particular challenge by expanding the parameter space to include the start and end time of any gravitational-wave emission as a subset of an observing run.

Activities

ACTIVITY LT-4.17-A: POST-MERGER NEUTRON STAR SEARCH METHODS WITH IMPROVED SENSITIVITY AND/OR ROBUSTNESS

Post-merger neutron star searches are a relatively new area of activity in the CW group. While a number of pipelines have been successfully developed so far, further improvements in analysis methods may still be possible. For instance, the likely rapid spindown and uncertain signal model for post-merger neutron stars present numerous challenges to obtaining optimal sensitivity, which new methods development could potentially address.

LT-4.18 Development of new and potentially more sensitive data analysis methods

Motivation

The CW group welcomes blue-sky research into new ideas for search methods which may yield increased sensitivity with respect to current algorithms. Many ideas used in CW data analysis have been imported from other fields of astronomy which also analyze long time series, such as radio pulsar astronomy, as well as from more general trends in data analysis, e.g., the use of Bayesian inference. Other successful ideas have come from engineering fields, such as the Viterbi algorithm used in digital communications.

Activities

ACTIVITY LT-4.18-A: ALTERNATIVE METHODS FOR COMPUTATIONALLY EXPENSIVE SEARCHES

The sensitivity of many CW searches, such as directed and all-sky searches, are fundamentally limited by their computational cost, which typically scales steeply with observation time. It is therefore important to pursue "blue skies" research into alternative analysis methods that are fundamentally less computationally expensive and/or scale more shallowly with observation time, thereby permitting more sensitive searches. Outcomes in this area are difficult to predict, nevertheless success could potentially be vital to a first CW detection.

ACTIVITY LT-4.18-B: IMPLEMENT THE SKYHOUGH CODE FOR DEMODULATED DATA

Develop and optimize a hierarchical search code to make use of all these previous skyHough code optimizations to be able to run on demodulated data, increasing the time baseline of the coherent step and, consequently, the depth of the search. Study the use of power-mixing "tau statistics".

ACTIVITY LT-4.18-C: ELLIPTICITY DISTRIBUTION INFERENCE

For any individual pulsar targeted by a CW search one can estimate the parameters defining the gravitational-wave signal. The amplitude of the signal, as observed at Earth, is defined by the mass quadrupole of the source and its distance from us. The mass quadrupole can itself be parameterized by the ellipticity of the star under assumptions about the equation of state and moment of inertia. For a population of sources it is interesting to understand the distribution of ellipticities across all pulsars, which may help constrain the underlying physics that gives rise to such a distribution. We will expand on the work in [130] to combine results from the targeted pulsar searches to infer the properties of various parameterized ellipticity distributions, and how these might vary for different sub-populations of pulsars, e.g., "young" versus recycled millisecond pulsars. It will be testing on results from the O2 known pulsar analysis [61] as a short author project. The work will be applicable to the results from the O3 targeted search.

ACTIVITY LT-4.18-D: MACHINE LEARNING TRANSIENT CW METHODS AND SEARCHES

Many CW and transient CW searches are computationally challenging and model-dependent, which means that we are bound to find only signals we expect, and we need a lot of resources to look for them. Machine learning can help to circumvent these problems: searches using convolutional neural networks take orders of magnitude less time than traditional methods, and are just as sensitive to the signals that follow our models and even ones that do not. Moreover, machine learning has the capabilities to estimate the parameters of transient CW signals. Finally, it does not necessarily have to be used to detect signals; rather, it can be used to generate waveforms [131], to veto likely false candidates, etc. We plan to continue efforts to run searches [132] with machine learning, to parameter estimate [133, 134], and to apply it in new ways.

LT-4.19 Use mock data challenges to compare data analysis pipelines

Motivation

Mock data challenges are a useful tool for comparing different data analyses pipeline. By subjecting each pipeline to a common set of tests, the benefits and costs of each pipeline can be rigorously assessed. Commonly, simulated data containing signals of varying strengths whose parameters are unknown to the analyst are prepared by a neutral party, and each pipeline is assessed based on the number of simulated signals it found. Successful mock data challenges organized within the CW group compared pipelines for directed searches for Scorpius X-1 [135] and all-sky searches for isolated sources [136].

Activities

ACTIVITY LT-4.19-A: SIMULATION INVESTIGATION FOR SCO X-1

The performance of CW pipelines to search for Sco X-1 will be testing with simulated signals injected into O2 data. In particular, simulations will be generated with varying amounts of spin wandering to check the practical limitations of CW pipelines. Results and conclusions will be reported in a short-author paper.

5 Stochastic Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst, CBC and DetChar groups in sections 8, 9 and 10, respectively.

Op-5.1 Search for an isotropic stochastic gravitational-wave background (short term)

Op-5.1.1 Scientific Case

The stochastic isotropic search targets the stochastic gravitational-wave background, which arises from a superposition of a variety of cosmological and astrophysical gravitational-wave sources. Potential cosmological sources include the amplification of vacuum fluctuations following inflation [137], phase transitions in the early universe [138, 139], and cosmic (super)strings [140, 141, 142, 143]. Astrophysical contributions to the stochastic background consist of an incoherent superposition of sources that are unresolved or too weak to be detected individually. The most promising contribution for terrestrial detectors comes from the population of compact binaries such as binary neutron stars [144] or binary black holes [145]. 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 would also be of great interest as it would give important constraints on the star formation history and the evolution of the mass distributions with redshift. The implication from Advanced LIGO/Virgo's first and second observing runs is that the stochastic gravitational-wave background from binary black holes and binary neutron stars is consistent with optimistic predictions, and is potentially observable with advanced detectors [145, 144, 146].

General relativity allows only for two gravitational-wave polarizations – the tensor plus and cross modes. Alternative theories, such as scalar-tensor theories [147, 148], $f(R)$ gravity [149, 150], bimetric [151] and massive [152] gravity theories, generically predict up to four additional vector and scalar polarization states. The direct measurement of gravitational-wave polarizations may therefore serve as a powerful phenomenological test of gravity.

Op-5.1.2 Methodology

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

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

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 [153, 154], which has served as the basis for all previous LIGO/Virgo stochastic searches [155, 156, 157, 158, 159, 160]. The stochastic pipeline estimates $\Omega_{\rm GW}(f)$ given some assumed power law $\Omega_{\rm GW}(f) \propto f^{\alpha}$. Cosmological sources such as inflation and cosmic string backgrounds are predicted to have $\alpha = 0$, while $\alpha = 2/3$ is appropriate for the signal from binaries.

ACTIVITY Op-5.1-A: SEARCH FOR AN ISOTROPIC STOCHASTIC BACKGROUND

TASK Op-5.1-A(i): O3 ANALYSIS

(i) Measure (or set upper limits on) the energy density of the isotropic stochastic background for different power laws and non-GR polarizations using the combined O1, O2, and O3 data from Advanced LIGO (LHO and LLO), Advanced Virgo, and (possibly) KAGRA; (ii) Using these measurements or upper limits, constrain theoretical models for the isotropic stochastic background, e.g., binary black holes, binary neutron stars and for the first time neutron star-black hole binaries.

FTE-months: 25.0 (includes all aspects of the search, review, and paper writing)

LT-5.1 Search for an isotropic stochastic gravitational-wave background (long term)

In addition to our standard isotropic analysis, there are several additional activities underway to improve the sensitivity of our search.

ACTIVITY LT-5.1-A: IMPLICATIONS AND ASTROPHYSICAL MODELING

Our measurements of the energy density of the stochastic gravitational-wave background will allow us to place observational constraints on specific theoretical models of the background. For example, applying the Bayesian parameter estimation techniques outlined in [161, 144, 162], we can estimate or place upper limits on the average chirp mass and merger rate of the binary black hole population. Understanding the observational implications also requires us to develop more accurate astrophysical models of the binary black hole background, and inflationary models. We will also consider extensions to backgrounds that have circular polarization. Mock data challenges can be used to test the recovery of simulated backgrounds corresponding to different theoretical models.

ACTIVITY LT-5.1-B: COMPONENT SEPARATION

An important extension of the standard isotropic search is to estimate the individual contributions of distinct sources of the background, because the true background is unlikely to be fully described as a single power law. Even if there is one strong (detectable) power law component, the upper limits on the weaker components will be affected by the strong one(s). One should perform a joint analysis considering all the physically allowed spectral shapes together. A “component separation” method was recently developed to put joint upper limits on the amplitudes of multiple spectral shapes [163]. This method uses the results produced by the isotropic search for each spectral shape and estimates the joint upper limit by deconvolving them via a mixing matrix. In addition to the component separation method, we also will implement a related approach using Bayesian parameter estimation to study more general models. This analysis can be applied in post-processing, using the measured cross-correlation spectrum as the fundamental data product.

ACTIVITY LT-5.1-C: FULLY BAYESIAN SEARCH

The standard isotropic analysis uses a hybrid of Bayesian and frequentist techniques to measure the background. This leaves open the possibility that some information is lost in the standard analysis. We propose to use BayesWave [164] to do a fully-Bayesian search for an isotropic stochastic gravitational-wave background. BayesWave is a set of Bayesian inference routines that are optimized for the detection and estimation of unmodeled gravitational-wave bursts. It is also capable of estimating noise power spectra and modeling glitches in the data, using a trans-dimensional reversible jump Markov chain Monte Carlo algorithm to determine the optimal number of parameters (and their values) needed to model these sources. BayesWave has recently been extended to estimate the amplitude and spectral index of a common correlated gravitational-wave component to the covariance matrix for a network of detectors. This allows us to use BayesWave to simultaneously estimate both the detector noise and gravitational-wave background contributions to the observed data in a fully Bayesian manner. By comparing the fully Bayesian approach with the standard isotropic pipeline, we will be able to see if the standard approach is losing information by working solely with the cross-correlation statistic (which ignores the auto-correlation terms present in the likelihood of the fully Bayesian approach).

ACTIVITY LT-5.1-D: DARK PHOTON SEARCH

Gravitational wave interferometers can also be used to search for the existence of dark photon dark matter directly [165]. Such a dark matter background will induce displacements of test masses and mimic a GW signal in a very narrow frequency band. Because they are nearly aligned, the two LIGO detectors experience nearly the same dark matter background; thus their observable signals are highly correlated. A straightforward analysis pipeline has been developed recently and results have been obtained from LIGO O1 data [2]. This pipeline will be applied to carry out a similar analysis for O2 and O3 data, and in parallel a more refined analysis strategy should be pursued. One can exploit a signal template using the theoretically predicted dark matter velocity distribution. A templated search should yield improved sensitivity to a dark photon dark matter background.

Op-5.2 Directional searches for persistent gravitational waves (short term)

Op-5.2.1 Scientific Case

While most prescriptions of the SGWB predict an isotropic signal, there are mechanisms that could introduce anisotropy [143, 166, 167, 168, 169, 170, 171]. For example, a confusion background may arise from binary mergers [161, 172, 173], core-collapse supernovae [174, 175], neutron-star excitations [176, 177], persistent emission from neutron stars [178, 179], and compact objects around supermassive black holes [180, 181]. Depending on the rate and redshift distribution of these objects, the corresponding SGWB could be isotropic or anisotropic. Such an anisotropic signal may appear with greater statistical significance in the anisotropic search than in the isotropic search.

The directional 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 stochastic directional search provides a crucial follow-up to characterize anisotropies present in stochastic signals detected by the isotropic search; it facilitates the detection of highly anisotropic stochastic sources (e.g., clustered in the Galactic plane) that might be missed by the isotropic search; it provides a robust and sensitive search for narrowband point sources from interesting persistent sources (such as accreting binary systems like Sco X-1, young neutron stars like SN1987A, or unknown neutron stars such as a localised population at the galactic center [182]); and it provides a possibility of cross-correlating the SGWB anisotropies with anisotropies in electromagnetic observations (galaxy counts, gravitational lensing) to extract further information on the origin and composition of the SGWB.

Op-5.2.2 Methodology

The anisotropic SGWB search estimates the energy density of the stochastic background while keeping the directional information [183]:

$$\Omega_{\rm GW}(f,\Theta) \equiv \frac{1}{\rho_c}\,\frac{d^3\rho_{\rm GW}}{d\ln f d^2\Theta} = \frac{2\pi^2 f^3}{3H_0^2}\,H(f)P(\Theta), \quad \Omega_{\rm GW}(f) = \int d\Theta\,\Omega_{\rm GW}(f,\Theta), \tag{2}$$

for Hubble parameter H_0 and sky location Θ. The frequency spectrum is typically assumed to be a power law in the frequency band of GW detectors: $H(f) = (f/f_0)^{\alpha-3}$. For a given value of the power index α (for example, $\alpha = 0$ for inflation and cosmic strings, $\alpha = 2/3$ for compact binaries, and $\alpha = 3$ gives a fiducial value for other astrophysical backgrounds such as supernovae), the objective of the search is to estimate $P(\Theta)$. Two approaches are pursued. In the radiometer algorithm, we assume the signal is characterized by a point source

$$P(\Theta) = \eta(\Theta_0)\delta^2(\Theta,\Theta_0), \tag{3}$$

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

$$P(\Theta) = \sum_{lm} P_{lm} Y_{lm}(\Theta). \tag{4}$$

Likelihood maximization leads to estimators of the angular content of the SGWB for the radiometer ($\hat{\eta}_\Theta$) and spherical harmonic ($\hat{P}_{lm}$) cases:

$$\hat{\eta}_\Theta = (\Gamma_{\Theta\Theta})^{-1} X_\Theta \tag{5}$$

$$\hat{P}_{lm} = \sum_{l'm'} (\Gamma^{-1})_{lm,l'm'} X_{l'm'} . \tag{6}$$

The Fisher matrix $\Gamma(f,t)$ encodes the uncertainty associated with deconvolving the raw cross-correlation measurement for different directions on the sky (see [184, 183, 185] for further description and details on its inversion).

ACTIVITY Op-5.2-A: DIRECTIONAL SEARCH FOR PERSISTENT GRAVITATIONAL WAVES

TASK Op-5.2-A(i): O3 ANALYSIS

(i) Measure (or constrain) the energy flux on the sky from point sources (radiometer analysis) and extended sources (spherical harmonic decomposition analysis) for two or three power-law spectral indices. (ii) Perform an unmodeled search for potentially interesting persistent GW sources from specific sky locations or from the galactic plane. (iii) Constrain published models of anisotropic GW backgrounds, for example from cosmic strings or compact binaries.

FTE-months: 30.0 (includes all aspects of the search, review, and paper writing)

LT-5.2 Directional searches for persistent gravitational waves (long term)

In addition to our standard directional analysis, there are several extensions planned or already in production.

ACTIVITY LT-5.2-A: ALL-SKY ALL-FREQUENCY SEARCH FOR UNMODELED PERSISTENT SOURCES

Recent work [186] demonstrates that data compression using sidereal folding [187] can facilitate an extremely efficient narrowband search looking in all directions and at all frequencies. The all-sky, all-frequency extension to the point-source radiometer targets unknown neutron stars in binary systems as well as all other narrowband sources, providing a sensitive tool for discovering *any* persistent point source, which does not conform to the assumptions made by template-based searches. The search method has been tested by injecting and recovering synthetic signals in the presence of instrumental artifacts, using time-shifted O1 data [188]. Additionally, new methods have been introduced to produce sky maps in a highly efficient way by taking advantage of the compactness of the folded data and HEALPix pixelization tools for further standardization and optimization, as implemented in the code `PyStoch` [189]. Building on these developments, we plan to perform an all-sky, all-frequency radiometer search using O1 and O2 data.

ACTIVITY LT-5.2-B: COMPONENT SEPARATION USING NARROWBAND MAPS

Like the isotropic search, directional searches are also performed separately for multiple spectral indices in standard analyses. A method is being developed to generate skymaps for multiple spectral components. However, deconvolution of skymaps, even with one index poses serious challenges, which only gets amplified when multiple components are present. Exploration studies are being performed, initially considering two or three power-law spectral indices.

ACTIVITY LT-5.2-C: MODELS FOR ANISOTROPIC BACKGROUNDS

Observation of anisotropy in the SGWB could indicate structure between now and the surface of last scattering, the scale of which could be used to inform models of our cosmological history. Recent theoretical developments have established the framework for estimating anisotropies in cosmological and astrophysical SGWB models [167, 169], and have applied the formalism to specific cases of the models due to BBH mergers [168, 170, 171, 190, 191, 192, 192, 193] and due to cosmic string networks [169]. We use the measured SGWB anisotropies to constrain theoretical SGWB models. We also investigate ways of correlating SGWB anisotropy measurements with electromagnetic proxies for the evolution of structure in the universe (galaxy counts, gravitational lensing, cosmic infrared background) so as to extract information about the evolution and composition of the SGWB. Finally, we plan to use the spherical harmonic search to study parameterized models of anisotropy, for example arising from neutron stars in the galactic plane [166] or in the galactic center [182].

Op-5.3 Search for very-long transient gravitational-wave signals

Op-5.3.1 Scientific Case

The long transient search looks for very long-lived transient signals ($\gtrsim 10$ hr, to as long as months) that might be otherwise overlooked or mistaken as an apparent stationary stochastic signal. There are several potential astrophysical sources for gravitational-wave transients on these time scales. For example, in Ref. [194], several scenarios associated with neutron stars are suggested, including non-axisymmetric Ekman flow occuring after a glitch and emission from free precession (with a damping time possibly lasting from weeks to years) [195, 196, 197]. Remnants of BNS mergers are particularly interesting as potential sources of very long transient signals. Futhermore, it is worthwhile to be prepared for a surprise: a very long-lived transient signal from an unexpected source. Recent work studying gravitational-wave emission from gravitationally bound axion clouds [198], potentially starting and stopping on the timescale of a few years, serves to illustrate this possibility. Finally, regardless of the specific source, one or more long-lived transient signals (or coherent long-duration noise) can produce an apparent signal in the isotropic and directional stochastic searches, while simultaneously evading detection in searches for short-duration transients. As a result, a dedicated search is necessary to understand the origin of apparent stochastic signals.

Op-5.3.2 Methodology

The transient searches will constrain the energy density $\Omega_{\rm gw}$ [153] due to transient phenomena. As a baseline, the transient searches are carried out using the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) [199, 200, 201, 202, 203]. STAMP works by cross-correlating data from two detectors to produce cross-power spectrograms [199]. Gravitational-wave signals appear as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [199, 204, 202, 203, 205]) in order to identify statistically significant clusters of pixels. Recently, a highly-parallel seedless clustering algorithm [202, 203] was implemented, and recent work [203] demonstrates that GPUs and multi-core CPUs facilitate dramatic speed-ups. Seedless clustering was used in the analysis of the Advanced LIGO O1 data. The results of an all-sky search for long transients using O1 and O2 data are presented in [8, 9].

We will analyze data on timescales of ≈ 10 hr–1 month in order to determine if there are individual long-lived transient signals contributing to the isotropic or directional stochastic measurements. We have run STAMP in all-sky mode on O1/O2 data used in the stochastic search, and we will run the same pipeline on the O3 data. In order to analyze these very long signals, we have added an extra stage of pre-processing in which the data are compressed through time-averaging as described in [206]. As an application of the STAMP very-long-transient pipeline, we will work in collaboration with the Burst group (Section Op-2.2) and CW group (Section Op-4.9) to search for post-BNS-merger gravitational-wave signals. Such a search for a long-lived remnant of GW170817 was conducted [207], with the STAMP pipeline being run as a directed unmodeled search, and we plan to repeat similar searches for remnants of any BNS mergers observed in O3.

The STAMP code package has also produced spin-off technology that has proven useful for detector characterization [208, 209] and follow-up/visualization of CBC triggers [205]. We expect continued development and maintenance of STAMP will be broadly useful for the Stochastic Group activities and the wider LSC/Virgo community.

ACTIVITY Op-5.3-A: SEARCH FOR VERY LONG TRANSIENTS

TASK Op-5.3-A(i): VLT CONTRIBUTION TO $\Omega_{\rm gw}$

FTE-months: 5.0

Measure (or set upper limits on) the energy density of the very long transient signals and their contribution to the overall $\Omega_{\rm gw}$. If a stochastic background is observed, contribute to developing the energy budget of the observed background by estimating the contribution of the very long transients.

TASK Op-5.3-A(ii): STUDY OF BNS MERGER REMNANTS

FTE-months: 5.0

Apply the search for very long transients to data following mergers of binary neutron stars. Coordinate the search and the publication with similar searches conducted in the burst and CW groups.

Op-5.4 Data Folding for Efficient Searches of Stochastic Gravitational-Wave Background

Op-5.4.1 Scientific Case

Searches for a persistent stochastic gravitational-wave background involves processing of cross-spectral density data from pairs of detectors with optimal spectral and spatial filters that maximise the signal-to-noise ratio. It was observed that the spatial part of the filter is periodic in time—it repeats itself after every sidereal day—and the time-dependent component of spectral filters and data are otherwise treated in the same way for all stochastic searches for persistent sources. These two symmetries can be utilized in order to *fold* stochastic cross-spectral data (called Stochastic Intermediate Data or SID) over one or more observing runs into a time-frequency map over a single sidereal day. This process of folding data does not involve any additional approximation (apart from the ones that are used in the standard searches) and it can also incorporate complex corrections that arise from the application of overlapping windows for preprocessing of data. The theory, implementation and validation of folding on real S5 data was presented in [187]. Using a folded data set not only saves an enormous amount of computation time, but it allows many other advantages for performing stochastic analyses in a convenient way, as listed below:

- The computation time required to perform an analysis on n sidereal days worth of data is reduced by a factor n when using folded data. Hence the speed-up to analyse S5 data was a factor of ~ 300.
- The folded data size is small. For a frequency bin size of 0.25 Hz and upper cut-off of 2 kHz, the data size is little more than a GigaByte. So the whole data set can comfortably fit in a laptop's memory.
- Once the folded data has been produced, all other analyses can follow from the same dataset, providing a good opportunity for cross-validation of results.

Op-5.4.2 Methodology

Folding essentially stacks time-frequency maps of data segments (typically few tens of seconds long) for the same sidereal time of every sidereal day of the dataset. The implementation described in [187] also incorporates complex corrections to account for overlapping window functions. The code was implemented in MATLAB as part of matapps. Scripts were also written to generate condor/DAG submission files, though the code is so fast that a serial mode run in an interactive session is often sufficient. The code has the ability to apply data quality cuts on the fly in multiple ways. However, in order to ensure consistency of the results, it may be better to use quality cuts applied by one standard search. The group is considering a modular approach where once a full analysis, perhaps the isotropic search, is done and data quality cuts are finalised, a common set of folded data would be created for all other long duration stochastic searches.

The efficiency and convenience of using folded data has motivated a new map-making code that enables making skymaps on a normal laptop and provides narrowband maps as an intermediate product. It uses PyCBC and healpy, in order to use HEALPix pixelisation and other tools which make it very easy to analyse anisotropic maps. This code also includes some additional computational tricks, which makes it possible to produce skymaps on a laptop in just few minutes.

In summary, the folding code and the new map making code are well equipped to provide compressed datasets in multiple ways, which can be readily used for different analyses at a much reduced computational cost and is very convenient for portable computers.

ACTIVITY Op-5.4-A: FOLDED STOCHASTIC DATA

TASK Op-5.4-A(i): PRODUCE FOLDED DATASET

FTE-months: 2.0

Produce the O3 folded data set, perhaps one set per week/month and one master set for the whole run.

TASK Op-5.4-A(ii): SKYMAPS FROM FOLDED DATA

FTE-months: 8.0

Produce skymaps from folded data, for use in the anistropic search described in Section Op-5.2. This will likely include skymaps corresponding to different frequency bands and detector baselines, as well as overall skymaps combined over baselines and frequency bands.

6 Burst+CBC+DetChar Joint Activity Plans

Op-6.1 Low-Latency searches for GW transients for EM follow-up

Develop, maintain, and staff online searches, including sky-localization, low-latency GRB searches, and Burst, CBD, and DetChar R&D for online analysis within the EM follow-up effort.

Motivation and goals

The prompt identification and dissemination within the transient astronomy community of gravitational-wave detections during the first two observing runs of LIGO-Virgo has led to the breakthrough discovery of GW170817, the first multi-messenger observation of astrophysical sources involving gravitational and electromagnetic waves. The observation has had profound implications from fundamental physics to cosmology, astrophysics and nuclear physics and has established a new era of observing transient events in the Universe: the one enabled by the rapid analysis of gravitational-wave data and the communication of the corresponding findings as close to real-time as possible.

The goal of this activity within LIGO-Virgo is to support the open, public alerts program of the Collaborations through the third and subsequent observing runs. Among key targets aimed include the further reducing of the latency of alerts potentially to pre-merger levels as well as increasing automation and robustness of the distribution of the public alerts. Additional goals include supporting science enabled by low-latency searches that go beyond "gold-plated" detections as such science is chosen to be pursued by the LIGO-Virgo Collaborations.

Major aspects and methods for this activity

Unmodeled and compact binary coalescence matched-filter searches have been developed aiming at detecting and localizing transient gravitational-wave sources in low latency for a rapid neutrino and electromagnetic follow-up. These searches started early in the initial LIGO and Virgo 2009-2010 science runs and continued during the first and second run of the Advanced detectors. Prompt identification and validation of gravitational-wave candidate signals enable to generate and send rapid alerts containing sky position, preliminary significance, distance, and basic classification to the observers. Parameter estimation follow-ups are then performed to send updates and support the electromagnetic and neutrino counterpart search. The notable improvement in sensitivity and lifetime of the LIGO and Virgo network planned for current and near-future observation runs is expected to increase the number of alerts. A major change did take place with the current third observing run which signaled the beginning of the open release for event candidates of high confidence. Lessons learned through the years-long experience and preparation will need to be addressed and drive development, improvement and organization of software and infrastructures to generate, validate and send gravitational-wave candidate signals with the goal of a rapid communication to the astronomical community.

Over the years, multiple search methods have been developed by the LIGO-Virgo Collaborations for the purpose of identifying transient gravitational waves, including their sky-localization and full parameter estimation. Key aspects of such methods in any low-latency searches include their speed and overall computational efficiency. Integral part for enabling prompt alerts is the automation of any data quality/vetoes and their inclusion in the low-latency public alert generation pipelines. Low-latency transient-finding research is generally undertaken under the auspicies of the Bursts and CBC groups, and correspondingly the low-latency identification of data quality/veto conditions (that, e.g., may inhibit the distribution of public alerts) is with the Detector Characterization group. There are several tasks that are part of the end-to-end workflow for the generation of public alerts that over the course of the recent observing runs of LIGO-Virgo have fallen on the intersection of the Bursts, CBC, DetChar groups and which de facto were primarily addressed by the low-latency group. We will briefly discuss these in what follows.

ACTIVITY Op-6.1-A: OPEN PUBLIC ALERT INFRASTRUCTURE

The generation of open public alerts (OPAs) is a fairly complex process that starts with the collection of interferometric data, their real-time calibration and distribution across the compute centers the Collaborations maintain. In this section we will discuss the pieces of infrastructure that were developed specifically for enabling the management and dissemination of transient events from LIGO-Virgo.

TASK Op-6.1-A(i): GRACEDB

Deploy, maintaion, and enhance GraceDb.

TASK Op-6.1-A(ii): GWCELERY

Deploy and maintaion GWCelery.

ACTIVITY Op-6.1-B: LOW-LATENCY OPEN PUBLIC ALERTS OPERATIONS

Produce Open Public Alerts and updates for events detected in low-latency. These alerts will accommodate measured/estimated quantities of the candidate astrophysical sources according to the policy established by the Collaborations (currently and broadly speaking, a measure of the significance of the event –false alarm rate–, the inferred source categorization and source properties including sky localization).

TASK Op-6.1-B(i): CWB ONLINE PIPELINE OPERATION

Deploy and maintain the cWB online search for gravitational wave bursts.

TASK Op-6.1-B(ii): OLIB ONLINE PIPELINE OPERATION

Deploy and maintain the omicron-LAL-Inference-Burst online search for gravitational wave bursts.

TASK Op-6.1-B(iii): GSTLAL ONLINE PIPELINE OPERATION

Deploy and maintain the GstLAL online search for BNS, NSBH, BBH, and IMBHB sources.

TASK Op-6.1-B(iv): MBTA ONLINE PIPELINE OPERATION

Deploy and maintain the MBTA online search for BNS, NSBH, BBH, and IMBHB sources.

TASK Op-6.1-B(v): PYCBC ONLINE PIPELINE OPERATION

Deploy and maintain the PyCBC online search for BNS, NSBH, BBH, and IMBHB sources.

TASK Op-6.1-B(vi): SPIIR ONLINE PIPELINE OPERATION

Deploy and maintain the PyCBC online search for BNS, NSBH, BBH, and IMBHB sources.

TASK Op-6.1-B(vii): MACHINE-LEARNING ENABLED ONLINE PIPELINE OPERATION

Commission a Machine-Learning based low-latency searches for GW transients.

TASK Op-6.1-B(viii): RAVEN ONLINE PIPELINE OPERATION

Deploy and maintain the RAVEN pipeline to search for coincidences between gravitational wave triggers and external electromagnetic/neutrino triggers.

TASK Op-6.1-B(ix): BAYESTAR SKY LOCALIZATION

Deploy and maintain Bayestar for rapid sky localization of low latency events.

TASK Op-6.1-B(x): IMMEDIATE SOURCE PROPERTIES INFERENCE

Deploy and maintain infrastructure for inferring source properties HasNS and HasRemnant for CBC events.

TASK Op-6.1-B(xi): IMMEDIATE SOURCE CATEGORIZATION INFERENCE

Deploy and maintain inference for categorical inference of CBC events into the source categories BNS, NSBH, BBH, a system with one component in the Mass Gap, or an event of terrestrial origin (e.g., an instrumental artifact).

ACTIVITY Op-6.1-C: MEDIUM-LATENCY OPEN PUBLIC ALERTS OPERATIONS

Updates to public alerts will be made based on information acquired with medium latency (hours).

TASK Op-6.1-C(i): ONLINE CBC PARAMETER ESTIMATION

Deploy and maintain online LALInference-based CBC parameter estimation infrastructure for determining extrinsic and intrinsic parameters of CBC events. This parameter estimation will produce more accurate sky maps, and the posterior sample chains can be used to make more refined updates to the source properties and the source categorization.

TASK Op-6.1-C(ii): SOURCE PROPERTIES UPDATE

Develop, deploy, and maintain infrastructure for updating source properties HasNS and HasRemnant for CBC events based on posterior sample chains produced by the online CBC parameter estimation.

TASK Op-6.1-C(iii): SOURCE CATEGORIZATION UPDATE

Develop, deploy, and maintain infrastructure for updating source categorization for CBC events based on posterior sample chains produced by the online CBC parameter estimation.

TASK Op-6.1-C(iv): UPDATES UPON EXTERNAL TRIGGERS

This task is primarily carried out by the Bursts-CBC GRB sub-group, although such medium-latency updates upon external triggers go beyond GRBs (e.g., CCSN, Magnetars, others). The Low Latency group will provide assistances in the form of infrastructure needed in order to enable such task.

ACTIVITY Op-6.1-D: ELECTROMAGNETIC ALERT ADVOCATES AND RAPID RESPONSE TEAM

We will work in increasing the robustness and reliability for fully autonomous alerts corresponding to significant gravitational-wave candidates. Upon need, humans-in-the-loop will be called upon to address circumstances with events that fall beyond the ones anticipated and/or reliably automated. We will provide the necessary infrastructure for interfacing GraceDB and gwcelery with such on-call operations.

TASK Op-6.1-D(i): RAPID RESPONSE TEAM

The Rapid Response Team will vet all events and is responsible for issuing updates or retractions within the critical first 24 hours.

TASK Op-6.1-D(ii): ELECTROMAGNETIC EVENT FOLLOWUP ADVOCATES

The EM Followup advocates are assigned to particular events and are responsible for coordinating and issuing updates to those events.

ACTIVITY Op-6.1-E: PRE-MERGER WARNING SYSTEM

The inspiral of low mass binaries, such as binary neutron star systems, can last for up to hours within the LIGO band. This presents the opportunity to issue an advance warning of an upcoming merger.

TASK Op-6.1-E(i): EARLY WARNING INFRASTRUCTURE

Design, develop, and deploy infrastructure capable of delivering early warning alerts.

TASK Op-6.1-E(ii): GSTLAL EARLY WARNING SYSTEM

Design, develop, and deploy a GstLAL pipeline capable of delivering alerts with negative latency.

TASK Op-6.1-E(iii): SPIIR EARLY WARNING SYSTEM

Design, develop, and deploy a SPIIR pipeline capable of delivering alerts with negative latency.

TASK Op-6.1-E(iv): MACHINE-LEARNING ENABLED EARLY WARNING SYSTEM

Commission a Machine-Learning based system capable of delivering alerts with negative latency.

TASK Op-6.1-E(v): RAPID SKY LOCALIZATION

Develop methods for rapidly obtain rough sky localization based on early warning pipelines (possibly within the pipelines themselves).

ACTIVITY Op-6.1-F: REVIEW OF LOW LATENCY INFRASTRUCTURE

The low-latency infrastructure will be maintained under software change control.

TASK Op-6.1-F(i): LOW LATENCY INFRASTRUCTURE REVIEW

Review all changes to the low-latency infrastructure and configuration prior to deployment.

ACTIVITY Op-6.1-G: INTER-CONNECTS WITH OTHER REAL-TIME OBSERVATORIES

TASK Op-6.1-G(i): AMON/SNEWS2.0

Upon the approval of the Collaborations, we will develop methods to provide inter-connects of LIGO-VIrgo alerts and overall low latency infrastructure to other astronomical observatories that are aiming for the real-time identification of transient astronomical events.

TASK Op-6.1-G(ii): SUB-THRESHOLD MULTI-MESSENGER SEARCHES

Upon the approval of the Collaborations, we will develop methods to provide inter-connects of LIGO-VIrgo alerts and overall low latency infrastructure to other astronomical observatories in order to support sub-threshold multi-messenger searches.

Expected products and/or outcomes

- Open Public Alerts and updates for events detected by online Burst and CBC pipelines.

7 Burst+CBC Joint Activity Plans

Op-7.1 Studies of extreme matter with pre-merger and post-merger gravitational waves R&D (Short Term)

Develop methods to uncover the nature of ultra dense matter in neutron stars inferred from observed BNS and NSBH signals, from tidal and post-merger signatures.

Motivation and goals

An outstanding issue in nuclear physics is the unknown equation of state (EOS) of neutron-star matter. This has two impacts on gravitational-wave science: First, we must understand (and address) any impact the presence of matter may have on statements from CBC searches and parameter estimation. Second, using both CBC and Burst methods, we hope to learn about the equation of state of matter at extreme densities from LIGO/Virgo detections.

The detection and parameter estimation of BNS/NSBH systems employ templates that include the late stages of inspiral, where neutron stars will be tidally deformed and possibly even tidally disrupted. The extent of this deformation is highly dependent on the mass of the star and the EOS of the nuclear matter inside the neutron star, so measuring the tidal parameters of the merging binary will constrain the EOS. In certain BNS scenarios—such as extremely large-radius stars or nonlinear couplings—these tidal interactions may also lead to the loss of signals if they are not incorporated into CBC searches.

Measurement of tidal parameters is immediately possible with post-Newtonian waveforms, however systematic errors are large and will limit the strength of the statements LIGO/Virgo can make. The ability to measure matter effects is constrained by the accuracy and speed of inspiral waveforms. Avenues for improvement include improved waveform models and high-frequency follow-up parameter estimation with numerical simulations. Improvements in EOS constraint may also result from optimally combining information from multiple detections, or from constraining equation-of-state parameters directly.

Astrophysical gravitational waves will also include the merger and high-frequency post-merger, which will be challenging for current-generation detectors to measure but carry additional information about neutron-star matter. Burst follow-up of CBC detections is needed to confirm or constrain the presence or absence of these post-merger signals and measure their properties. Data analysis methods that span the inspiral to post-merger stage of BNS events would strengthen overall statements about the EOS.

Multiple BNS/BHNS detections, giving a distribution of measured masses and/or coincident gravitational-wave and electromagnetic counterpart detections, are in themselves relevant for equation of state constraint. In particular, large measured NS masses could constrain more exotic forms of nuclear matter. Any signature of matter in an observed compact binary merger could also confirm whether one component object is a neutron star instead of a black hole. Therefore, tidal parameter measurement within CBC, identification of electromagnetic counterparts, and burst follow-up results can inform rates and population statements about the categories of observed mergers.

Major aspects and methods for this activity

ACTIVITY Op-7.1-A: SUBGROUP ADMINISTRATION

Management of the Extreme Matter subgroup.

TASK Op-7.1-A(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 2.0

LT-7.1 Studies of extreme matter with pre-merger and post-merger gravitational waves R&D (Long Term)

Develop methods to uncover the nature of ultra dense matter in neutron stars inferred from observed BNS and NSBH signals, from tidal and post-merger signatures (long term).

Major aspects and methods for this activity

ACTIVITY LT-7.1-A: SYSTEMATIC ERROR ASSESSMENT

Statements about tidal parameters are limited by uncertainties in the waveform evolution. Waveform injection and parameter estimation studies will be performed to assess the systematic errors in the measured tidal parameters. These studies will explore the impact of differences in waveform model, spin priors, and calibration errors.

ACTIVITY LT-7.1-B: WAVEFORM DEVELOPMENT AND COMPARISON

The ability to measure tidal parameters is limited by uncertainties in both point-particle and matter-dependent contributions to the waveform evolution. A detailed analysis of the differences between state-of-the-art waveforms for systems with tides, as well as differences with numerical simulations, is required to inform the waveform development outlined in Op-3.3.

Inspiral waveforms for NS-NS systems in the presence of massive scalar fields to be used to constrain the mass and decay constant of the axion or axion-like particles will be developed.

ACTIVITY LT-7.1-C: RAPID ANALYSIS METHODS

Parameter estimation for systems containing neutron stars is not possible for some of the currently implemented tidal effective one body models due to their long evaluation time. Improvements such as surrogate waveform models for the aligned spin waveforms with tidal interactions will be produced.

ACTIVITY LT-7.1-D: BNS POST-MERGER REMNANT AND SIGNAL PROPERTIES

A number of modeled and unmodeled data analysis techniques for constraining the energetics and spectral content of of BNS postmerger signals have been proposed and some applied to GW170817. The efficacy and optimization of such methods will be studied further using numerical simulations of BNS mergers. Techniques to combine information from pre- and post-merger observations, as well as combining measurements from multiple events (i.e., “stacking”) will be developed. Further detector characterization studies will be pursued in an effort to improve high frequency instrumental sensitivity and to refine and optimize analyses of high frequency data.

Studies will be performed to investigate whether the post-merger waveform associated with the NS resulting from the merger event in the presence of massive scalar fields can provide further constraints on both the axion field and the nuclear equation of state.

Development of waveform models for the post-merger can also be used to complement the inspiral, working towards obtaining a unified inspiral-merger-postmerger model.

ACTIVITY LT-7.1-E: RESONANT MODE IMPLICATIONS FOR NEUTRON STAR COALESCENCES

Various mode excitations through the inspiral to merger of neutron stars provide useful modeling frameworks and astrophysical implications. This include p-g mode instabilities in inspiral, resonant r-mode excitations, and approach to f-mode in the final stages of merger. Methods for identifying the presence and significance of such energy transfers will be developed.

ACTIVITY LT-7.1-F: MULTI-SIGNAL UNDERSTANDING OF COMMON CHARACTERISTICS

As a population of neutron-star signals is revealed, methods for usefully combining the information from a full catalog to learn about the underlying physics of dense matter will be developed and implemented.

ACTIVITY LT-7.1-G: CONNECTIONS WITH NUCLEAR PHYSICS AND HIGH-ENERGY ASTROPHYSICS

Extreme matter constraints also stem from investigations of terrestrial nuclear physics experiment, nuclear and QCD theory, and other astronomical observations of neutron stars. LIGO/Virgo analyses will continually need updating to incorporate state-of-the-art methods and models from these fields; for example new equation of state models and constraints and observations of neutron stars used to set our priors.

Op-7.2 Search for GWs from intermediate mass black hole binaries

Search for high mass ($\sim 100\ \mathrm{M}_\odot$ or more) binary black hole systems using CBC and Burst methods.

Motivation and goals

Stellar-mass black holes, originating from core collapse of massive stars, have been observed in the mass range up to $\sim 65\,\mathrm{M}_\odot$. Due to the pair instability, it is expected that normal stellar evolution will not result in black holes with mass roughly in the range 65 to 100 $\mathrm{M}_\odot$. Massive black holes, exceeding $10^5\ \mathrm{M}_\odot$, appear to be generic in galactic centers. Intermediate-mass black holes (IMBHs) are postulated to occupy the mass range between these two. IMBHs exceeding the $65\,\mathrm{M}_\odot$ mass limit of stellar-mass black holes may form in dense stellar environments upon the merger of multiple stellar-mass black holes [210, 211, 212]. These IMBHs may then form binaries and merge with stellar-mass black holses in dense environments.

IMBHs with a mass of a few hundred solar masses may generically exist in globular clusters [213, 214]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [215], or as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [216]. 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 [217]. Binaries including two IMBHs could also form as a result of evolution of isolated binaries with very high initial stellar masses [218].

So far, no IMBHs in the mass range of interest $65\,\mathrm{M}_\odot\ \mathrm{M} \lesssim 1000\,\mathrm{M}_\odot$ for Advanced detectors have been detected. Thus, a single detection will be revolutionary, as it will prove unambiguously that black holes exist in the mass range between stellar-mass and super-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 super-massive black holes.

The searches will be conducted both with matched filter algorithms using CBC templates and Burst algorithms, which do not rely on templates. The matched filter yields the optimal detection efficiency for signals of known form in stationary, Gaussian noise and thus requires a sufficiently accurate signal waveform model for use as a template. The IMBHB Burst search is robust to a variety of features that may create mismatch between the observed signal and BBH template banks, including high mass ratios, mis-aligned spins, eccentricity, precession, deviations from general relativity, or detector noise artifacts. Therefore, the IMBHB search benefits from the combination of the two complementary analysis techniques.

O3 deliverables

ACTIVITY Op-7.2-A: O3 SEARCHES AND PUBLICATIONS

The plan for O3 is for two papers on IMBHB results, one each for O3a and O3b, corresponding to the O3a and O3b CBC catalog updates and papers.

TASK Op-7.2-A(i): PREPARE BURST SEARCH

Improve and upgrade the burst IMBHB search algorithms for O3a and O3b data taking runs.

FTE-months: 1.0

TASK Op-7.2-A(ii): NR WAVEFORMS

In collaboration with numerical relativity (NR) community, continue development and refinement of the IMBHB NR waveforms for interpretation of the results.

FTE-months: 5.0

TASK Op-7.2-A(iii): RUN THE OFFLINE PIPELINES

Run the IMBH-specific pipelines on the O3 data. Report results regularly.

FTE-months: 3.0

TASK Op-7.2-A(iv): INTERFACE WITH CBC CATALOGS

Report results and contribute to the O3a and O3b CBC catalogs and catalog papers.

FTE-months: 4.0

TASK Op-7.2-A(v): REVIEW AND PUBLISH RESULTS

Collect results and write paper for both O3a and O3b.

FTE-months: 5.0

TASK Op-7.2-A(vi): EXCEPTIONAL EVENTS

Follow up any IMBHB candidates. Make the case for or against a single-event LVC publication. Collect results and write paper.

FTE-months: 5.0

ACTIVITY Op-7.2-B: ONLINE SEARCHES

The IMBHB mass range is included as a separate stream of the low latency all-sky Burst pipeline discussed in Section Op-2.1. Similarly, the CBC low latency searches include templates in the IMBHB mass range.

ACTIVITY Op-7.2-C: SUBGROUP ADMINISTRATION

Management of the IMBHB subgroup.

TASK Op-7.2-C(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

FTE-months: 3.0

LT-7.2 Search for GWs from intermediate mass black hole binaries R&D

ACTIVITY LT-7.2-A: NR WAVEFORMS

Continue to work with the numerical relativity (NR) community to develop waveforms for interpretation of IMBHB results.

ACTIVITY LT-7.2-B: POPULATION STUDIES

Develop and refine population studies for existing IMBHB formation models to be used for the astrophysical interpretation of IMBHB results.

ACTIVITY LT-7.2-C: SEARCH ALGORITHM UPGRADE

Improve and upgrade CBC/Burst IMBHB search algorithms for upcoming observing runs.

ACTIVITY LT-7.2-D: SENSITIVITY STUDIES

Study the sensitivity of current CBC/Burst searches to precessing IMBHBs using Numerical Relativity Injections.

Op-7.3 Multimessenger search for GWs and GRBs

Follow up GRB alerts with deeper searches for simultaneous GW (CBC or burst) signals: communicate online associations and perform sub-threshold analyses. Includes joint analysis of sub-threshold candidates with GRB missions.

Motivation and goals

Gamma-ray bursts (GRBs) are extremely energetic bursts of gamma-rays from cosmological sources observed by orbiting satellite detectors at a rate of about one per day. Two phenomenologically recognized categories have been identified [219]: short-duration (< 2 s) GRBs with generally harder spectra, and long-duration (> 2 s) GRBs with generally softer spectra. Astrophysical evidence has led to the hypothesis that these categories herald the creation of a compact object [a black hole (BH) or a neutron star (NS)] by way of two distinct pathways, both of which involve the emission of transient gravitational waves.

The NS-NS and NS-BH coalescences have been invoked as a short GRB progenitor candidates for decades [220, 221, 222, 223, 224]. The joint observation of GRB 170817A and GW170817 has confirmed that NS-NS coalescences are the progenitors of at least some short GRBs [225]. Any future coincident observations of GWs and short GRBs would also be a major scientific result, demanding a rapid publication. Any possible association should be communicated with low latency to enable follow-up observations of any GRB of interest.

Long GRBs are associated with the gravitational collapse of massive stars. The wide range of observable properties they display has led to the speculation that there may be sub-classes involving different mechanisms, with astrophysical details far from being fully understood. Any significant GW detection would presumably contribute to our understanding of the underlying astrophysics. Some models predict GW emission associated with the accretion disk itself, or with a post-collapse proto-NS, which would give rise to long-duration ($\lesssim 1$ 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.

Methodology

To search for gravitational waves associated with GRBs, we use triggered (using GRB time and sky position), coherent algorithms that target either NS-NS and NS-BH binary inspiral signals [226] in the case of short GRBs, or generic GW burst signals [11] for all GRBs. These searches are more sensitive than the corresponding all-sky ones. We run them both online (few-hour latency) and offline. We use an additional algorithm [227] to search online (minutes latency) for coincidences between low-latency, all-sky GW triggers and GRBs.

We continue to develop methods to utilize sub-threshold GW triggers, sub-threshold GRB triggers, or both. An offline search using sub-threshold all-sky CBC triggers to search for coincident GRBs with Fermi was established with the O1 publication [O1 sub-th paper].

O3 deliverables

ACTIVITY Op-7.3-A: TRIGGERED GRB SEARCH AND PUBLICATIONS - OFFLINE

The following tasks are necessary for implementing the standard offline, triggered GRB search and to report results. There will be separate upper limits papers for O3a and O3b, in addition to any exceptional events papers.

TASK Op-7.3-A(i): CATALOG THE GRBS

FTE-months: 3.0

Collect and catalog the GRBs from Swift, Fermi, and IPN to be used in the triggered searches.

TASK Op-7.3-A(ii): RUN THE SEARCH PIPELINES

FTE-months: 5.0

Run the Burst and CBC pipelines on the appropriate GRB triggers, as catalogued above.

TASK Op-7.3-A(iii): COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW

FTE-months: 5.0

Report results and prepare publications separately for O3a and O3b.

TASK Op-7.3-A(iv): EXCEPTIONAL EVENTS

FTE-months: 6.0

Follow up any exceptional event candidates identified in the all-sky Burst or CBC searches, or resulting from the above triggered searches. Make the case for or against a single-event publication.

ACTIVITY Op-7.3-B: ONLINE SEARCHES

TASK Op-7.3-B(i): RAVEN

FTE-months: 6.0

Complete the review of the O3 RAVEN code, including sky position overlap. Monitor the operation of RAVEN as a low-latency method for detection of coincident GW and external candidates. Follow up candidates.

TASK Op-7.3-B(ii): MEDIUM LATENCY

FTE-months: 6.0

Complete the review of the online, medium latency versions of the GW-GRB pipelines (CBC and Burst), including their interfacing with the low-latency infrastructure. Monitor the results and follow up any candidates of interest.

ACTIVITY Op-7.3-C: SUB-THRESHOLD SEARCHES

Carry out the programs described in the MOUs with the Fermi and Swift collaborations for exploiting potential associations of (sub-threshold) GW triggers with (sub-threshold) Fermi-GBM or Swift triggers.

TASK Op-7.3-C(i): TARGETED SEARCHES

FTE-months: 3.0

Define methods and goals for an O3 search.

TASK Op-7.3-C(ii): UNTARGETED SEARCHES

FTE-months: 3.0

Define methods and goals for an O3 search.

ACTIVITY Op-7.3-D: SUBGROUP ADMINISTRATION

Management of the GRB subgroup.

TASK Op-7.3-D(i): SUBGROUP LEADERSHIP

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-7.3 Multimessenger search for GWs and GRBs R&D

ACTIVITY LT-7.3-A: CBC-GRB PIPELINE

Complete development of a targeted, coherent matched-filtering CBC search which is consistent with the pyCBC framework.

ACTIVITY LT-7.3-B: NS FLARES

Develop method for follow-up of compact binary merger triggers with targeted Fermi-GBM search for orbitally-modulated NS flares [228].

ACTIVITY LT-7.3-C: LONG-DURATION SEARCH

Complete the development of a cross-correlation search for longer duration GWs, targeting GRBs with X-ray plateaus.

ACTIVITY LT-7.3-D: SUB-THRESHOLD SEARCHES

Continue development of methods to exploit sub-threshold GRBs (from Fermi, Swift) and/or sub-threshold GW triggers.

Op-7.4 Multimessenger search for GWs and fast radio bursts

Follow up FRBs with coherent Burst and CBC searches, similarly to the GRB-GW method.

Motivation and methods

Since the publication in summer 2013 of four Fast Radio Bursts (FRBs) identified in Parkes Telescope data [229] 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 multitude of FRBs have been published so far [230], including repeating sources [231], and an increasing number of radio telescopes are becoming involved in FRB identification, most notably the CHIME detector [CHIME].

Currently, while numerous papers have suggested plausible sources for these radio transients, their origin (or origins if there are distinct classes) is unclear. Not all plausible mechanisms for emission of FRBs are likely to result in simultaneous gravitational wave emission at detectable frequencies. However, compact binary coalescences, neutron star asteroseismology, and cosmic string cusps are all proposed mechanisms for production of both gravitational waves and short duration radio transients in the frequency ranges of interest. See [232] and references therein for descriptions of the relevant models. Identification of a clear coincidence between an FRB and a transient gravitational wave, while challenging at current sensitivities, would be of tremendous scientific value in determining the nature of FRBs in addition to being a major achievement in the field of gravitational-wave astronomy.

Given the unknown nature of FRBs, it is appropriate to apply both CBC and Burst pipelines in triggered searches, essentially mirroring the externally triggered GRB searches, except for the choice of triggers and on-source windows.

O3 Deliverables

ACTIVITY Op-7.4-A: OFFLINE TRIGGERED SEARCH AND PUBLICATION

The following tasks are necessary for implementing the O3 FRB-GW search.

TASK Op-7.4-A(i): CATALOG THE FRBS

FTE-months: 2.0

Collect FRB triggers from the O3 run. It is understood that these triggers may not be available until well into the O3 run. It is possible that new MOUs between the LVC and the radio collaborations will be necessary.

TASK Op-7.4-A(ii): RUN THE SEARCH PIPELINES

FTE-months: 5.0

Run the modified GRB Burst and CBC pipelines over the above triggers.

TASK Op-7.4-A(iii): COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW FTE-months: 5.0

Report results and prepare a publication for O3.

TASK Op-7.4-A(iv): EXCEPTIONAL EVENTS FTE-months: 4.0

In the event of a GW-FRB detection or an astrophysically interesting upper limit, make the case for a single-event publication.

Op-7.5 Multimessenger search for GWs and high-energy neutrinos

Perform searches for sources of GWs and high-energy neutrinos.

Motivation and methods

Some dynamical processes with strong 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 (HEN) [233, 234]. 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 [235], its surroundings [236], and the nature of relativistic outflows [237, 238]. 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 [239, 240].

In O1 and O2 we worked closely with the IceCube and ANTARES collaborations to develop and perform sensitive multimessenger analyses to search for neutrinos associated with GW candidates, and in particular with GW150914 [241], LVT151012 and GW151226 [242], and GW170817 [243]. No coincident neutrinos were found. The results were used to constrain the neutrino flux from these sources.

The method employed uses temporal and spatial coincidence between the GW and HEN triggers to identify detection candidates. The same pipeline (GWHEN) can be used in both offline or online instances of the search.

O3 Deliverables

ACTIVITY Op-7.5-A: CARRY OUT O3 SEARCH

Perform the multimessenger search between GW events and high-energy neutrinos.

TASK Op-7.5-A(i): PIPELINE REVIEW FTE-months: 2.0

Complete the review of the GWHEN pipeline for O3. This will allow its results to be made public as LVC products.

TASK Op-7.5-A(ii): MONITOR O3 FTE-months: 4.0

Follow up GW candidates in low latency and report GWHEN results via public GCN notices.

TASK Op-7.5-A(iii): COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW FTE-months: 6.0

Collect and/or catalog triggers from IceCube and ANTARES from the O3 run. Run the GWHEN pipeline in offline mode. Report results and prepare a publication for O3.

TASK Op-7.5-A(iv): EXCEPTIONAL EVENTS FTE-months: 4.0

In the event of a GW-HEN detection or an astrophysically interesting upper limit, make the case for a single-event publication.

LT-7.5 Multimessenger search for GWs and high-energy neutrinos R&D

ACTIVITY LT-7.5-A: INCORPORATE AUGER TRIGGERS

Incorporate high energy cosmic ray triggers from the Pierre Auger Observatory into the low-latency GWHEN coincidence analysis, along with IceCube and ANTARES.

Op-7.6 Measuring the Nuclear Equation of State from Pre-Merger and Post-Merger GWs

Determine the nature of ultra dense matter in neutron stars inferred from observed BNS and NSBH signals, from tidal and post-merger signatures.

Motivation and goals

This project will become active if an event or multiple events are determined which contain a neutron star. If substantial constraints on the equation of state are possible, then a companion paper to either the O3a or O3b Catalogs will be written. Otherwise, results will be included in the potential detection paper.

Major aspects and methods for this activity

Activities and tasks will come into scope upon the identification of an NS-NS or NS-BH event for which constraints on the equation of state are possible.

ACTIVITY Op-7.6-A: TIDAL PARAMETER ESTIMATION

Analysis of neutron star-mass systems will be done with tidal waveform models as a baseline. Especially if there is a possibility of BHNS, the current default of independent component deformations is expected. Statements about tidal constraint (or lack of constraint) and implications for neutron star EOS and radius will be be included any publication on source properties.

TASK Op-7.6-A(i): MEASUREMENT OF TIDAL INTERACTION

Measure and interpret the tidal interaction between binary components.

ACTIVITY Op-7.6-B: COMMON EQUATION OF STATE ANALYSES AND NEUTRON STAR RADIUS

FTE-months: 2.0 (1 FTE months per NS binary)

For likely double neutron star systems, analysis with the astrophysically reasonable assumption that both objects are described by a common equation of state provides the most informative statements about neutron star equation of state and radius.

Tidal parameters and radii of a BNS components will be generated using EoS-insensitive relations to enforce a common EoS. Model selection for BBH/NSBH/BNS/etc.

Tidal parameters and radii of a BNS components and EoS in density-pressure space will be generated using an EoS parameterization.

Masses, tidal deformabilities and EoS based on Gaussian process prior for EoS can produce posteriors for mass-radius relation, central density/pressure, maximum NS mass, and do model selection on candidate EoSs, BNS/NSBH/BBH.

Comparison of evidences between tabulated neutron star equations of state.

ACTIVITY Op-7.6-C: POST MERGER CONSTRAINTS

FTE-months: 2.0 (1 FTE months per NS binary)

Constrain the gravitational wave emission produced by a post-merger remnant (if not a direct collapse to form a black hole).

ACTIVITY Op-7.6-D: MULTIPLE SIGNAL STATEMENTS

FTE-months: 2.0 (1 FTE months per NS binary)

Since the equation of state is expected to be universal, combined analyses of multiple BNS mergers can provide improved measurements of this equation of state. This activity involves measuring equation of state parameters or equation of state model selection using multiple events.

Expected products and/or outcomes

1. With detections of BNS/BHNS, a constraint (or non-constraint) statement on the EOS of nuclear matter will be made. It will include CBC estimation of tidal parameters.
2. Following an extraordinary BNS detection (such as GW170817), provide targeted follow-up analyses of putatitve high-frequency post-merger gravitational wave emission using unmodeled and, where available, model-based parameter estimation techniques to:
    - Identify or reject plausible emission models by measuring or constraining the energetics of the post-merger emission.
    - Constrain the EOS via spectral analysis of the post-merger signal.

Note that studies targeting long-duration (days-months) post-merger signals are being coordinated between the long burst/stochastic and the CW group and will lead to a companion publication (see section Op-4.9 for CW contribution and full paper discussion).

8 Burst+Stochastic Joint Activity Plans

Op-8.1 Search for GWs from cosmic strings

Motivation and methods

A cosmic network of strings may form as a result of phase transitions in the early Universe [244]. When a U(1) symmetry is broken in multiple causally disconnected spacetime regions, one-dimensional topological defects, i.e. strings, are expected to form [245]. 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 [246, 247, 248, 249, 250]. Cosmic strings produced in string-theory-motivated models (dubbed "cosmic superstrings") have received much attention since they could provide observational signatures of string theory [251, 252].

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational-wave emission from loops [253, 254]. When two string segments meet, they may exchange partners. When a string intercommutes with itself, a closed loop breaks off. The loop oscillates, radiates gravitationally, and eventually decays. Special points on the cosmic string loop play an important role: cusps and kinks. Cusps are points along the string with large Lorentz boosts. Kinks are loop discontinuities that forms every time intercommuting occurs. Both cusps and kinks produce powerful bursts of gravitational radiation [255].

Cosmic string GW events are searched individually using matched-filtering techniques or as a stochastic background of all signals in the Universe [256, 257]. The two searches are conducted over LIGO-Virgo data and provide complementary results. In particular, observational constraints on cosmic string models are given as bounds on the string tension $G\mu$ $(c = 1)$, where G is Newton's constant and μ the mass per unit length. These constraints are then used to drive the theoretical developments and cosmic string network simulations.

Major deliverables for this activity

ACTIVITY Op-8.1-A: O3 SEARCH FOR GW BURSTS

TASK Op-8.1-A(i): COMPLETE CONVERSION OF SEARCH CODE

FTE-months: 4.0

Update the pipeline code by implementing methods used in GstLAL CBC pipeline. This enables a more powerful noise rejection, as well as a better memory management and speed up the analysis.

TASK Op-8.1-A(ii): RUN SEARCH PIPELINE AND REVIEW RESULTS

FTE-months: 4.0

Run the templated search for GW bursts from cosmic strings over O3 data. If no clear GW detection, determine significance of upper limits relative to those published for O1-O2.

TASK Op-8.1-A(iii): DETERMINE MODEL PARAMATERS

FTE-months: 4.0

Decide which models/simulations predicting the loop distribution should be used to constrain cosmic string parameters.

ACTIVITY Op-8.1-B: O3 STOCHASTIC BACKGROUND SEARCH

TASK Op-8.1-B(i): DETERMINE MODEL PARAMATERS

FTE-months: 3.0

Decide which models/simulations predicting the loop distribution should be used to constrain cosmic string parameters.

TASK Op-8.1-B(ii): PARAMETER ESTIMATION

FTE-months: 3.0

For the chosen cosmic (super)strings models, perform the parameter estimation using the latest (O3) results of the stochastic searches to compute excluded or preferred regions of the parameter space.

ACTIVITY Op-8.1-C: PUBLICATION

TASK Op-8.1-C(i): DETERMINE PUBLICATION PRODUCT

FTE-months: 2.0

In case of a detection, or a significant improvement of upper limits relative to previous results, prepare a collaboration paper. Otherwise, report results internally and decide if a short author-list paper is warranted. The decision about publication will be based on a discussion across the burst and stochastic groups and will incorporate improvements in results of both burst and stochastic searches.

LT-8.1 Search for GWs from cosmic strings R&D (Long Term)

ACTIVITY LT-8.1-A: BURST ALGORITHM DEVELOPMENT

Recent searches for GW bursts from cosmic strings have been limited by noise artifacts, specifically “blip glitches." Determining how to mitigate the effects of such artifacts in the search is crucial for improving upper limits or for making a detection claim.

ACTIVITY LT-8.1-B: IMPROVED MODELS

It is expected that theoretical developments will continue to provide the impetus towards new types of cosmic string related phenomena and improved cosmic string templates for GW burst searches.

9 Stochastic+CBC Joint Activity Plans

LT-9.1 Search for the stochastic background from unresolvable binary black hole mergers

LT-9.1.1 Scientific Case

The recent detections by aLIGO of several binary black-hole (BBH) mergers suggests the near-term possibility of detecting the stochastic background of weaker, unresolvable BBH signals out to large redshift. Rate estimates predict one such event every $\sim$2 minutes on average, with each merger lasting $\mathcal{O}(1 \text{ second})$. Thus, the duty cycle is $\lesssim 10^{-2}$, implying a “popcorn-like" *highly non-stationary* stochastic signal. Although the standard cross-correlation search can be used to search for such a background, the low duty cycle of the expected signal renders the standard (Gaussian-stationary) search *sub-optimal*, since most of the segments analyzed will consist of only detector noise. Here we propose a joint activity between the stochastic and compact binary coalescence (CBC) groups to develop and implement a Bayesian search strategy (originally proposed by Smith and Thrane [258]), which is optimally-suited to handle the non-stationarity of the expected background from BBH mergers.

LT-9.1.2 Methodology

The search methodology is based on Smith et al. [258] which applies Bayesian parameter estimation to all available data. The search uses the output of `lalinference_nest` to construct a probability density on the *astrophysical duty cycle* which we take to be the fraction of analyzed data segments which contain a CBC signal

$$p(\xi|d) = \prod_{i=1}^{N} \left[\xi \mathcal{Z}_s^i + (1-\xi)\mathcal{Z}_n^i + \text{glitch terms}\right] . \tag{7}$$

The data d are broken up into N segments d_i, each of duration T; ξ denotes the probability that a particular segment contains a signal, which is related to the rate R via $R = \xi/T$; $\mathcal{Z}_s^i$ and $\mathcal{Z}_n^i$ are respectively the signal and noise evidences of the i^{th} data segment and are the outputs of `lalinference_nest`. For readability, the glitch-model terms have been omitted. The search treats non-Gaussian glitches in the data as uncorrelated CBC-like signals in two or more detectors. These glitch terms are also outputs of `lalinference_nest` and this particular glitch model was shown in [258] to yield unbiased estimates of the astrophysical duty cycle in O1 background data. Using Bayesian inference, one can then calculate either a Bayes factor for the signal+noise to noise-only models, which can be used as a detection statistic, e.g.,

$$B = p(\xi > 0|d)/p(\xi = 0|d) \tag{8}$$

to estimate the rate of BBH events. It is the *mixture* form of the likelihood that allows one to handle the non-stationarity.

Because the search applies Bayesian parameter estimation to compute the signal and noise evidences of the data, we also obtain posterior PDFs of the CBC parameters (such as masses and spins) irrespective of whether the data contains a signal or not. The PDFs from each data segment can, in principle, be combined in a Bayesian way to infer the properties of the whole population of CBC signals.

The proposed search in O3 will focus on searching for “high-mass” BBH systems, which we take to be BBH systems with chirp masses in the range $12M_\odot \leq M_c \leq 45M_\odot$. This enables us to keep computational costs manageable as it only requires analyzing data segments that are up to 4s in duration.

It was estimated in [258] that the BBH background can be detected using around one day of design sensitivity data. We expect that using O3 data we can make a confident detection using around one week of data. While the computational cost of the search is high (due to the application of Bayesian parameter estimation), we expect to be able to analyze data in real time using a modest fraction of the LIGO Data Grid computing resources.

ACTIVITY LT-9.1-A: IMPLEMENTATION AND MOCK DATA CHALLENGE VALIDATION

1. Develop a set of data analysis routines to implement the above search such that it is both computationally feasible and robust against non-Gaussian features in the detector noise.
2. Perform a large-scale mock data challenge (MDC) of the proposed search method on synthetic data and O2 background data, including tests of its efficacy relative to the standard Gaussian-stationary search. Compare the performance of this proposed search to the existing CBC all-sky search and rate estimation techniques.
3. Develop tools to extract CBC-population parameters, e.g., mass spectrum.
4. Develop the necessary computational tools to be able to search for weak BBH signals at cosmological distances (luminosity distances greater than ~ 15 Gpc).
5. Publish the results of the MDC.

Assuming that the above activities are performed sucessfully, we can then move to applying this search to O3 data.

ACTIVITY LT-9.1-B: O3 ANALYSIS

1. Run the search on O3 data. Detect the background of BBH mergers and measure the astrophysical duty cycle.
2. Perform inference on the population properties of the BBH background, such as the mass spectrum, spin and redshift distributions.
3. Prepare full collaboration paper on search results.

10 Stochastic+DetChar Joint Activity Plans

Op-10.1 Data quality investigations for stochastic searches

Op-10.1.1 Scientific Case

The stochastic searches assume that the detector noise is Gaussian, stationary, and uncorrelated between different sites. However, in reality, detector noise can break all of these assumptions. Correlated noise can arise due to instrumental effects such as electronic lines coherent between sites, or due to environmental effects such as geophysical Schumann resonances. Understanding and accounting for these effects is crucial to making astrophysical statements about the stochastic background with LIGO/Virgo data. Throughout this section we include references to codes in the detector characterization section.

Op-10.1.2 Methodology

The stochastic searches rely on cross correlating data from different detectors. Common noise lines at two sites can occur due to similar equipment in the laboratory, electronics that have been synchronized by GPS, 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. We use several tools to identify and determine the causes of noise lines (codes O.RD.1.1, O.RD.1.2, O.C.1.4), as described in detail in section Op-5.1 of [259]. First, we have developed several key tools for data quality and detector characterisation (code O.C.5), including STAMP-PEM and the coherence tool, physical environment monitors that study subsystem coherence at different frequency resolutions, and StochMon, an online coherence monitoring tool that is updated hourly and includes standard result plots as well as diagnostic plots such as coherence spectra. During engineering and observing runs StochMon is regularly monitored by members of the stochastic group. Second, 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. Noise lines that would affect the stochastic search (and by extension, also the CW search) can be identified during the observing runs, and possibly addressed at the sites.

We have previously observed correlated broadband magnetic fields in magnetometer channels at widely separated detectors [260]. The primary sources of these correlated fields are geophysical Schumann resonances [260]. 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 (codes F.C.2.1, F.C.3.3) . Noise subtraction techniques, especially with respect to the correlated electromagnetic noise, are being studied [261]. 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. Another approach being pursued is to use Bayesian parameter estimation to measure the noise contribution from Schumann resonances at the same time as the gravitational-wave background.

Finally, while the stochastic searches target persistent stochastic gravitational-wave backgrounds from broadband and narrowband sources, they are sensitive to intermittent signals from transients, which can arise from environmental or instrumental sources, or even astrophysical ones. We will simulate software signals characteristic of transients, and then analyze this using the stochastic search pipeline. The results will inform interpretation of a signal.

ACTIVITY Op-10.1-A: DETECTOR CHARACTERIZATION FOR STOCHASTIC SEARCHES

TASK Op-10.1-A(i): INSTRUMENTAL CORRELATIONS BETWEEN DETECTORS

FTE-months: 12.0

Perform studies of instrumental and environmental correlations between detectors. This includes searches for broadband correlations, e.g, using environment sensors, as well as narrowband correlations, e.g., induced by GPS synchronization across sites. The studies will result in lists of correlated frequency bins that will need to be excluded from stochastic searches, including how these bins evolve over run time. In addition, the studies will result in a list of contaminated run times that should be excluded from the stochastic searches.

TASK Op-10.1-A(ii): SCHUMANN RESONANCES

FTE-months: 6.0

Perform measurements of the coupling of magnetic fields to the strain channels at all detectors, and study how they vary over time and how they depend on the location and orientation of magnetic injections. Estimate the contribution of the correlated Schumann resonances to the measurement of $\Omega_{\rm gw}$ and use parameter estimation formalism to separate this contribution from the true stochastic background contributions, and thereby mitigate this effect. Explore possibilities of removing the Schumann resonances contributions from the strain data, e.g., using the developed Wiener filtering techniques and magnetometer data.

TASK Op-10.1-A(iii): STUDY OF NOISE IMPACT ON STOCHASTIC SEARCHES

FTE-months: 6.0

Perform a set of simulations that include the stochastic background and various forms of transient noise sources, and study the effect these noise sources have on the stochastic searches.

A Total FTE Commitments

Activity Plan		FTE-months Op	 LT
Overview and Executive Summary		72.0	-
Op-2.1:	Search for short-duration GW bursts	133.0	-
LT-2.1:	Search for short-duration GW bursts R&D (Long Term)	-	-
Op-2.2:	Search for long-duration GW bursts	39.0	-
LT-2.2:	Search for long-duration GW bursts R&D (Long Term)	-	-
Op-2.3:	Search without templates for GWs from binary stellar mass black holes	27.0	-
LT-2.3:	Search without templates for GWs from binary stellar mass black holes R&D (Long Term)	-	3.0
Op-2.4:	GW burst signal characterization	26.0	-
LT-2.4:	GW burst signal characterization R&D (Long Term)	-	-
Op-2.5:	Search for GW transients from isolated neutron stars	12.0	-
LT-2.5:	Search for GW transients from isolated neutron stars R&D (Long Term)	-	-
Op-2.6:	Search for GWs from core-collapse supernova	27.0	-
LT-2.6:	Search for GWs from core-collapse supernova R&D (long term)	-	-
Subtotal for Burst Group Activity Plans		192.0	3.0
Op-3.1:	CBC Parameter Estimation R&D (Short Term)	49.0	-
LT-3.1:	CBC Parameter Estimation R&D (Long Term)	-	-
Op-3.2:	Tests of General Relativity R&D (Short Term)	38.0	-
LT-3.2:	Tests of General Relativity R&D (Long Term)	-	-
Op-3.3:	CBC Waveform Models R&D (Short Term)	267.0	-
LT-3.3:	CBC Waveform Models R&D (Long Term)	-	-
Op-3.4:	Binary Coalescence Rates and Population R&D (Short Term)	84.0	-
LT-3.4:	Binary Coalescence Rates and Population R&D (Long Term)	-	30.0
Op-3.5:	CBC Cosmology R&D (Short Term)	44.0	-
LT-3.5:	CBC Cosmology R&D (Long Term)	-	-
Op-3.6:	CBC All Sky Search R&D (Short Term)	248.0	-
LT-3.6:	CBC All Sky Search R&D (Long Term)	-	-
Op-3.7:	O3a Catalog of Compact Binaries	96.2	-
Op-3.8:	O3b Catalog of Compact Binaries	89.2	-
Op-3.9:	O3a Astrophysical Distribution of Compact Binaries	24.7	-
Op-3.10:	O3b Astrophysical Distribution of Compact Binaries	24.7	-
Op-3.11:	O3a Strong-Field Tests of General Relativity	32.2	-
Op-3.12:	O3b Strong-Field Tests of General Relativity	32.2	-
Op-3.13:	O3a Hubble Constant Measurements	56.2	-
Op-3.14:	O3b Hubble Constant Measurements	12.2	-
Op-3.15:	Search for sub-solar-mass compact binary coalescences	11.0	-
Op-3.16:	Characterizing exceptional CBC events	48.0	-
Subtotal for CBC Group Activity Plans		1156.6	30.0
Op-4.1:	Targeted searches for known pulsars	36.0	-
Op-4.2:	Narrow-band searches for known pulsars	30.0	-

Activity Plan		FTE-months	
		Op	LT
Op-4.3:	Targeted searches for non-tensorial emission from known pulsars	9.0	-
Op-4.4:	Directed searches targeting Cassiopeia A and other Galactic supernova remnants	15.0	-
Op-4.5:	Directed searches targeting Scorpius X-1 and other low-mass X-ray binaries	30.0	-
Op-4.6:	Directed searches targeted the Galactic center	12.0	-
Op-4.7:	All-sky searches for isolated sources	36.0	-
Op-4.8:	All-sky searches for unknown sources in binaries	21.0	-
Op-4.9:	Searches for long-transient emission from a post-merger neutron star	24.0	-
Op-4.10:	Searches for long-lived transient emission following a pulsar glitch	24.0	-
Op-4.11:	Searches for continuous emission from axion clouds around black holes	27.0	-
Op-4.12:	Support for continuous wave searches: Follow-up of interesting candidates	6.0	-
Op-4.13:	Support for continuous wave searches: Detector characterization	18.0	-
Op-4.14:	Support for continuous wave searches: Data preparation	18.0	-
Op-4.15:	Support for continuous wave searches: Scientific software maintenance	6.0	-
LT-4.16:	Further improvement and optimization of existing data analysis pipelines	-	-
LT-4.17:	Development of model-robust/agnostic data analysis methods	-	-
LT-4.18:	Development of new and potentially more sensitive data analysis methods	-	-
LT-4.19:	Use mock data challenges to compare data analysis pipelines	-	-
Subtotal for CW Group Activity Plans		312.0	-
Op-5.1:	Search for an isotropic stochastic gravitational-wave background (short term)	25.0	-
LT-5.1:	Search for an isotropic stochastic gravitational-wave background (long term)	-	-
Op-5.2:	Directional searches for persistent gravitational waves (short term)	30.0	-
LT-5.2:	Directional searches for persistent gravitational waves (long term)	-	-
Op-5.3:	Search for very-long transient gravitational-wave signals	10.0	-
Op-5.4:	Data Folding for Efficient Searches of Stochastic Gravitational-Wave Background	10.0	-
Subtotal for Stochastic Group Activity Plans		75.0	-
Op-6.1:	Low-Latency searches for GW transients for EM follow-up	-	-
Subtotal for Burst+CBC+DetChar Joint Activity Plans		-	-
Op-7.1:	Studies of extreme matter with pre-merger and post-merger gravitational waves R&D (Short Term)	2.0	-
LT-7.1:	Studies of extreme matter with pre-merger and post-merger gravitational waves R&D (Long Term)	-	-
Op-7.2:	Search for GWs from intermediate mass black hole binaries	26.0	-
LT-7.2:	Search for GWs from intermediate mass black hole binaries R&D	-	-
Op-7.3:	Multimessenger search for GWs and GRBs	40.0	-
LT-7.3:	Multimessenger search for GWs and GRBs R&D	-	-
Op-7.4:	Multimessenger search for GWs and fast radio bursts	16.0	-
Op-7.5:	Multimessenger search for GWs and high-energy neutrinos	16.0	-
LT-7.5:	Multimessenger search for GWs and high-energy neutrinos R&D	-	-

Activity Plan		FTE-months Op	 LT
Op-7.6:	Measuring the Nuclear Equation of State from Pre-Merger and Post-Merger GWs	6.0	-
Subtotal for Burst+CBC Joint Activity Plans		106.0	-
Op-8.1:	Search for GWs from cosmic strings	20.0	-
LT-8.1:	Search for GWs from cosmic strings R&D (Long Term)	-	-
Subtotal for Burst+Stochastic Joint Activity Plans		20.0	-
LT-9.1:	Search for the stochastic background from unresolvable binary black hole mergers	-	-
Subtotal for Stochastic+CBC Joint Activity Plans		-	-
Op-10.1:	Data quality investigations for stochastic searches	24.0	-
Subtotal for Stochastic+DetChar Joint Activity Plans		24.0	-
Grand Total		1957.6	33.0

References

[1] B. P. Abbott et al. GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. 2018.

[2] H.-K. Guo, K. Riles, F.-W. Yang, and Y. Zhao. Searching for dark photon dark matter in LIGO O1 data. *arXiv:1905.04316*, 2019.

[3] Benjamin P. Abbott et al. All-sky search for short gravitational-wave bursts in the first Advanced LIGO run. *Phys. Rev. D*, 95(4):042003, 2017.

[4] B. P. Abbott et al. All-sky search for short gravitational-wave bursts in the second Advanced LIGO and Advanced Virgo run. *Phys. Rev. D*, 100(2):024017, 2019.

[5] S. Klimenko et al. A coherent method for detection of gravitational wave bursts. *Class. Quantum Grav.*, 25(11):114029–+, June 2008.

[6] Ryan Lynch, Salvatore Vitale, Reed Essick, Erik Katsavounidis, and Florent Robinet. Information-theoretic approach to the gravitational-wave burst detection problem. *Phys. Rev. D*, 95(10):104046, 2017.

[7] Neil J. Cornish and Tyson B. Littenberg. BayesWave: Bayesian Inference for Gravitational Wave Bursts and Instrument Glitches, 2014.

[8] B. P. Abbott et al. All-sky search for long-duration gravitational wave transients in the first Advanced LIGO observing run. *Classical and Quantum Gravity*, 35(6):065009, 2018.

[9] B. P. Abbott et al. All-sky search for long-duration gravitational-wave transients in the second Advanced LIGO observing run. *Phys. Rev. D*, 99(10):104033, 2019.

[10] E. Thrane, S. Kandhasamy, C. D. Ott, W. G. Anderson, N. L. Christensen, M. W. Coughlin, S. Dorsher, S. Giampanis, V. Mandic, A. Mytidis, T. Prestegard, P. Raffai, and B. Whiting. Long gravitational-wave transients and associated detection strategies for a network of terrestrial interferometers. *Phys. Rev. D*, 83(8):083004, April 2011.

[11] 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.

[12] E. Chassande-Mottin et al. Wavelet graphs for the direct detection of gravitational waves. In *XXVth GRETSI Colloquium*, 2015.

[13] 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.

[14] B.P. Abbott. Search for Eccentric Binary Black Hole Mergers with Advanced LIGO and Advanced Virgo during their First and Second Observing Runs. 2019.

[15] K. S. Thorne. Multipole Expansions of Gravitational Radiation. *Rev. Mod. Phys.*, 52:299–339, 1980.

[16] Tyson B. Littenberg and Neil J. Cornish. Bayesian inference for spectral estimation of gravitational wave detector noise. *Phys. Rev. D*, 91(8):084034, 2015.

[17] S. Klimenko et al. Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors. *Phys. Rev. D*, 93(4):042004, 2016.

[18] B. P. Abbott et al. Observing gravitational-wave transient GW150914 with minimal assumptions. *Phys. Rev. D*, 93(12):122004, 2016. [Addendum: Phys. Rev. D 94, no.6, 069903 (2016)].

[19] Benjamin P. Abbott et al. GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2. *Phys. Rev. Lett.*, 118(22):221101, 2017.

[20] B. P. Abbott et al. Implementation and testing of the first prompt search for gravitational wave transients with electromagnetic counterparts. *Astron. Astrophys.*, 539:A124, 2012.

[21] Bence Bécsy, Peter Raffai, Neil J. Cornish, Reed Essick, Jonah Kanner, Erik Katsavounidis, Tyson B. Littenberg, Margaret Millhouse, and Salvatore Vitale. Parameter estimation for gravitational-wave bursts with the BayesWave pipeline. *Astrophys. J.*, 839(1):15, 2017. [Astrophys. J.839,15(2017)].

[22] Reed Essick, Salvatore Vitale, Erik Katsavounidis, Gabriele Vedovato, and Sergey Klimenko. Localization of short duration gravitational-wave transients with the early Advanced LIGO and Virgo detectors. *Astrophys. J.*, 800(2):81, 2015.

[23] 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.

[24] 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? *Astrophys. J. Lett.*, 665:L55–L58, August 2007.

[25] 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.

[26] B. Abbott et al. Search for gravitational-wave bursts from soft gamma repeaters. *Phys. Rev. Lett.*, 101(21):211102, 2008.

[27] B. P. Abbott et al. Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm. *Astrophys. J. Lett.*, 701:L68–L74, August 2009.

[28] J. Abadie et al. Search for Gravitational Wave Bursts from Six Magnetars. *Astrophys. J. Lett.*, 734:L35, 2011.

[29] J. Abadie et al. A search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar. *Phys. Rev. D*, 83:042001, 2011.

[30] B. P. Abbott et al. Search for Transient Gravitational-wave Signals Associated with Magnetar Bursts during Advanced LIGO's Second Observing Run. *Astrophys. J.*, 874(2):163, 2019.

[31] B. P. Abbott et al. An Optically Targeted Search for Gravitational Waves emitted by Core-Collapse Supernovae during the First and Second Observing Runs of Advanced LIGO and Advanced Virgo. *Phys. Rev. D*, 2019.

[32] B. P. Abbott et al. Tests of general relativity with GW150914. *Phys. Rev. Lett.*, 116(22):221101, 2016.

[33] B. P. Abbott et al. Binary Black Hole Mergers in the First Advanced LIGO Observing Run. *Phys. Rev. X*, 6(4):041015, Oct 2016.

[34] B. P. Abbott et al. Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1. *arXiv e-prints*, page arXiv:1903.04467, Mar 2019.

[35] B. P. Abbott et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.*, 119(16):161101, 2017.

[36] B. P. Abbott et al. Tests of General Relativity with GW170817. *Phys. Rev. Lett.*, 123(1):011102, Jul 2019.

[37] Subrahmanyan Chandrasekhar. The maximum mass of ideal white dwarfs. *Astrophys. J.*, 74:81–82, 1931.

[38] F. X. Timmes, S. E. Woosley, and Thomas A. Weaver. The Neutron star and black hole initial mass function. *Astrophys. J.*, 457:834, 1996.

[39] J. G. Martinez, K. Stovall, P. C. C. Freire, J. S. Deneva, F. A. Jenet, M. A. McLaughlin, M. Bagchi, S. D. Bates, and A. Ridolfi. Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry. *Astrophys. J.*, 812(2):143, 2015.

[40] Yudai Suwa, Takashi Yoshida, Masaru Shibata, Hideyuki Umeda, and Koh Takahashi. On the minimum mass of neutron stars. *Mon. Not. Roy. Astron. Soc.*, 481(3):3305–3312, 2018.

[41] John Antoniadis, Paulo C.C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, et al. A Massive Pulsar in a Compact Relativistic Binary. *Science*, 340(6131):1233232, 2013.

[42] Bernard J. Carr. The Primordial black hole mass spectrum. *Astrophys. J.*, 201:1–19, 1975.

[43] Karsten Jedamzik. Primordial black hole formation during the qcd epoch. *Phys. Rev. D*, 55:5871–5875, 1997.

[44] Peter Widerin and Christoph Schmid. Primordial black holes from the QCD transition? *Preprint: arXiv astro-ph/9808142*, 1998.

[45] Julian Georg and Scott Watson. A Preferred Mass Range for Primordial Black Hole Formation and Black Holes as Dark Matter Revisited. *JHEP*, 09:138, 2017.

[46] Christian T. Byrnes, Mark Hindmarsh, Sam Young, and Michael R. S. Hawkins. Primordial black holes with an accurate QCD equation of state. *JCAP*, 1808(08):041, 2018.

[47] Sarah Shandera, Donghui Jeong, and Henry S. Grasshorn Gebhardt. Gravitational Waves from Binary Mergers of Subsolar Mass Dark Black Holes. *Phys. Rev. Lett.*, 120(24):241102, 2018.

[48] Chris Kouvaris and Peter Tinyakov. Constraining Asymmetric Dark Matter through observations of compact stars. *Phys. Rev. D*, 83:083512, 2011.

[49] Arnaud de Lavallaz and Malcolm Fairbairn. Neutron Stars as Dark Matter Probes. *Phys. Rev. D*, 81:123521, 2010.

[50] Itzhak Goldman and Shmuel Nussinov. Weakly interacting massive particles and neutron stars. *Phys. Rev. D*, 40:3221–3230, Nov 1989.

[51] Joseph Bramante and Fatemeh Elahi. Higgs portals to pulsar collapse. *Phys. Rev. D*, 91(11):115001, 2015.

[52] Joseph Bramante and Tim Linden. Detecting Dark Matter with Imploding Pulsars in the Galactic Center. *Phys. Rev. Lett.*, 113(19):191301, 2014.

[53] Joseph Bramante, Tim Linden, and Yu-Dai Tsai. Searching for dark matter with neutron star mergers and quiet kilonovae. *Phys. Rev. D*, 97(5):055016, 2018.

[54] Chris Kouvaris, Peter Tinyakov, and Michel H. G. Tytgat. NonPrimordial Solar Mass Black Holes. *Phys. Rev. Lett.*, 121(22):221102, 2018.

[55] J. Aasi et al. Gravitational Waves from Known Pulsars: Results from the Initial Detector Era. *Astrophys. J.*, 785(2):119, 2014.

[56] D.I. Jones. Gravitational wave emission from rotating superfluid neutron stars. *Monthly Notices of the Royal Astronomical Society*, 402:2503–2519, March 2010.

[57] Matthew Pitkin, Maximiliano Isi, John Veitch, and Graham Woan. A nested sampling code for targeted searches for continuous gravitational waves from pulsars. *arXiv*, 1705.08978, May 2017.

[58] 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. *Classical and Quantum Gravity*, 27(19):194016, 2010.

[59] B. Abbott et al. Beating the Spin-Down Limit on Gravitational Wave Emission from the Crab Pulsar. *Astrophys. J. Lett.*, 683:L45, August 2008.

[60] J. Abadie et al. Beating the Spin-down Limit on Gravitational Wave Emission from the Vela Pulsar. *Astrophys. J.*, 737:93, August 2011.

[61] B. P. Abbott et al. Searches for Gravitational Waves from Known Pulsars at Two Harmonics in 2015-2017 LIGO Data. *Astrophys. J.*, 879:10, July 2019.

[62] 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. *Phys. Rev. D*, 91(2):022004, January 2015.

[63] S Mastrogiovanni, P Astone, S D'Antonio, S Frasca, G Intini, P Leaci, A Miller, C Palomba, O J Piccinni, and A Singhal. An improved algorithm for narrow-band searches of continuous gravitational waves. *Classical and Quantum Gravity*, 34(13):135007, 2017.

[64] B. P. Abbott et al. Narrow-band search for gravitational waves from known pulsars using the second LIGO observing run. *Phys. Rev. D*, 99:122002, Jun 2019.

[65] Maximiliano Isi, Matthew Pitkin, and Alan J. Weinstein. Probing dynamical gravity with the polarization of continuous gravitational waves. *Phys. Rev. D*, 96:042001, Aug 2017.

[66] B. P. Abbott et al. First Search for Nontensorial Gravitational Waves from Known Pulsars. *Phys. Rev. Lett.*, 120(3):031104, January 2018.

[67] P. Jaranowski, A. Królak, and B. F. Schutz. Data analysis of gravitational-wave signals from spinning neutron stars: The signal and its detection. *Phys. Rev. D*, 58(6):063001, 1998.

[68] J. Abadie et al. First Search for Gravitational Waves from the Youngest Known Neutron Star. *Astrophys. J.*, 722:1504, 2010.

[69] J. Aasi et al. Searches for Continuous Gravitational Waves from Nine Young Supernova Remnants. *Astrophys. J.*, 813:39, November 2015.

[70] B. P. Abbott et al. Searches for Continuous Gravitational Waves from 15 Supernova Remnants and Fomalhaut b with Advanced LIGO. *Astrophys. J.*, 875(2):122, April 2019.

[71] S. J. Zhu, M. A. Papa, H.-B. Eggenstein, R. Prix, K. Wette, B. Allen, O. Bock, D. Keitel, B. Krishnan, B. Machenschalk, M. Shaltev, and X. Siemens. Einstein@Home search for continuous gravitational waves from Cassiopeia A. *Phys. Rev. D*, 94(8):082008, 2016.

[72] L. Sun, A. Melatos, S. Suvorova, W. Moran, and R. J. Evans. Hidden Markov model tracking of continuous gravitational waves from young supernova remnants. *Phys. Rev. D*, 97:043013, Feb 2018.

[73] Ling Sun, Andrew Melatos, and Paul D. Lasky. Tracking continuous gravitational waves from a neutron star at once and twice the spin frequency with a hidden Markov model. *Phys. Rev. D*, 99:123010, Jun 2019.

[74] O. J. Piccinni, P. Astone, S. D'Antonio, S. Frasca, G. Intini, P. Leaci, S. Mastrogiovanni, A. Miller, C. Palomba, and A. Singhal. A new data analysis framework for the search of continuous gravitational wave signals. *Classical and Quantum Gravity*, 36:015008, 2019.

[75] L. Bildsten. Gravitational Radiation and Rotation of Accreting Neutron Stars. *Astrophys. J. Lett.*, 501:L89, 1998.

[76] Sanjeev Dhurandhar, Badri Krishnan, Himan Mukhopadhyay, and John T. Whelan. Cross-correlation search for periodic gravitational waves. *Phys. Rev. D*, 77:082001, 2008.

[77] John T. Whelan, Santosh Sundaresan, Yuanhao Zhang, and Prabath Peiris. Model-based cross-correlation search for gravitational waves from Scorpius X-1. *Phys. Rev. D*, 91:102005, 2015.

[78] B. P. Abbott et al. Upper Limits on Gravitational Waves from Scorpius X-1 from a Model-Based Cross-Correlation Search in Advanced LIGO Data. *Astrophys. J.*, 847(1):47, 2017.

[79] Grant David Meadors, Evan Goetz, Keith Riles, Teviet Creighton, and Florent Robinet. Searches for continuous gravitational waves from Scorpius X-1 and XTE J1751-305 in LIGO's sixth science run. *Phys. Rev. D*, 95(4):042005, 2017.

[80] 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. *Phys. Rev. D*, 93(12):123009, jun 2016.

[81] S. Suvorova, P. Clearwater, A. Melatos, L. Sun, W. Moran, and R. J. Evans. Hidden Markov model tracking of continuous gravitational waves from a binary neutron star with wandering spin. II. Binary orbital phase tracking. *Phys. Rev. D*, 96:102006, Nov 2017.

[82] B. P. Abbott et al. Search for gravitational waves from Scorpius X-1 in the first Advanced LIGO observing run with a hidden Markov model. *Phys. Rev. D*, 95(12):122003, 2017.

[83] J. Aasi et al. Directed search for gravitational waves from Scorpius X-1 with initial LIGO data. *Phys. Rev. D*, 91(6):062008, March 2015.

[84] P. Astone, K. M. Borkowski, P. Jaranowski, M. Pietka, and A. Królak. Data analysis of gravitational-wave signals from spinning neutron stars. V. A narrow-band all-sky search. *Phys. Rev. D*, 82(2):022005, July 2010.

[85] Arunava Mukherjee, Chris Messenger, and Keith Riles. Accretion-induced spin-wandering effects on the neutron star in Scorpius X-1: Implications for continuous gravitational wave searches. *Phys. Rev. D*, 97:043016, February 2018.

[86] Fermi-LAT Collaboration. Characterizing the population of pulsars in the inner Galaxy with the Fermi Large Area Telescope. *arXiv*, 1705.00009, 2017.

[87] A. Abramowski et al. Acceleration of petaelectronvolt protons in the Galactic Centre. *Nature*, 531:476, 2016.

[88] Samuel K. Lee, Mariangela Lisanti, Benjamin R. Safdi, Tracy R. Slatyer, and Wei Xue. Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy. *Phys. Rev. Lett.*, 116:051103, 2016.

[89] Richard Bartels, Suraj Krishnamurthy, and Christoph Weniger. Strong support for the millisecond pulsar origin of the Galactic center GeV excess. *Phys. Rev. Lett.*, 116:051102, 2016.

[90] D. Hooper, I. Cholis, and T. Linden. TeV Gamma-Rays from Galactic Center Pulsars. *Physics of the Dark Universe*, 21:40, 2018.

[91] Ornella Piccinni. *An enhanced sensitivity procedure for continuous gravitational wave detection: targeting the Galactic Center*. PhD thesis, University of Rome Sapienza, 2018. http://hdl.handle.net/11573/1109197.

[92] B. Abbott et al. All-sky search for periodic gravitational waves in LIGO S4 data. *Phys. Rev. D*, 77:022001, Jan 2008.

[93] Vladimir Dergachev. Description of PowerFlux 2 algorithms and implementation. Technical Report T1000272-v5, LIGO, 2010.

[94] P. Astone, A. Colla, S. D'Antonio, S. Frasca, and C. Palomba. Method for all-sky searches of continuous gravitational wave signals using the frequency-Hough transform. *Phys. Rev. D*, 90(4):042002, August 2014.

[95] 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. D*, 70:082001, 2004.

[96] J. Aasi et al. Implementation of an F-statistic all-sky search for continuous gravitational waves in Virgo VSR1 data. *Classical and Quantum Gravity*, 31(16):165014, August 2014.

[97] E. Goetz and K. Riles. An all-sky search algorithm for continuous gravitational waves from spinning neutron stars in binary systems. *Classical and Quantum Gravity*, 28:215006, 2011.

[98] 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. D*, 90:062010, May 2014.

[99] P. B. Covas and Alicia M. Sintes. New method to search for continuous gravitational waves from unknown neutron stars in binary systems. *Phys. Rev. D*, 99:124019, Jun 2019.

[100] B. P. Abbott et al. Search for Post-merger Gravitational Waves from the Remnant of the Binary Neutron Star Merger GW170817. *Astrophys. J. Lett.*, 851(1):L16, 2017.

[101] B. P. Abbott et al. Search for Gravitational Waves from a Long-lived Remnant of the Binary Neutron Star Merger GW170817. *Astrophys. J.*, 875(2):160, apr 2019.

[102] Andreas Bauswein, Oliver Just, Hans-Thomas Janka, and Nikolaos Stergioulas. Neutron-star radius constraints from GW170817 and future detections. *Astrophys. J. Lett.*, 850(2):L34, 2017.

[103] Ben Margalit and Brian D. Metzger. Constraining the Maximum Mass of Neutron Stars From Multi-Messenger Observations of GW170817. *Astrophys. J. Lett.*, 850(2):L19, 2017.

[104] Nikhil Sarin, Paul D. Lasky, Letizia Sammut, and Greg Ashton. X-ray guided gravitational-wave search for binary neutron star merger remnants. *Phys. Rev. D*, 98(4):043011, 2018.

[105] Shunke Ai, He Gao, Zi-Gao Dai, Xue-Feng Wu, Ang Li, Bing Zhang, and Mu-Zi Li. The allowed parameter space of a long-lived neutron star as the merger remnant of GW170817. *Astrophys. J.*, 860(1):57, 2018.

[106] Ling Sun and Andrew Melatos. Application of hidden Markov model tracking to the search for long-duration transient gravitational waves from the remnant of the binary neutron star merger GW170817. *Phys. Rev. D*, 99:123003, Jun 2019.

[107] Sharan Banagiri, Ling Sun, Michael W. Coughlin, and Andrew Melatos. Search strategies for long gravitational-wave transients: Hidden Markov model tracking and seedless clustering. *Phys. Rev. D*, 100:024034, Jul 2019.

[108] Miquel Oliver, David Keitel, and Alicia M. Sintes. Adaptive transient Hough method for long-duration gravitational wave transients. *Phys. Rev. D*, 99:104067, May 2019.

[109] C. Palomba, P. Astone, and S. Frasca. Adaptive Hough transform for the search of periodic sources. *Classical and Quantum Gravity*, 22:S1255–S1264, 2005.

[110] Andrew Miller, Pia Astone, Sabrina D'Antonio, Sergio Frasca, Giuseppe Intini, Iuri La Rosa, Paola Leaci, Simone Mastrogiovanni, Federico Muciaccia, Cristiano Palomba, Ornella J. Piccinni, Akshat Singhal, and Bernard F. Whiting. Method to search for long duration gravitational wave transients from isolated neutron stars using the generalized frequency-Hough transform. *Phys. Rev. D*, 98:102004, Nov 2018.

[111] P. D. Lasky, N. Sarin, and L. Sammut. Long-duration waveform models for millisecond magnetars born in binary neutron star mergers. Technical Report LIGO-T1700408, LIGO, 2017.

[112] Reinhard Prix, Stefanos Giampanis, and Chris Messenger. Search method for long-duration gravitational-wave transients from neutron stars. *Phys. Rev. D*, 84:023007, 2011.

[113] Brynmor Haskell and Andrew Melatos. Models of Pulsar Glitches. *Int. J. Mod. Phys.*, D24(03):1530008, 2015.

[114] David Keitel and Gregory Ashton. Faster search for long gravitational-wave transients: GPU implementation of the transient $\mathcal{F}$-statistic. *Classical and Quantum Gravity*, 35(20):205003, 2018.

[115] David Keitel, Graham Woan, Matthew Pitkin, Courtney Schumacher, Brynley Pearlstone, Keith Riles, Andrew G. Lyne, Jim Palfreyman, Benjamin Stappers, and Patrick Weltevrede. First search for long-duration transient gravitational waves after glitches in the Vela and Crab pulsars. *arXiv*, 1907.04717, 2019.

[116] Gregory Ashton and David Keitel. PyFstat-v1.2, doi:10.5281/zenodo.1243931, May 2018.

[117] Eric Thrane, Vuk Mandic, and Nelson Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. *Phys. Rev. D*, 91(10):104021, 2015.

[118] G. Ashton and R. Prix. Hierarchical multistage MCMC follow-up of continuous gravitational wave candidates. *Phys. Rev. D*, 97(10):103020, May 2018.

[119] S. D'Antonio, C. Palomba, P. Astone, S. Frasca, G. Intini, I. La Rosa, P. Leaci, S. Mastrogiovanni, A. Miller, F. Muciaccia, O. J. Piccinni, and A. Singhal. Semicoherent analysis method to search for continuous gravitational waves emitted by ultralight boson clouds around spinning black holes. *Phys. Rev. D*, 98:103017, Nov 2018.

[120] Maximiliano Isi, Ling Sun, Richard Brito, and Andrew Melatos. Directed searches for gravitational waves from ultralight bosons. *Phys. Rev. D*, 99:084042, Apr 2019.

[121] K. Wette, S. Walsh, R. Prix, and M. A. Papa. Implementing a semicoherent search for continuous gravitational waves using optimally constructed template banks. *Phys. Rev. D*, 97:123016, June 2018.

[122] Sinéad Walsh, Karl Wette, Maria Alessandra Papa, and Reinhard Prix. Optimizing the choice of analysis method for all-sky searches for continuous gravitational waves with Einstein@Home. *Phys. Rev. D*, 99:082004, April 2019.

[123] David Keitel. Robust semicoherent searches for continuous gravitational waves with noise and signal models including hours to days long transients. *Phys. Rev. D*, 93:084024, Apr 2016.

[124] Réjean J. Dupuis and Graham Woan. Bayesian estimation of pulsar parameters from gravitational wave data. *Phys. Rev. D*, 72(10):102002, Nov 2005.

[125] LIGO Scientific Collaboration. LIGO Algorithm Library - LALSuite. Free software (GPL), doi:10.7935/GT1W-FZ16, 2018.

[126] B. P. Abbott et al. Full band all-sky search for periodic gravitational waves in the O1 LIGO data. *Phys. Rev. D*, 97:102003, May 2018.

[127] B. P. Abbott et al. All-sky search for periodic gravitational waves in the O1 LIGO data. *Phys. Rev. D*, 96:062002, Sep 2017.

[128] B. P. Abbott et al. All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO O2 data. *Phys. Rev. D*, 100:024004, Jul 2019.

[129] Grant David Meadors, Badri Krishnan, Maria Alessandra Papa, John T. Whelan, and Yuanhao Zhang. Resampling to accelerate cross-correlation searches for continuous gravitational waves from binary systems. *Phys. Rev. D*, 97:044017, February 2018.

[130] M. Pitkin, C. Messenger, and X. Fan. Hierarchical Bayesian method for detecting continuous gravitational waves from an ensemble of pulsars. *Phys. Rev. D*, 98(6):063001, September 2018.

[131] Joongoo Lee et al. A Deep Learning Model on Gravitational Waveforms in Merging and Ringdown Phases of Binary Black Hole Coalescence. Technical Report LIGO-P1900207, LIGO, 2019.

[132] Andrew Miller et al. How effective is machine learning to detect long transient gravitational waves from neutron stars in a real search? Technical Report LIGO-P1900157, LIGO, 2019.

[133] Daniel George and EA Huerta. Deep neural networks to enable real-time multimessenger astrophysics. *Phys. Rev. D*, 97(4):044039, 2018.

[134] Hunter Gabbard, Michael Williams, Fergus Hayes, and Chris Messenger. Matching matched filtering with deep networks for gravitational-wave astronomy. *Phys. Rev. Lett.*, 120(14):141103, 2018.

[135] C. Messenger, H. J. Bulten, S. G. Crowder, V. Dergachev, D. K. Galloway, E. Goetz, R. J. G. Jonker, P. D. Lasky, G. D. Meadors, A. Melatos, S. Premachandra, K. Riles, L. Sammut, E. H. Thrane, J. T. Whelan, and Y. Zhang. Gravitational waves from Scorpius X-1: A comparison of search methods and prospects for detection with advanced detectors. *Phys. Rev. D*, 92(2):023006, July 2015.

[136] S. Walsh, M. Pitkin, M. Oliver, S. D'Antonio, V. Dergachev, A. Królak, P. Astone, M. Bejger, M. Di Giovanni, O. Dorosh, S. Frasca, P. Leaci, S. Mastrogiovanni, A. Miller, C. Palomba, M. A. Papa, O. J. Piccinni, K. Riles, O. Sauter, and A. M. Sintes. Comparison of methods for the detection of gravitational waves from unknown neutron stars. *Phys. Rev. D*, 94(12):124010, December 2016.

[137] E. W. Kolb & M. S. Turner. *The Early Universe*. Westview Press, 1994.

[138] A. A. Starobinskii. Spectrum of relic gravitational radiation and the early state of the universe. *JETP Lett.*, 30, 1979.

[139] R. Bar-Kana. Limits on Direct Detection of Gravitational Waves. *Phys. Rev. D*, 50, 1994.

[140] T. W. B. Kibble. Topology of cosmic domains and strings. *J. Phys. A*, 9, 1976.

[141] T. Damour & A. Vilenkin. Gravitational radiation from cosmic (super)strings: bursts, stochastic background, and observational windows. *Phys. Rev. D*, 71, 2005.

[142] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys. Rev. D*, 81:104028, 2010.

[143] S. Olmez, V. Mandic, and X. Siemens. Anisotropies in the Gravitational-Wave Stochastic Background. *J. Cosmol. Astropart. Phys.*, 2012:009, 2011.

[144] Benjamin P. Abbott et al. GW170817: Implications for the Stochastic Gravitational-Wave Background from Compact Binary Coalescences. *Phys. Rev. Lett.*, 120(9):091101, 2018.

[145] B. P. Abbott et al. Gw150914: Implications for the stochastic gravitational-wave background from binary black holes. *Phys. Rev. Lett.*, 116:131102, Mar 2016.

[146] B. P. Abbott et al. Search for the isotropic stochastic background using data from Advanced LIGO's second observing run. *Phys. Rev. D*, 100:061101(R), 2019.

[147] C. Brans and R.H. Dicke. Mach's principle and a relativistic theory of gravitation. *Phys. Rev.*, 124:925–935, 1961.

[148] Y. Fujii and K. Maeda. *The Scalar-Tensor Theory of Gravitation*. Cambridge Monograph on Mathematical Physics. Cambridge University Press, Cambridge, 2002.

[149] Thomas P. Sotiriou and Valerio Faraoni. f(R) Theories Of Gravity. *Rev. Mod. Phys.*, 82:451–497, 2010.

[150] Antonio De Felice and Shinji Tsujikawa. f(R) Theories. *Living Rev. Relativity*, 13(3), 2010.

[151] Matt Visser. Mass for the graviton. *General Relativity and Gravitation*, 30(12):1717–1728, 1998.

[152] Claudia de Rham, Gregory Gabadadze, and Andrew J. Tolley. Resummation of massive gravity. *Phys. Rev. Lett.*, 106:231101, Jun 2011.

[153] Bruce Allen and Joseph D. Romano. Detecting a stochastic background of gravitational radiation: Signal processing strategies and sensitivities. *Phys. Rev. D*, 59:102001, 1999.

[154] N Christensen. Measuring the Stochastic Gravitational Radiation Background with Laser Interferometric Antennas. *Phys. Rev. D*, 46:5250, 1992.

[155] B Abbott et al. Searching for a Stochastic Background of Gravitational Waves with the Laser Interferometer Gravitational-Wave Observatory. *Astrophys. J.*, 659:918, 2007.

[156] 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.

[157] B. Abbott et al. Searching for Stochastic Gravitational Waves with LIGO. *Nature*, 460:990, 2009.

[158] J. Aasi et al. Improved Upper Limits on the Stochastic Gravitational–Wave Background from 2009–2010 LIGO and Virgo Data. *Phys. Rev. Lett.*, 113:231101, 2014.

[159] J. Aasi et al. Searching for stochastic gravitational waves using data from the two colocated LIGO Hanford detectors. *Phys. Rev. D*, 91:022003, 2015.

[160] Benjamin P. Abbott et al. Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO's First Observing Run. *Phys. Rev. Lett.*, 118(12):121101, 2017.

[161] 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.

[162] 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.

[163] Abhishek Parida, Sanjit Mitra, and Sanjay Jhingan. Component Separation of a Isotropic Gravitational Wave Background. *JCAP*, 1604(04):024, 2016.

[164] Neil J Cornish and Tyson B Littenberg. Bayeswave: Bayesian inference for gravitational wave bursts and instrument glitches. *CQG*, 32(13):135012, 2015.

[165] Aaron Pierce, Keith Riles, and Yue Zhao. Searching for dark photon dark matter with gravitational-wave detectors. *Phys. Rev. Lett.*, 121:061102, Aug 2018.

[166] D. Talukder, E. Thrane, S. Bose, and T. Regimbau. Measuring neutron-star ellipticity with measurements of the stochastic gravitational-wave background. *Phys. Rev. D*, 89(12):123008, June 2014.

[167] G. Cusin, C. Pitrou, and J.-P. Uzan. Anisotropy of the astrophysical gravitational wave background i: analytic expression of the angular power spectrum and correlation with cosmological observations. *Phys. Rev. D*, 96:103019, 2017.

[168] Giulia Cusin, Irina Dvorkin, Cyril Pitrou, and Jean-Philippe Uzan. First Predictions of the Angular Power Spectrum of the Astrophysical Gravitational Wave Background. *Phys. Rev. Lett.*, 120(23):231101, Jun 2018.

[169] Alexander C. Jenkins and Mairi Sakellariadou. Anisotropies in the stochastic gravitational-wave background: Formalism and the cosmic string case. *Phys. Rev. D*, 98(6):063509, Sep 2018.

[170] Alexander C. Jenkins, Mairi Sakellariadou, Tania Regimbau, and Eric Slezak. Anisotropies in the astrophysical gravitational-wave background: Predictions for the detection of compact binaries by LIGO and Virgo. *Phys. Rev. D*, 98(6):063501, 2018.

[171] Alexander C. Jenkins, Richard O'Shaughnessy, Mairi Sakellariadou, and Daniel Wysocki. Anisotropies in the astrophysical gravitational-wave background: The impact of black hole distributions. *Phys. Rev. Lett.*, 122(11):111101, 2019.

[172] T Regimbau & B Chauvineaux. A stochastic background from extra-galactic double neutron stars. *Class. Quantum Grav.*, 24:627, 2007.

[173] A. J. Farmer & E. S. Phinney. The gravitational wave background from cosmological compact binaries. *Mon. Not. R. Ast. Soc.*, 346:1197, 2003.

[174] E Howell et al. The gravitational wave background from neutron star birth throughout the cosmos. *Mon. Not. R. Ast. Soc.*, 351:1237, 2004.

[175] 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.

[176] 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.

[177] G Sigl. Cosmological gravitational wave background from phase transitions in neutron stars. *J. Cosmol. Astropart. Phys.*, JCAP04:002, 2006.

[178] T Regimbau & J A de Freitas Pacheco. Cosmic background of gravitational waves from rotating neutron stars. *Astron. Astrophys.*, 376:381, 2001.

[179] T Regimbau & J A de Freitas Pacheco. Gravitational wave background from magnetars. *Astron. Astrophys.*, 447:1, 2006.

[180] L Barack & C Cutler. Confusion noise from LISA capture sources. *Phys. Rev. D*, 70:122002, 2004.

[181] G Sigl & J Schnittman & A Buonanno. Gravitational-wave background from compact objects embedded in AGN accretion disks. *Phys. Rev. D*, 75:024034, 2007.

[182] Francesca Calore, Tania Regimbau, and Pasquale Dario Serpico. Probing the Fermi-LAT GeV Excess with Gravitational Waves. *Phys. Rev. Lett.*, 122(8):081103, Mar 2019.

[183] B Abbott et al. Directional limits on persistent gravitational waves using LIGO S5 science data. *Phys. Rev. Lett.*, 107:271102, 2011.

[184] E Thrane, S Ballmer, J D Romano, S Mitra, D Talukder, S Bose, and V Mandic. Probing the anisotropies of a stochastic gravitational-wave background using a network of ground-based laser interferometers. *Phys. Rev. D*, 80:122002, 2009.

[185] B. P. Abbott et al. Directional Limits on Persistent Gravitational Waves from Advanced LIGO's First Observing Run. *Phys. Rev. Lett.*, 118(12):121102, March 2017.

[186] 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.

[187] A. Ain, P. Dalvi, and S. Mitra. Fast gravitational wave radiometry using data folding. *Phys. Rev. D*, 92(2):022003, July 2015.

[188] Boris Goncharov and Eric Thrane. An all-sky radiometer for narrowband gravitational waves using folded data. *arXiv*, 1805.03761, 2018.

[189] Anirban Ain, Jishnu Suresh, and Sanjit Mitra. Very fast stochastic gravitational wave background map-making using folded data: PyStoch. *arXiv*, 1803.08285, 2018.

[190] Alexander C. Jenkins and Mairi Sakellariadou. Shot noise in the astrophysical gravitational-wave background. *arXiv*, 1902.07719, 2019.

[191] Giulia Cusin, Irina Dvorkin, Cyril Pitrou, and Jean-Philippe Uzan. Stochastic gravitational wave background anisotropies: astrophysical dependencies in the LIGO/Virgo and LISA bands. *arXiv*, 1904.07757, 2019.

[192] Giulia Cusin, Irina Dvorkin, Cyril Pitrou, and Jean-Philippe Uzan. Properties of the stochastic astrophysical gravitational wave background: Astrophysical sources dependencies. *Phys. Rev. D*, 100(6):063004, Sep 2019.

[193] Alexander C. Jenkins, Joseph D. Romano, and Mairi Sakellariadou. Estimating the angular power spectrum of the gravitational-wave background in the presence of shot noise. *arXiv*, 1907.06642, 2019.

[194] R Prix, S Giampanis, and C Messenger. Search method for long-duration gravitational-wave transients from neutron stars. *Phys. Rev. D*, 84:023007, 2011.

[195] 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.

[196] D I Jones and N Andersson. Gravitational waves from freely precessing neutron stars. *Mon. Not. R. Ast. Soc.*, 331:203, 2002.

[197] L. Gualtieri, R. Ciolfi, and V. Ferrari. Structure, deformations and gravitational wave emission of magnetars. *Classical and Quantum Gravity*, 28(11):114014, Jun 2011.

[198] A Arvanitaki, M Baryakhtar, and X Huang. Discovering the qcd axion with black holes and gravitational waves. *Phys. Rev. D*, 91:084011, 2015.

[199] 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.

[200] T. Prestegard, E. Thrane, et al. Identification of noise artifacts in searches for long-duration gravitational-wave transients. *Class. Quantum Grav.*, 29:095018, 2012.

[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] E Thrane and M Coughlin. Searching for gravitational-wave transients with a qualitative signal model: seedless clustering strategies. *Phys. Rev. D*, 88:083010, 2013.

[203] E. Thrane and M. Coughlin. Seedless clustering in all-sky searches for gravitational-wave transients. *Phys. Rev. D*, 89:063012, 2014.

[204] T. Prestegard and E. Thrane. Burstegard: a hierarchical clustering algorithm, 2012. Technical report LIGO-L1200204, `https://dcc.ligo.org/LIGO-L1200204/public`.

[205] M. Coughlin, E. Thrane, and N. Christensen. Detecting compact binary coalescences with seedless clustering. *Phys. Rev. D*, 90(8):083005, 2014.

[206] E Thrane, V Mandic, and N Christensen. Detecting very long-lived gravitational-wave transients lasting hours to weeks. *Phys. Rev. D*, 91:104021, 2015.

[207] B. P. Abbott et al. Search for gravitational waves from a long-lived remnant of the binary neutron star merger GW170817. *Astrophys. J.*, 875(2):160, apr 2019.

[208] P. Meyers, M. W. Coughlin, and J. Luo. Investigating Environmental Noise Using the Stochastic Transient Analysis Multi-Detector Pipeline (STAMP-PEM), 2014.
Technical report LIGO-G1400354, `https://dcc.ligo.org/LIGO-G1400354`.

[209] 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.

[210] D. Gerosa and E. Berti. Are merging black holes born from stellar collapse or previous mergers? *Phys. Rev. D*, 95(12):124046, June 2017.

[211] M. Fishbach, D. E. Holz, and B. Farr. Are LIGO's Black Holes Made from Smaller Black Holes? *Astrophys. J. Lett.*, 840:L24, May 2017.

[212] Yang Yang, Imre Bartos, V. Gayathri, Saavik Ford, Zoltan Haiman, Sergey Klimenko, Bence Kocsis, Szabolcs Márka, Zsuzsa Márka, Barry McKernan, and Richard O'Shaugnessy. Hierarchical Black Hole Mergers in Active Galactic Nuclei. *arXiv e-prints*, page arXiv:1906.09281, Jun 2019.

[213] M. C. Miller and E. J. M. Colbert. Intermediate-Mass Black Holes. *International Journal of Modern Physics D*, 13:1–64, January 2004.

[214] Nathan W. C. Leigh, Nora Lützgendorf, Aaron M. Geller, Thomas J. Maccarone, Craig Heinke, and Alberto Sesana. On the coexistence of stellar-mass and intermediate-mass black holes in globular clusters. *Mon. Not. Roy. Astron. Soc.*, 444(1):29–42, 2014.

[215] J. M. Fregeau, S. L. Larson, M. C. Miller, R. O'Shaughnessy, and F. A. Rasio. Observing IMBH-IMBH Binary Coalescences via Gravitational Radiation. *Astrophys. J. Lett.*, 646:L135–L138, August 2006.

[216] P. Amaro-Seoane and M. Freitag. Intermediate-Mass Black Holes in Colliding Clusters: Implications for Lower Frequency Gravitational-Wave Astronomy. *Astrophys. J. Lett.*, 653:L53–L56, December 2006.

[217] Jonathan R. Gair, Ilya Mandel, M. Coleman Miller, and Marta Volonteri. Exploring intermediate and massive black-hole binaries with the Einstein Telescope. *General Relativity and Gravitation*, 43(2):485–518, Feb 2011.

[218] 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. *Astrophys. J.*, 789:120, July 2014.

[219] E. Nakar. Short-hard gamma-ray bursts. *Physics Reports*, 442:166–236, April 2007.

[220] S. I. Blinnikov, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev. Exploding Neutron Stars in Close Binaries. *Soviet Astronomy Letters*, 10:177–179, April 1984.

[221] Bohdan Paczynski. Gamma-ray bursters at cosmological distances. *Astrophys. J. Lett.*, 308:L43–L46, 1986.

[222] D Eichler, M Livio, T Piran, and D Schramm. *Nature*, 340:126, 1989.

[223] Bohdan Paczynski. Cosmological gamma-ray bursts. *Acta Astron.*, 41:257–267, 1991.

[224] R Narayan, Paczynski, and T Piran. *Astroph. J.*, 395:L83, 1992.

[225] B. P. Abbott et al. Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. *Astrophys. J. Lett.*, 848:13, 2017.

[226] A. R. Williamson, C. Biwer, S. Fairhurst, I. W. Harry, E. Macdonald, D. Macleod, and V. Predoi. Improved methods for detecting gravitational waves associated with short gamma-ray bursts. *Phys. Rev. D*, 90(12):122004, 2014.

[227] Alex L. Urban. *Monsters in the Dark: High Energy Signatures of Black Hole Formation with Multimessenger Astronomy*. Ph.D. dissertation, University of Wisconsin-Milwaukee, May 2016.

[228] Jeremy D. Schnittman, Tito Dal Canton, Jordan Camp, David Tsang, and Bernard J. Kelly. Electromagnetic Chirps from Neutron Star-Black Hole Mergers. *arXiv*, 1704.07886, 2017.

[229] 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.

[230] 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. *Pub. Astron. Soc. Aust.*, 33:e045, Sep 2016.

[231] L. G. Spitler, J. M. Cordes, J. W. T. Hessels, D. R. Lorimer, M. A. McLaughlin, S. Chatterjee, F. Crawford, J. S. Deneva, V. M. Kaspi, R. S. Wharton, B. Allen, S. Bogdanov, A. Brazier, F. Camilo, P. C. C. Freire, F. A. Jenet, C. Karako-Argaman, B. Knispel, P. Lazarus, K. J. Lee, J. van Leeuwen, R. Lynch, A. G. Lyne, S. M. Ransom, P. Scholz, X. Siemens, I. H. Stairs, K. Stovall, J. K. Swiggum, A. Venkataraman, W. W. Zhu, C. Aulbert, and H. Fehrmann. Fast Radio Burst Discovered in the Arecibo Pulsar ALFA Survey. *The Astrophysical Journal*, 790(2):101, 2014.

[232] B. P. Abbott et al. Search for transient gravitational waves in coincidence with short-duration radio transients during 2007–2013. *Phys. Rev. D*, 93:122008, Jun 2016.

[233] S. Ando, B. Baret, I. Bartos, B. Bouhou, E. Chassande-Mottin, A. Corsi, I. Di Palma, A. Dietz, C. Donzaud, D. Eichler, C. Finley, D. Guetta, F. Halzen, G. Jones, S. Kandhasamy, K. Kotake, A. Kouchner, V. Mandic, S. Márka, Z. Márka, L. Moscoso, M. A. Papa, T. Piran, T. Pradier, G. E.

Romero, P. Sutton, E. Thrane, V. Van Elewyck, and E. Waxman. Colloquium: Multimessenger astronomy with gravitational waves and high-energy neutrinos. *Reviews of Modern Physics*, 85:1401–1420, October 2013.

[234] I. Bartos, P. Brady, and S. Márka. How gravitational-wave observations can shape the gamma-ray burst paradigm. *Classical and Quantum Gravity*, 30(12):123001, June 2013.

[235] B. Baret et al. Bounding the time delay between high-energy neutrinos and gravitational-wave transients from gamma-ray bursts. *Astroparticle Physics*, 35:1–7, August 2011.

[236] 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. *Phys. Rev. D*, 86(8):083007, October 2012.

[237] I. Bartos, A. M. Beloborodov, K. Hurley, and S. Márka. Detection Prospects for GeV Neutrinos from Collisionally Heated Gamma-ray Bursts with IceCube/DeepCore. *Physical Review Letters*, 110(24):241101, June 2013.

[238] K. Murase, K. Kashiyama, K. Kiuchi, and I. Bartos. Gammy-Ray and Hard X-Ray Emission from Pulsar-aided Supernovae as a Probe of Particle Acceleration in Embryonic Pulsar Wind Nebulae. *Astrophys. J.*, 805:82, May 2015.

[239] 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. *Phys. Rev. D*, 85(10):103004, May 2012.

[240] M. W. E. Smith, D. B. Fox, D. F. Cowen, P. Mészáros, G. Tešić, J. Fixelle, I. Bartos, P. Sommers, A. Ashtekar, G. Jogesh Babu, S. D. Barthelmy, S. Coutu, T. DeYoung, A. D. Falcone, S. Gao, B. Hashemi, A. Homeier, S. Márka, B. J. Owen, and I. Taboada. The Astrophysical Multimessenger Observatory Network (AMON). *Astroparticle Physics*, 45:56–70, May 2013.

[241] S. Adrián-Martínez, A. Albert, M. André, M. Anghinolfi, G. Anton, M. Ardid, J.-J. Aubert, T. Avgitas, B. Baret, J. Barrios-Martí, and et al. High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube. *Phys. Rev. D*, 93(12):122010, June 2016.

[242] A. Albert et al. Search for high-energy neutrinos from gravitational wave event GW151226 and candidate LVT151012 with ANTARES and IceCube. *Phys. Rev. D*, 96(2):022005, Jul 2017.

[243] A. Albert, M. André, M. Anghinolfi, M. Ardid, J.-J. Aubert, J. Aublin, T. Avgitas, B. Baret, J. Barrios-Martí, S. Basa, and et al. Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory. *Astrophys. J. Lett.*, 850:L35, December 2017.

[244] T. W. B. Kibble. Topology of Cosmic Domains and Strings. *J. Phys. A*, 9:1387–1398, 1976.

[245] A. Vilenkin and E. Shellard. *Cosmic strings and other Topological Defects*. Cambridge University Press, 2000.

[246] Andrei D. Linde. Hybrid inflation. *Phys. Rev. D*, 49:748–754, 1994.

[247] Edmund J. Copeland, Andrew R. Liddle, David H. Lyth, Ewan D. Stewart, and David Wands. False vacuum inflation with Einstein gravity. *Phys. Rev. D*, 49:6410–6433, 1994.

[248] 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.

[249] Saswat Sarangi and S.H. Henry Tye. Cosmic string production towards the end of brane inflation. *Phys. Lett. B*, 536:185–192, 2002.

[250] Rachel Jeannerot, Jonathan Rocher, and Mairi Sakellariadou. How generic is cosmic string formation in SUSY GUTs. *Phys. Rev. D*, 68:103514, 2003.

[251] Edward Witten. Cosmic superstrings. *Physics Letters B*, 153:243 – 246, 1985.

[252] Edmund J. Copeland, Levon Pogosian, and Tanmay Vachaspati. Seeking String Theory in the Cosmos. *Class. Quant. Grav.*, 28:204009, 2011.

[253] Thibault Damour and Alexander Vilenkin. Gravitational radiation from cosmic (super)strings: Bursts, stochastic background, and observational windows. *Phys. Rev. D*, 71:063510, 2005.

[254] S. Olmez, V. Mandic, and X. Siemens. Gravitational-Wave Stochastic Background from Kinks and Cusps on Cosmic Strings. *Phys. Rev. D*, 81:104028, 2010.

[255] Thibault Damour and Alexander Vilenkin. Gravitational wave bursts from cosmic strings. *Phys. Rev. Lett.*, 85:3761–3764, 2000.

[256] 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.

[257] J. Aasi et al. Improved Upper Limits on the Stochastic Gravitational-Wave Background from 2009–2010 LIGO and Virgo Data. *Phys. Rev. Lett.*, 113(23):231101, 2014.

[258] Rory Smith and Eric Thrane. The optimal search for an astrophysical gravitational-wave background. *Phys. Rev. X*, 8(2):021019, 2018.

[259] The LSC and Virgo Commissioning, Calibration, Detector Characterization, and Computing Groups. LSC-Virgo Operations White Paper (Summer 2019 edition), 2019.
`https://dcc.ligo.org/LIGO-T1900521/public`.

[260] 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.

[261] Michael W. Coughlin et al. Measurement and subtraction of Schumann resonances at gravitational-wave interferometers. *arXiv*, 1802.00885, 2018.