LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION
KAGRA COLLABORATION

Technical Document **LIGO-T2000424-v2**
VIR-0666B-20
JGW-T2011802-v2

The LSC-Virgo-KAGRA Observational Science White Paper (Summer 2020 edition)

The LSC-Virgo-KAGRA Observational Science Working Groups

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Processed with LaTeX on 2020/08/07

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1 Overview and Executive Summary

Gravitational wave (GW) searches and astrophysics in the LIGO Scientific Collaboration (LSC), Virgo Collaboration and KAGRA 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.

The LSC, Virgo Collaboration and KAGRA Collaboration are separate entities but work together closely, especially on data analysis. We often refer to the LSC and Virgo together as 'LVC', and refer to the LSC-Virgo-KAGRA combination as 'LVK'.

This ***LSC-Virgo-KAGRA Observational Science White Paper***, which is updated yearly (and was formerly called the *LSC-Virgo White Paper on Gravitational Wave Data Analysis and Astrophysics*), 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. Each activity plan has a prefix which associates it with either Section 2 or Section 4 of the LIGO Scientific Collaboration Program 2020-2021:

- Section 2, *Scientific Operations and Scientific Results* (prefix "Op-"), includes activities to produce and publish observational results from the most recent observing run (O3), as well as some critical infrastructure preparations for the next observing run (O4).
- Section 4, *Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics: Enhanced Analysis Methods* (prefix "LT-") includes longer-term developments which we will pursue to advance the scientific frontiers of GW observational science.

The LSC Program Committee and Virgo Core Program Committee set specific goals for collaboration work on an annual basis, using this white paper and other inputs. While this white paper concerns 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-T2000294, VIR-0551A-20).

Direct detection of gravitational waves was the result of decades of development of 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, starting with just the two Advanced LIGO detectors but with Advanced Virgo joining the run for the month of August 2017. 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, and ended on March 27, 2020. At the time of writing this white paper, the astrophysical search working groups are fully focused on analyzing O3 data and producing a wide range of publications. The O3 run was 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 is O3b. Some analyses are being run and published on each half run, while others will use the entire O3 data set.

Epoch	Run Name	Run Duration	Typical Binary Neutron Star (BNS) Range (Mpc)			$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		
			LIGO	Virgo	KAGRA	LIGO	Virgo	
2015–16	O1	4 months	80	–	–	50	–	actual
2016–17	O2	9 months	100	30	–	60	25	actual
2019–20	O3	11 months	110–130	50	1	80–90	35	actual
2021–23	O4	12 months	160–190	90–120	25–130	110–120	65–80	projected
2024–26	O5	TBD	330	150–160	130+	210	100–155	projected

Table 1: Observing schedule, actual and projected sensitivities for the Advanced LIGO, Advanced Virgo and KAGRA detectors. Adapted from *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA* (LIGO-P1200087, VIR-0288C-12), curated by the LVK Joint Run Planning Committee.

Scientific Operations and Observational Results

LSC-Virgo data analysis activities with the goal of producing results from 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-KAGRA Observational Science Working Group			
	Burst	CBC	CW	SGWB
Highest priority	Search for short-duration GW bursts (both online and offline)	Responding to exceptional compact binary coalescence detections	Targeted searches for high-interest known pulsars, e.g. Crab, Vela	Searches for an isotropic stochastic GW background
	Search for long-duration GW bursts	Cataloging detections of coalescence of neutron star and black hole binaries and their meaured parameters	Narrow-band searches for high-interest known pulsars	Directional searches for anisotropic stochastic GW backgrounds
	Responding to exceptional GW burst and multi-messenger detections	Characterizing the astrophysical distribution of compact binaries	Directed searches for high-interest point sources, e.g. Cassiopeia A, Scorpius X-1	Detector characterization, data quality, and correlated noise studies specific to SGWB searches
	Searches without templates from GWs from binary black holes	Testing General Relativity with compact binaries	All-sky searches for unknown sources, either isolated or in binary systems	
	GW burst signal characterization	Low-latency searches to enable multimessenger astronomy	Long-transient searches for emission from nearby post-merger neutron stars	
		Multimessenger search for CBC-GRB coincidences	Follow-up searches of any promising candidates found by other searches	
		Measuring the neutron star equation of state	Detector characterization, data preparation, scientific software maintenance	
		Determination of the Hubble constant		
High priority	Triggered multi-messenger searches	Improved searches for intermediate mass black hole binaries and intermediate mass-ratio inspirals	Targeted 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	Search for gravitationally lensed signals from compact binary coalesceces	Long-transient searches for emission from distant post-merger neutron stars	Implications and astrophysical modeling
		Improved waveform models for signals expected during the O4 run		All-sky all-frequency search for unmodeled persistent sources
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	Component separation
		Optimized search for stochastic background of gravitational waves from CBCs	Searches for continuous emission from ultra-light boson clouds around black holes	Searching for the SGWB-EM sky correlations

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-KAGRA Observational Science 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	Implement optimal method to search for stochastic background from CBC events
	Plans for the detection of exceptional multi-messenger sources	Improved models of population inference	Development of model-robust/agnostic data analysis methods	
		Improvements to statistical measurement of the Hubble constant		
		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 CCSN 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. [Section Op-2.1]

   - **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-2.5, Op-6.2, Op-6.4, Op-6.6]

   - **Searches without templates for 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-6.1]

   - **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-2.5, Op-6.2, Op-6.4, Op-6.6, Op-6.3]

   - **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. [Section Op-6.2]

   - **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-7.1]

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

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, the O3 run has completed and a multitude of new events have been detected. These are in addition to the several binary black hole coalesceneces and a binary neutron star merger that were observed in O1 and O2. 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.

An O3a catalog reporting significant events discovered during the first half of O3 along with several companion papers are nearing completion and are not included in this white paper. We are preparing for the next major update to the catalog, which will contain significant events detected during the second half of O3 (O3b). We are preparing to do more detailed estimation of population distributions of binary masses and spins, more sensitive tests of general relativity using a much larger statistical sample of signals, and improved measurements of the Hubble constant through direct and statistical methods. Furthermore, we anticipate detections of new classes of compact binary coalescences, and, with additional neutron star mergers, we will be able to make more precise measurements of the neutron star equation of state. 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 build a clearer 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, local Lorentz invariance and the mass 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.
- **Low-latency searcheds 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 searching data in near-real-time and 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. (The Operations White Paper describes other essential components of this effort, including data quality checks and the infrastructure associated with collating information and distributing alerts.)
- **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 developement in 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.
- **Search for gravitationally lensed binary coalescences**.
  Gravitational lensing of gravitational waves can result in magnification of gravitational wave signals as well as multiple images, which has the effect that the same source is seen as multiple events separated in time. Strong and weak lensing can alter the gravitational waveform in ways that could allow us to determine that a signal has been lensed. Detection of a lensed signal would allow us to make inferences about cosmology and population of compact binaries and would allow us to perform improved tests of the number of gravitational wave polarization states.

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

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 the addition of KAGRA, 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 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 (a few thousand) 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. *Ultra-light boson clouds around black holes* may also produce long-lived continuous wave signals.

1.3.1 Scientific Operations and O3 Observational Results

The CW group is undertaking a comprehensive search program using data from 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 ultra-light boson clouds around black holes (Section Op-4.11).

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

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

[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.

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**
   - 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 phase transition 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.

   - **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.

   - **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.

3. **Additional priority**

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

   - **GW-EM Correlations.** Measure possible correlations between GW anisotropy maps and maps of matter structure obtained through electromagnetic approaches (galaxy counts, gravitational lensing and others).

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

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.

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; 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 [1], refine it to use theoretical signal template, and apply it to O2 and O3 data.

1.5 Working Group Leadership Roles

Each of the four astrophysical search working groups (CBC, Burst, CW, SGWB) is led by Co-Chairs, with at least one from each collaboration. The LSC and Virgo Co-Chairs have specific responsibility for coordinating and facilitating most O3 papers, but data analysis will be increasingly coordinated with KAGRA group chairs and members in the coming year. Because the working groups have many active members and encompass a large scientific scope, the Co-Chair role demands a considerable amount of time and energy.

Some of the working groups have defined formal subgroups devoted to developing and maintaining specific technical capabilities and pursuing various science goals. Several of these subgroups span two or more working groups where the science suggests overlap in sources or methods.

Each paper being prepared has a designated Editorial Team (or Paper Writing Team), formed at the onset of paper preparation, and a paper project manager (or co-manager).

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 (or Observational Science) Coordinator. The Data Analysis Coordinators facilitate the overall process of planning, producing and reviewing scientific analyses and papers, and lead weekly Data Analysis Coordination (DAC) meetings, among other tasks. FTE-months: 8.0 (DAC co-chairs)

2 Burst Group Activity Plans

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

Since O1, the search for unmodeled transients has benefited from independent implementations of burst analysis pipelines [2, 3]. Each analysis uses a measurement basis (Fourier, wavelet or others) in order to identify coherent excess power in the data from multiple detectors (cWB [4], oLIB [5] and BayesWave [6]). 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, an all-sky search for transient events is 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.

Critical task for O4

ACTIVITY Op-2.1-A: LOW-LATENCY SEARCHES FOR PUBLIC ALERTS

TASK Op-2.1-A(i): CWB ONLINE PIPELINE OPERATION

FTE-months: 1.0

Deploy and maintain the cWB online search for gravitational wave bursts for O4. This activity includes all flavors of low latency searches that generate burst alerts (allsky and BBH). This also includes the source properties inference (skymaps and unmodelled source properties). The low-latency searches are analyzing the LIGO, Virgo and KAGRA data.

TASK Op-2.1-A(ii): BAYESWAVE ONLINE PIPELINE OPERATION FTE-months: 1.0

Deploy and maintain the BayesWave online search for gravitational wave bursts for O4. This activity includes all flavors of low latency searches that generate burst alerts (allsky and BBH). This also includes the source properties inference (skymaps and unmodelled source properties). The low-latency searches are analyzing the LIGO, Virgo and KAGRA data.

TASK Op-2.1-A(iii): OLIB ONLINE PIPELINE OPERATION FTE-months: -

Deploy and maintain the oLIB online search for gravitational wave bursts for O4. This activity includes all flavors of low latency searches that generate burst alerts (allsky and BBH). This also includes the source properties inference (skymaps and unmodelled source properties). The low-latency searches are analyzing the LIGO, Virgo and KAGRA data.

TASK Op-2.1-A(iv): DEFINITION OF BURST LOW LATENCY ALERTS FTE-months: 0.5

Discuss and decide the nature of the all-sky Burst alerts during O4.

Major deliverables for O3

ACTIVITY Op-2.1-B: SEARCH FOR SHORT-DURATION GW TRANSIENT SIGNALS IN LIGO AND VIRGO O3 DATA

TASK Op-2.1-B(i): COMPLETE THE ALL-SKY BURST SEARCH FTE-months: 3.0

Run cWB and BayesWaves pipelines on O3a and O3b data set and produce final results.

TASK Op-2.1-B(ii): SIGNAL INJECTIONS FTE-months: 3.0

Perform the signal injections to assess the pipeline efficiency following the methodology developed after O2.

TASK Op-2.1-B(iii): FOLLOW-UP DETECTION CANDIDATES FTE-months: 1.0

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): REPORT RESULTS AND REVIEW FTE-months: 1.0

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): PUBLISH RESULTS FTE-months: 4.0

Publish a collaboration paper reporting any signals found by the short-duration search in the O3 data, 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. Note that the required FTE-months are accounted in the detchar section of the Operations white paper.

TASK Op-2.1-C(i): DATA QUALITY PRODUCTS — FTE-months: 1.0

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: 1.0

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: 2.0

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. This integration is already in place for some pipelines, but still needs to be done for others.

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 [7, 8] 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 [4], stampas [9] and X-SphRad [10] pipelines, focuses on signals that last up to several hundreds of seconds while other searches (see Op-5.3 and Op-4.9) target signals lasting up to several weeks.

Major deliverables for O3

ACTIVITY Op-2.2-A: SEARCH FOR LONG-DURATION GW TRANSIENT SIGNALS IN LIGO AND VIRGO O3 DATA

TASK Op-2.2-A(i): COMPLETE THE ALL-SKY LONG-DURATION BURST SEARCH — FTE-months: -

Search for GW signals in LIGO and Virgo O3a and O3b 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: -

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): FOLLOW-UP DETECTOR CANDIDATES — FTE-months: -

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): REPORT RESULTS AND REVIEW — FTE-months: -

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

TASK Op-2.2-A(v): PUBLISH RESULTS — FTE-months: -

Publish a collaboration paper reporting any signals found by the long-duration search in the O3 data, 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: 2.0

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: TOWARDS A 4-DETECTOR NETWORK

Analyze KAGRA data by the existing pipelines, both in low-latency and offline. This integration is already in place for some pipelines, but still needs to be done for others.

ACTIVITY LT-2.2-B: PIPELINE IMPROVEMENTS FOR O4

TASK LT-2.2-B(i): CWB

FTE-months: -

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 [11].

TASK LT-2.2-B(ii): STAMPAS

FTE-months: -

Test the performance and review the new python based stampas pipeline.

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

FTE-months: -

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-C: PARAMETER ESTIMATION

TASK LT-2.2-C(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-6.1.

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-6.1.

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 $e >\sim 0.05$ [12], therefore dedicated burst searches for these potential sources represent a viable alternative [13]. In practice, the current EBBH analysis uses the results of the generic binary stellar mass black hole search carried out with cWB pipeline [4].

Major deliverables and critical tasks remaining for O3

ACTIVITY Op-2.3-A: STELLAR MASS BBH SEARCH

TASK Op-2.3-A(i): OFFLINE SEARCH — FTE-months: 4.0

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

TASK Op-2.3-A(ii): FOLLOWING-UP DETECTION CANDIDATES — FTE-months: 1.0

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(iii): 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(iv): REPORTING RESULTS AND REVIEW — FTE-months: 1.0

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(v): CONTRIBUTE TO GW CATALOG AND PAPER — FTE-months: 1.0

GW detections with significances similar to, or greater than, those from the CBC templated search, would be candidates to appear in the GWTC for O3b and in 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): OPTIMIZING THE BBH SEARCH

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

TASK LT-2.3-B(ii): METHODS FOR IMPROVING THE EBBH 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(iii): 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(iv): 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 [14]. 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 [6, 15, 16]. 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 [17, 18]. In addition, burst searches provide a measurement of the polarization state for detected gravitational-wave events [16]. 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 [19, 20, 21]. 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 for O3

ACTIVITY Op-2.4-A: WAVEFORM RECONSTRUCTION FOR THE GW TRANSIENT CATALOG AND PAPER

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

Deliver waveform reconstructions, with uncertainty, for all detected sources during O3a and O3b.

TASK Op-2.4-A(ii): PRODUCTION OF SKYMAPS — FTE-months: -

Deliver position reconstruction skymaps for all detected sources during O3a and O3b.

TASK Op-2.4-A(iii): CONTRIBUTE TO O3 GW CATALOGS AND PAPERS — FTE-months: -

Deliver waveform reconstructions, waveform matching results and reconstructed skymaps 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).

TASK Op-2.4-A(iv): REPORTING RESULTS AND REVIEW — FTE-months: -

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.

ACTIVITY Op-2.4-B: SUBGROUP ADMINISTRATION

Management of the GW burst signal characterization burst subgroup.

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

FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

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 RECONSTRUCTION

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

TASK LT-2.4-A(ii): POLARIZATION STUDIES

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

ACTIVITY LT-2.4-B: IMPACT OF CALIBRATION ERROR ON BURST SEARCHES

TASK LT-2.4-B(i): IMPACT OF CALIBRATION ERROR ON SKY LOCALIZATION AND WAVEFORM RECONSTRUCTION OF BURST SOURCES

Development of methods to quantify the impact of calibration error on burst searches. For example, how relative calibration error between the detectors impact the sky localization of the sources.

Op-2.5 Search for GWs from core-collapse supernova

Motivation and methods

Once a star with mass $M \gtrsim 10M_\odot$ 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 [22]. 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-2.5-A: OPTICALLY TRIGGERED SEARCH

TASK Op-2.5-A(i): COLLECT TRIGGERS FTE-months: 0.5

Review the identification of candidate CCSNe 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-2.5-A(ii): RUN THE GW SEARCH FTE-months: 0.5

Conclude the search for GWs associated with the CCSN time and sky position, similarly to the O1-O2 search, using cWB dedicated pipeline [4]. Provide an estimate of the upper limits found by the CCSN search in O3.

TASK Op-2.5-A(iii): REPORTING RESULTS AND REVIEW FTE-months: 0.5

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

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

Publish a collaboration paper reporting any upper limits found by the CCSN search targeting sources within 20 Mpc maximum in O3 in case of significant improvements compared to O1-O2.

ACTIVITY Op-2.5-B: CCSN EXTRAORDINARY EVENT

TASK Op-2.5-B(i): RUN THE SEARCH

Run all search pipelines (including cWB dedicated pipeline described in Op-2.5-A(ii)) associated to the external trigger and determine its significance.

TASK Op-2.5-B(ii): PARAMETER ESTIMATION

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

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

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-2.5-B(iv): PUBLISHING RESULTS

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

ACTIVITY Op-2.5-C: SUBGROUP ADMINISTRATION

Management of the CCSN subgroup.

TASK Op-2.5-C(i): SUBGROUP LEADERSHIP FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-2.5 Search for GWs from core-collapse supernova R&D (long term)

ACTIVITY LT-2.5-A: O4 PREPAREDNESS ACTIVITIES

TASK LT-2.5-A(i): DEVELOP A PLAN FOR AN EXTRAORDINARY DETECTION

Develop a plan to respond to a near-galactic CCSN in O4, including searches triggered by neutrino and/or electromagnetic observations.

ACTIVITY LT-2.5-B: DEVELOPMENT ACTIVITIES

The following are continuing developments.

TASK LT-2.5-B(i): CCSN WAVEFORM DEVELOPMENT

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

TASK LT-2.5-B(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-2.5-B(iii): SUB-THRESHOLD NEUTRINO-GW COINCIDENT SEARCH

Develop a joint sub-threshold neutrino/GW search.

TASK LT-2.5-B(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-2.5-B(v): SINGLE-INTERFEROMETER DETECTION

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

TASK LT-2.5-B(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 and Stochastic groups in sections 6 and 8.

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 the remainder of O3, and in preparation for O4, 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, O2 and O3 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 uncertanties in the estimated noise PSDs.

TASK Op-3.1-A(ii): MARGINALISATION OVER WAVEFORM UNCERTAINTY

FTE-months: 1.0

The systematic differences between waveform models can be incorporated in a statistical model that allows for uncertainty in the waveforms as well as in the parameter of the signal itself. This will allow us to mitigate the effect of waveform systematic errors in the estimation of source properties. This is particularly important for novel classes of sources where numerical simulations are sparsely distributed and current waveform models have less data to train on.

TASK Op-3.1-A(iii): 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(iv): PARALLELIZED SAMPLING ALGORITHMS

FTE-months: 1.0

The goal is to reduce wall-time latency of parameter estimation using CPU-parallelized algorithms for use on exceptional candidate events which warrant expensive cutting edge signal models.

TASK Op-3.1-A(v): 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, Virgo and KAGRA 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(vi): 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 functionailty from C to Python to become more development-friendly, in part covered by the increaesed usage of the Bilby codebase, and the tighter integration of `rapid_pe`, LALInference and Bilby.

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

FTE-months: 3.0

Working closely with the CBC waveform models R&D group (Sec. Op-3.4) 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

TASK Op-3.1-A(viii): RAPID LOCALIZATION WITH HIGHER ORDER MODES

FTE-months: 3.0

The rapid localization code, BAYESTAR, which is designed to enable electromagnetic follow-up of CBC signals, will be extended to incorporate higher order multipole contributions to the gravitational-wave signal, possibly in concert with extensions to the interface between BAYESTAR and online search pipelines.

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-3.4) which include and explore more physical effects (e.g., multi-modal effects, amplitude corrections, eccentricity), 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., SEOBNRv4P 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-3.5], and the Studies of extreme matter with pre-merger and post-merger GWs R&D group

[Sec. Op-3.3]), 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.

TASK Op-3.1-B(iv): REQUIREMENTS AND CONSTRAINTS FROM CALIBRATION UNCERTAINTY — FTE-months: 2.0

The use of marginalisation over uncertanties in the data calibration connects the astrophysical and instrumental inference. Therefore, investigating what requirements on the calibration uncertanties are, for both low- and high-latency analyses, in order to ensure unbiased astrophysical PE results. This also includes accounting for potential systematic errors in the calibration. The work is to be done in coordination with the calibration groups in LIGO, Virgo and KAGRA.

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 O4.

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 in preparation for O4.

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 in preparation for O4.

ACTIVITY Op-3.1-D: PARAMETER ESTIMATION ANALYSIS, INTEGRATION AND AUTOMATION

As the number of GW event candidates increase, a greater focus on autmation of the PE analysis is required.

TASK Op-3.1-D(i): AUTOMATION OF GENERATING PE CONFIGURATION FILES — FTE-months: 1.0

Given inputs from search pipelines, the generation of a configuration file from which an PE analysis can be initiated needs to be automated. This also includes defining both pipeline settings as well as parameter/analysis bounds and constraints.

TASK Op-3.1-D(ii): AUTOMATION OF GENERATION OF INPUT DATA TO PE ANALYSES — FTE-months: 1.0

A PE analysis on real GW data requires input files which can be generated and collated in a pre-processing step. This includes computing PSDs, fetching calibration uncertainty inputs and potential glitch-removal from the data.

TASK Op-3.1-D(iii): AUTOMATION OF INITIALISATION AND MONITORING OF PE ANALYSES — FTE-months: 1.0

Once a PE analysis is defined, the initialisation (and submission of the analysis into a computing queue) and monitoring of said analysis is to be automated. This includes development and maintenance of a centralised overview board where ongoing analyses can be monitored.

TASK Op-3.1-D(iv): AUTOMATION OF POSTPROCESSING OF PE ANALYSES FTE-months: 1.0

For a completed PE analysis, the finalised results are to be archived in a version controlled and automated way. This also includes generation of comparisons and diagnostics of the analyses to ensure convergence of the samples, and also to avoid problematic railing against prior bounds. This is also a requirement for improvements to the overall PE review process.

ACTIVITY Op-3.1-E: PE WITH MATTER EFFECTS

LIGO/Virgo made the first detection of a binary neutron star (BNS) merger in 2017, with one more certain BNS detection in O3 together with a small number of neutron star-black hole (NSBH) candidates. 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-E(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-E(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-E(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 and improve methods to do a multiple event equation of state estimation.

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: 3.0

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. Continued development and improvement of parallized sampling algorithms will address the cost of using expensive waveform models in PE.

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-3.7).

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-3.5) and the Stochastic group (Sec. 8).

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-3.7).

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 and/or machine learning techniques) 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, the possible existence of exotic compact objects and gravitational lensing, are also pursued within the group.

Major aspects and methods for this activity

ACTIVITY Op-3.2-A: GRAVITATIONAL-WAVE PROPERTIES

TASK Op-3.2-A(i): TESTING THE MULTIPOLAR STRUCTURE OF GRAVITATIONAL WAVES — FTE-months: 2.0

Develop tests that use the multipolar structure of gravitational waves to test their consistency with general relativity.

TASK Op-3.2-A(ii): SEARCHES FOR NON-STANDARD POLARIZATION PROPERTIES — FTE-months: 1.0

Develop model agnostic and theory-specific analyses for non-tensorial polarizations and vacuum birefringence.

ACTIVITY Op-3.2-B: TESTING THE REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS

Sufficiently loud signals from massive compact objects will allow us to test their immediate environments.

TASK Op-3.2-B(i): TESTS OF THE NATURE OF THE MERGER REMNANT — FTE-months: 3.0

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

TASK Op-3.2-B(ii): ECHO SEARCHES — FTE-months: 6.0

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

ACTIVITY Op-3.2-C: GRAVITATIONAL LENSING

The gravitational-wave lensing sub-group under the Testing General Relativity group is primarily responsible for finding signatures of gravitational-wave lensing within the GW signals observed by LIGO and Virgo, and for developing associated data analysis and modeling infrastructure. These include (but are not limited to) searches for lensing magnification, multiple images produced by strong lensing, microlensing beating patterns and diffraction effects, as well as modeling of the gravitational lenses and their population, stochastic background, and other modeling of gravitational-wave lensing.

TASK Op-3.2-C(i): POSTERIOR-BASED SEARCH PIPELINE — FTE-months: 3.0

Develop and improve posterior-based parameter estimation searches for lensed multiple images

TASK Op-3.2-C(ii): JOINT PARAMETER ESTIMATION PIPELINE — FTE-months: 3.0

Develop and improve joint parameter estimation searches using template-based approaches

TASK Op-3.2-C(iii): SUB-THRESHOLD SEARCH PIPELINES — FTE-months: 3.0

Update template-based sub-threshold search pipelines for application to the O3 data set.

TASK Op-3.2-C(iv): MICROLENSING SEARCH PIPELINE
Develop templates and parameter estimation methodologies to target microlensed events. FTE-months: 3.0

TASK Op-3.2-C(v): TESTS OF THE GRAVITATIONAL-WAVE POLARIZATION THROUGH LENSED EVENTS FTE-months: 2.0
Develop model agnostic and theory-specific analyses to test for the gravitational-wave polarization with strongly lensed gravitational waves.

ACTIVITY Op-3.2-D: SUBGROUP ADMINISTRATION

Management of the Testing General Relativity subgroup.

TASK Op-3.2-D(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, resonant excitations, 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: GRAVITATIONAL LENSING

Improve the modeling of lens populations and lensing rates. 2) Investigate the use of improved lens models in data analysis pipelines. 3) Develop methods to infer properties of the source population from detections of lensed gravitational-wave signals as well as the stochastic background. 4) Improve the inference tools to detect and characterize lensing signatures from existing detections, including the investigation of wave-optics effects and multiple images, prior choices, and selection effects. 5) Improve sub-threshold search pipelines to detect lensed counterparts of transient gravitational-wave signals. 6) Develop methods to make astrophysical inference (e.g., nature of dark matter) from lensing signatures in gravitational-wave signals.

Op-3.3 Studies of Extreme Matter 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 binary neutron star (BNS)/neutron star black hole binary (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-3.3-A: SUBGROUP ADMINISTRATION

Management of the Extreme Matter subgroup.

TASK Op-3.3-A(i): SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership. FTE-months: 2.0

LT-3.3 Studies of Extreme Matter 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-3.3-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-3.3-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-3.4.

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-3.3-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-3.3-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-3.3-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-3.3-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-3.3-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-3.4 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 O4 results.

ACTIVITY Op-3.4-A: NEW WAVEFORM MODELS

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

TASK Op-3.4-A(i): IMPROVE BH-BH WAVEFORM MODELS

FTE-months: 36.0

Waveform models for BBH systems that include the effects of precession and sub-dominant multipoles have been developed, implemented and reviewed in collaboration code. We aim to further develop BBH models, delivering improvements in terms of accuracy, physical content and computational efficiency. This may include the development of new models as well as the refinement of existing models, e.g., through a re-calibration of IMR waveforms to larger NR data sets. A particular focus will be the parameter space of high mass ratios.

TASK Op-3.4-A(ii): IMPROVE NS-NS WAVEFORM MODELS

FTE-months: 36.0

This includes improved modelling of BNS tidal and spin effects by comparison to numerical relativity simulations or improved analytical understanding, as well as modelling sub-dominant multipoles. We aim to develop models that include as many of these effects as possible.

TASK Op-3.4-A(iii): IMPROVE BH-NS WAVEFORM MODELS

FTE-months: 36.0

This includes improved modelling on NS tidal and spin effects, improved modelling of sub-dominant multipoles and the accurate modelling of the merger/disruption of the NS. We aim to develop models that include as many of these effects as possible.

TASK Op-3.4-A(iv): INCLUDE ECCENTRICITY IN BH-BH 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 have an IMR model for BH-BH systems with moderate eccentricity and aligned spins implemented in LAL and reviewed by O4. Further work will address effects of spin precession and subdominant modes on eccentric IMR waveforms.

TASK Op-3.4-A(v): IMPROVED NR-CALIBRATED FITS FOR SPECIFIC BH-BH, BH-NS AND NS-NS PROPERTIES

FTE-months: 24.0

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.

We also aim to implement in LAL accurate NR-calibrated fits for tidally interacting binaries that include the remnant black hole mass and spin, radiated energy, peak luminosity and postmerger frequencies fits.

TASK Op-3.4-A(vi): 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-3.4-B: EVALUATION OF WAVEFORM MODELS

Waveform models will be evaluated in the following ways.

TASK Op-3.4-B(i): CROSS-VALIDATION BETWEEN DIFFERENT NR CODES FOR CBC SYSTEMS

FTE-months: 12.0

Cross-validation between different NR codes for BH-BH, NS-NS and BH-NS 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.

TASK Op-3.4-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. Develop and improve NR follow-up methods.

TASK Op-3.4-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 and numerical relativity simulations. In particular at significantly unequal mass-ratios and/or high spins, and also paying attention to sub-dominant modes.

ACTIVITY Op-3.4-C: ALGORITHMIC AND COMPUTATIONAL IMPROVEMENTS TO WAVEFORM MODELS

TASK Op-3.4-C(i): OPTIMIZATIONS OF IMPORTANT WAVEFORM MODELS FTE-months: 12.0

The evaluation time of waveform models needs to be low enough to i) be used in parameter estimation of long signals, ii) be run multiple times on the same event to study the impact of analysis hyperparameters, and finally iii) to cope with the large number of events expected.

We will pursue methods to speed up existing waveform models, e.g., through the use of surrogate/reduced-order-modelling or the reduced-order-quadrature method.

ACTIVITY Op-3.4-D: WAVEFORM REVIEW

TASK Op-3.4-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-3.4-E: CODE MAINTENANCE AND INFRASTRUCTURE IMPROVEMENT

TASK Op-3.4-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-3.4-E(ii): IMPROVEMENT OF COMMON INFRASTRUCTURE FTE-months: 10.0

Examples: Development of common waveform tools, e.g., to aid in waveform reviews. Standardized waveform conventions across models. Increase support for eccentric waveforms, e.g., in the numerical relativity injection infrastructure.

ACTIVITY Op-3.4-F: SUBGROUP ADMINISTRATION

Management of the Waveforms subgroup.

TASK Op-3.4-F(i): SUBGROUP LEADERSHIP FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.4 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-3.4-A: ECCENTRIC IMR WAVEFORM MODELS FOR CBC SYSTEMS: PRECESSION, SUB-DOMINANT MODES, TIDAL EFFECTS, OPTIMIZATION

Include effects of spin-precession, sub-dominant modes and matter in the development of signal models for binary coalescence with orbital eccentricity (BH-BH, NS-NS and NS-BH systems). Improve evaluation speed of eccentric waveform models.

ACTIVITY LT-3.4-B: WAVEFORM MODELS FOR BINARIES ON UNBOUND ORBITS

Develop waveform models for hyperbolic and parabolic encounters.

ACTIVITY LT-3.4-C: ACCURATE AND LONG NUMERICAL RELATIVITY SIMULATIONS

Perform numerical relativity simulations for all types of CBC systems with sufficient accuracy and length to quantify waveform modeling errors at sensitivities of future GW detectors.

ACTIVITY LT-3.4-D: INVESTIGATE APPLICATION OF NEW MATHEMATICAL TOOLS TO WAVEFORM MODELING

Exploration of novel methods that may lead to the development of models that include more physical effects, or that may significantly speed up existing waveform models, but do not necessarily lead to deliverable waveforms in the short term.

ACTIVITY LT-3.4-E: SUPPORT FOR EXTERNAL CODES AND PYTHON INFRASTRUCTURE FTE-months: -

Add support for external codes (e.g., gwsurrogate) and Python infrastructure.

Op-3.5 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 modeling to improve understanding of astrophysical processes and environments.

Motivation and methods

The primary charge of the Rates and Population subgroup is to infer the properties of astrophysical populations of merging binaries through statistical and phenomenological modeling. These properties include the mass, spin, intrinsic merger rate, and spatial distributions. Models of such population properties are compared with the outputs of CBC searches and of parameter estimation algorithms to perform inference and to categorize and establish the significance of new events as they arise. With increasing statistics and more detailed modeling, inference on relevant physical quantities affecting populations will be incorporated.

Binary merger events are considered in four categories: the binary black hole (BBH) and 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 NSBH and intermediate mass black hole binary (IMBHB) categories we establish upper limits on rate. The implied boundaries, corresponding to possible divisions in outcomes of astrophysical processes, e.g. core collapse supernovae or binary mass transfer, are not precisely defined. The distributions of events within each category are influenced by a rich set of astrophysical phenomena which we wish to explore. With the 10 BBH and 1 BNS found in O1 and O2, we began to probe features in the distributions of CBC masses, spins, and redshifts.

As the binary merger census expands in number and cosmological reach, additional population features are becoming measurable and subpopulations may become resolvable. With a few hundred events, we are likely able to determine details about the origin of the components, as well as probe correlations between mass and spin distributions. The infrastructure developed in the context of BBH may be flexible enough to encompass more event categories as they are discovered, however broadening the base of statistical methods may be required. In addition to the interface with CBC searches, and with other subgroups quantifying properties of individual binary mergers (CBC Waveforms, CBC Parameter Estimation, CBC Extreme Matter), we also expect Rates/Population work to influence the structure of future catalogs of compact binaries and associated data products.

This group may also interface with communities developing astrophysical model simulations (for instance population synthesis or cluster dynamics) in various contexts, and may undertake opportunistic projects leveraging our modeling to access specific astrophysical processes or properties which are otherwise inaccessible.

Major aspects and methods for this activity

ACTIVITY Op-3.5-A: METHODS TO MEASURE SEARCH SENSITIVITY

Develop methods to efficiently measure the spacetime sensitivity of a network of interferometers delineated by source parameters and redshift, integrating this estimate 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.

TASK Op-3.5-A(i): SIMULATED SIGNAL CAMPAIGNS

FTE-months: 2.0

Decide on distributions of simulated CBCs to cover the relevant binary parameter spaces and implement with sufficiently accurate waveforms to measure selection effects with accuracy comparable to or better than other statistical and systematic errors affecting population analysis. Create and curate data products resulting from analyzing simulations with search pipelines.

TASK Op-3.5-A(ii): SEMI-ANALYTIC SENSITIVITY ESTIMATES

FTE-months: 2.0

Model and regress the sensitivity of search pipelines using (semi-)analytic methods and/or machine learning to obtain a rapid and flexible approximate estimate, given population parameters, model waveforms and detector sensitivity data (network PSDs). Calibrate such estimates against large-scale injections as above.

TASK Op-3.5-A(iii): INTERFACE WITH POPULATION INFERENCE

FTE-months: 1.0

Any method designed to measure sensitivity to specific populations must be integrated into analyses which require selection function estimates over population hyperparameters. This interface may require additional resampling or reweighting steps which must be computationally efficient without introducing unwanted biases.

ACTIVITY Op-3.5-B: RATE/POPULATION ANALYSIS FOR LOW LATENCY

Integrate models, techniques, and inferences from Rates and Population activities with the science output of Low Latency operations.

TASK Op-3.5-B(i): RAPID ASTROPHYSICAL CLASSIFICATION OF LOW-LATENCY EVENTS

FTE-months: 1.0

Consume outputs of low latency CBC searches to estimate probabilities of astrophysical origin and classification between BNS, NS-BH, BBH source types, based on previous rate/population results, implemented so as to add minimally to GCN Notice latency. Methods have been demonstrated and likely require ongoing optimization and maintenance.

ACTIVITY Op-3.5-C: MONITORING AND UPDATING POPULATION INFERENCE

In order to identify exceptional events at/beyond the boundaries of known populations, spot significant emerging population features and enable preliminary explorations of astrophysical implications, the R&P group will periodically update inferences on known populations during observing runs.

TASK Op-3.5-C(i): MID-LATENCY POPULATION UPDATES

FTE-months: 2.0

Infrastructure will be developed and maintained to identify and collect preliminary detection and parameter estimation results on a few-week cadence, and update inferences on standard distributions over mass, spin magnitude/alignment, rate and redshift evolution.

ACTIVITY Op-3.5-D: COMMON CODE AND DATA PRODUCT 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. 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. 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. In the longer term we may benefit from integration of codebases using similar methods (notably, hierarchical population inference) into a single pipeline.

TASK Op-3.5-D(i): HIERARCHICAL INFERENCE FOR PARAMETERIZED MODELS

FTE-months: 6.0

Maintain and optimize codebases for Bayesian hierarchical inference on population model hyperparameters using MCMC or other sampling methods. Extend the inference framework to include mixture models and address resulting issues of priors and sampling. Implement hierarchical inference based on direct (non-Markov-Chain) likelihood estimates as in the `rapid_pe` pipeline.

TASK Op-3.5-D(ii): INFERENCE ON NON-PARAMETRIC MODELS

FTE-months: 4.0

Maintain and extend methods for non-parametric models to explore features of the binary merger population without imposing physically motivated functional forms (e.g. binned mass/spin models, Gaussian mixture models).

TASK Op-3.5-D(iii): MODEL CHECKING AND OUTLIER IDENTIFICATION

FTE-months: 2.0

Maintain and refine methods for checking consistency of modeled populations with actual recovered det ection sets (e.g. posterior population checks, cumulative distribution tests) and for detecting possible population outliers, i.e. events apparently inconsistent with current models.

TASK Op-3.5-D(iv): INCLUSION OF MARGINAL EVENTS IN RATE/POPULATION INFERENCE

FTE-months: 2.0

Implement and refine methods to quantify and account for noise event contamination in population inferences by leveraging search pipeline estimates of background event distributions. For rate estimation this corresponds to existing two- or more-component Poisson mixture methods (see the task 'Population-Based Template Weighting and Rate Estimate' below).

TASK Op-3.5-D(v): CURATION OF DATA PRODUCTS

FTE-months: 1.0

Decide on and implement common formats for collecting data products from Rates and Populations activities, ensuring the data products are easily accessible and usable for public release.

ACTIVITY Op-3.5-E: POPULATION ASTROPHYSICS

As more fine-grained features and properties of the population become measurable, we will make more detailed studies linking them with potential underlying physical phenomena and mechanisms.

TASK Op-3.5-E(i): MASS DISTRIBUTION MODELS — FTE-months: 3.0

Develop and refine models describing the masses of merging binaries, either descriptive or connected to various possible formation channels. Continue to extend existing single-component modeling of BBH to multiple components / mixtures, with inclusion of more physical content in models as appropriate.

TASK Op-3.5-E(ii): COMPONENT SPIN DISTRIBUTION MODELS — FTE-months: 3.0

Develop and refine models describing the spin magnitudes and orientations of merging binaries and apply results of model inference to distinguish formation scenarios.

TASK Op-3.5-E(iii): REDSHIFT EVOLUTION AND SPATIAL DEPENDENCE OF MERGER POPULATION — FTE-months: 2.0

Continue to refine models required to infer rate and mass spectrum dependence on redshift. Implement methods to test for and measure potential anistropies in the merger distribution.

TASK Op-3.5-E(iv): INFERENCE ON ASTROPHYSICALLY MOTIVATED POPULATION PROPERTIES — FTE-months: 4.0

Identify features in mass / spin / redshift-dependent event distributions which arise from astrophysical processes. Interpretation and inference on these within the framework of phenomenological and physically motivated models in the literature.

ACTIVITY Op-3.5-F: INTEGRATION AND FEEDBACK WITH OTHER R&D GROUPS

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

TASK Op-3.5-F(i): POPULATION-BASED TEMPLATE WEIGHTING AND RATE ESTIMATE — FTE-months: 2.0

Binary merger search pipelines can be optimized for detecting events with a known parameter distribution by incorporating a template-dependent weighting in their ranking statistics. The resulting ranking statistic is also 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 via simple hard parameter cuts or by more sophisticated methods allowing overlapping signal populations. Methods will be maintained and updated in accuracy of modeling, flexibility and computational cost.

TASK Op-3.5-F(ii): SIMULATION-BASED SENSITIVITY ESTIMATION — FTE-months: 2.0

Carrying out a computationally intensive 'broad range' simulation campaign requires accurate waveforms and may require maintenance and optimization of search pipelines. Methods to substitute for such campaigns, for instance with machine learning tools, may be developed and implemented within searches.

TASK Op-3.5-F(iii): IMPACT OF WAVEFORM SYSTEMATICS ON INFERENCE — FTE-months: 3.0

Coordinating with the waveform and parameter estimation groups, when warranted we will assess the impact of model systematics on population inference. As in O2, a handle on such systematics is available by repeating population inferences with parameter samples obtained from different waveform models. This requires multiple reviewed catalogs of event parameters, preferably including effects of higher GW multipole emission. Tools such as Jenson-Shannon divergence will be required to assess difference between models.

TASK Op-3.5-F(iv): EOS MEASUREMENTS IN POPULATIONS OF NEUTRON STARS — FTE-months: 3.0

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-3.5-F(v): REEXAMINING EVENTS WITH POPULATION PRIORS — 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.

TASK Op-3.5-F(vi): POPULATION IMPACTS ON COSMOLOGY — FTE-months: 2.0

'Standard siren' methods for measuring the expansion history of the Universe require accurate accounting for selection effects, and thus modeling of relevant populations over mass, spin and redshift. Thus, the current best knowledge of the binary merger population should be applied. Similar considerations apply to studies of strongly lensed GW events.

TASK Op-3.5-F(vii): TESTS OF GR WITH EVENT POPULATIONS — FTE-months: 2.0

When applying parameterized tests of GR to multiple detections, different assumptions may be made on the behaviour of beyond-GR parameters: methods used in population analysis, specifically hierarchical inference, will clarify and generalize such assumptions. Such methods are to be implemented for current GR tests or possible extensions.

ACTIVITY Op-3.5-G: RATES AND POPULATIONS METHODS AND CODE REVIEW

TASK Op-3.5-G(i): REVIEW OF PARTICULAR METHOD — FTE-months: 8.0

Integrated method and code review for particular methods used in LVC publications.

ACTIVITY Op-3.5-H: SUBGROUP ADMINISTRATION

Management of the Rates and Populations subgroup.

TASK Op-3.5-H(i): SUBGROUP LEADERSHIP — FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.5 Binary Coalescence Rates and Population R&D (Long Term)

This section highlights developments that may *optionally* be deployed during the O4 run, or further in future, and thus are not required to be tested before O4 data taking.

Major aspects and methods for this activity

ACTIVITY LT-3.5-A: METHODS TO MEASURE SEARCH SENSITIVITY

Extend Monte Carlo or similar methods to estimate selection effects to so far neglected effects on binary signals and regions of parameter space.

TASK LT-3.5-A(i): SIMULATED SIGNAL CAMPAIGNS FOR ECCENTRIC BINARIES FTE-months: 2.0

Create and perform simulation campaigns for binary coalescences including significant non-zero orbital eccentricity. This relies on the existence of sufficiently accurate waveform models, which are largely not available at present: see Op-3.4.

ACTIVITY LT-3.5-B: COMMON CODE AND DATA PRODUCT DEVELOPMENT

TASK LT-3.5-B(i): MIXTURE MODEL FOR SIGNAL AND NOISE POPULATIONS FTE-months: 4.0

Implement a fully self-consistent mixture model analysis that can simultaneously infer the population and rate of both foreground (astrophysical) and background (noise) events, using data from binary merger searches, DetChar and parameter estimation. 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-3.5-B(ii): RATES AND POPULATION COMMON TOOLKIT FTE-months: 4.0

Integrated package of search-independent and flexible tools for inference over merger rates and populations. `https://git.ligo.org/RatesAndPopulations/lvc-rates-and-pop/`

ACTIVITY LT-3.5-C: POPULATION ASTROPHYSICS

TASK LT-3.5-C(i): IDENTIFICATION AND EXPLOITATION OF BBH MASS SCALES FOR COSMOLOGY FTE-months: 4.0

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.

Op-3.6 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-3.6-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-3.6-A(i): COSMOLOGY CODE IMPROVEMENTS — FTE-months: 18.0

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

ACTIVITY Op-3.6-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-3.6-B(i): MOCK DATA CHALLENGE: CONSTRUCTION OF MOCK DATA SET — FTE-months: 6.0

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-3.6-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-3.6-C: REVIEW OF COSMOLOGY PIPELINE

Continuing method and code review of the cosmology pipeline.

TASK Op-3.6-C(i): REVIEW OF COSMOLOGY PIPELINE METHODS — FTE-months: 12.0

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

TASK Op-3.6-C(ii): REVIEW OF COSMOLOGY PIPELINE CODE — FTE-months: 24.0

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

TASK Op-3.6-C(iii): REVIEW OF COSMOLOGY PIPELINE MOCK DATA RESULTS — FTE-months: 6.0

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

ACTIVITY Op-3.6-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-3.6-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-3.6-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-3.6-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-3.6-E: SUBGROUP ADMINISTRATION

Management of the Cosmology subgroup.

TASK Op-3.6-E(i): SUBGROUP LEADERSHIP — FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.6 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). Develop methods for constraints and model selection of primordial black hole (PBHs) based on CBC observations. Develop or extend techniques and methods to constrain particle dark matter models from CBC observations in combination with continuous waves and stochastic GW limits.

Motivation and methods

With a large number of events, precision cosmology will be possible using gravitational wave observations of CBCs, combining those with optical counterparts with those without. As the precision of the measurement increases, it will become necessary to fully understand potential systematic sources of error.

Gravitational-wave observations provide a novel way to probe the nature and origin of dark matter in cosmology as well as primordial black holes (PBHs) expected to be formed due to inhomogeneities in the early universe. The methods involved in PBH searches and constraints include the computation of the GW signatures (*e.g.* mass function, rates in different binary formation channels, spin distributions) in different PBH scenarios. Additionally, statistical methods for model selection (PBH versus astrophysical models) would constrain the theoretical PBH models. In several models of dark matter, new particles or fields can leave imprints in the GW signals from CBCs or produce continuous waves or stochastic GW backgrounds.

Major aspects and methods for this activity

ACTIVITY LT-3.6-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-3.6-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 evolution 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-3.6-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. Bringing these analyses together will require methodological studies and close links with other groups, in particular Rates and Populations.

ACTIVITY LT-3.6-D: EXTENSION OF SUB-SOLAR SEARCH TO MORE EXTREME MASS RATIOS

The search for sub-solar black hole binaries with a maximal component mass of $2M_\odot$ is the subject of another section of this white paper. This activity rather consists in extending that search to binaries with a larger primary component mass (dubbed as sub-solar binaries with *higher mass ratios* below). Methods include the production of new template banks for this mass range, running searches, setting new limits of the merger rate of such binaries, and interpretation of these limits in terms of constraints on the possible PBH mass function, abundance and binary formation channels.

TASK LT-3.6-D(i): SUB-SOLAR BLACK HOLE TEMPLATE BANK WITH HIGHER MASS RATIOS — FTE-months: 4.0

Design a template bank for sub-solar black holes with higher mass ratios.

TASK LT-3.6-D(ii): SEARCH FOR SUB-SOLAR BLACK HOLES WITH HIGHER MASS RATIO — FTE-months: 4.0

Develop a search pipeline for sub-solar black holes with higher mass ratios.

TASK LT-3.6-D(iii): METHODS OF INTERPRETATION OF SEARCHES FOR SUB-SOLAR BLACK HOLES WITH LOW MASS RATIO — FTE-months: 4.0

Develop methods for using search results to set new limits on the rate of PBHs and constraints on PBH mass function, abundance, and binary formation channels.

ACTIVITY LT-3.6-E: MODEL SELECTION OF PBH VS ASTROPHYSICAL SCENARIOS, BASED ON THE CBC MASS AND SPIN DISTRIBUTIONS

Development or extension of statistical methods for the Bayesian selection of PBH models versus astrophysical scenarios, based on the rate, mass and spin distributions of CBC observations. Computation of improved constraints on viable PBH models.

TASK LT-3.6-E(i): BAYESIAN MODEL SELECTION FOR PBHS — FTE-months: 4.0

Develop tools for Bayesian model selection of PBH models versus astrophysical scenarios based on the inferred rate and mass distributions.

ACTIVITY LT-3.6-F: POSSIBLE PBH INTERPRETATION OF EXCEPTIONAL OR SPECIAL EVENTS

For exceptional CBC events, the component masses and spins as well as the inferred merger rates could hint to a primordial origin rather than an astrophysical one. Assuming a primordial origin, the implications of these events for PBH scenarios could be investigated. Methods would include CBC parameter estimations and merger rate inference based on PBH-inspired mass functions instead of ones expected for neutron stars or astrophysical black holes.

TASK LT-3.6-F(i): METHODS FOR IDENTIFYING PBHS IN EXCEPTIONAL EVENTS — FTE-months: 4.0

Develop tools that can be used to identify an exceptional event as a PBH candidate.

ACTIVITY LT-3.6-G: SYNERGIES BETWEEN CBC OBSERVATIONS AND LIMITS ON CWS AND THE SGWB

The PBH scenarios able to explain CBC observations can be further tested against the limits on continuous GWs from inspiralling light PBH binaries, set by all-sky or targetted searches, and on the stochastic GW background from PBH binaries (primordial or in PBH clusters), close encounters and formation in the early universe. Moreover synergy between CBC observations and continuous waves and / or the stochastic background lead the way to other aspects of dark matter science. Superradiance from (scalar, vector or tensor) ultra-light boson clouds has an effect on the black hole spins. It is therefore possible to set limits on models with ultra-light bosons from spin measurements in black hole mergers. Limits on CW signals from all-sky or directed searches (towards galactic center, known X-ray binaries, or dwarf galaxies) is another way to constrain these models. Stochastic and continuous wave techniques can further be used to constrain the dark photon – the dark photon is expected to couple to the baryons in the detector mirrors, inducing a quantum-mechanical force that can be interpreted as a GW strain.

TASK LT-3.6-G(i): JOINT INFERENCE

FTE-months: 4.0

Develop methods for joint inference using CBC, CW, and SGWB search results.

Op-3.7 CBC All Sky Search InfraOps R&D

Short term development and tuning of search pipelines for online/offline running; generate template banks; assess data quality issues relevant to CBC detection. Requirements for going into O4 operations.

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-3.7-A: O3 (AND CRUCIAL O4) 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.

During O3 3-detector operations were the norm, and we expect that O4 will be first 4-detector observing run of the advanced detector era. Pipelines must be ready to handle this multi-detector data in O4.

In addition a number of the most important observations have been made with data from only a single detector. Reliably estimating single-detector significance is challenging and a number of pipelines are working to develop methods to estimate significance of events seen in only a single observatory.

TASK Op-3.7-A(i): 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-3.7-A(ii): CONTINUE OPTIMIZING THE GSTLAL SEARCH SENSITIVITY FOR O3 FINAL RESULTS

Incremental improvements to the GstLAL pipeline's search sensitivity during the O3 run. FTE-months: 12.0

TASK Op-3.7-A(iii): CONTINUE OPTIMIZING THE GSTLAL SEARCH SENSITIVITY FOR O4

Incremental improvements to the GstLAL pipeline's search sensitivity in preparation of the O4 run. FTE-months: 12.0

TASK Op-3.7-A(iv): CONTINUE OPTIMIZING THE GSTLAL COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the GstLAL pipeline's computational performance in preparation of the O4 run. FTE-months: 12.0

TASK Op-3.7-A(v): CONTINUE OPTIMIZING THE GSTLAL ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

Improvements to GstLAL online analysis that reduce latency of alerts and allow for BNS alerts $\sim$ 30 seconds before merger. FTE-months: 24.0

TASK Op-3.7-A(vi): DEVELOPMENT OF AN OFFLINE MBTA SEARCH

Allow MBTA to analyse data in an "offline" mode and submit results for the O3b catalog. FTE-months: 6.0

TASK Op-3.7-A(vii): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR MBTA

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA. FTE-months: 6.0

TASK Op-3.7-A(viii): CONTINUE OPTIMIZING THE MBTA SEARCH SENSITIVITY FOR O4

Incremental improvements to the MBTA pipeline's search sensitivity in preparation of the O4 run. FTE-months: 12.0

TASK Op-3.7-A(ix): CONTINUE OPTIMIZING THE MBTA COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the MBTA pipeline's computational performance in preparation of the O4 run. FTE-months: 3.0

TASK Op-3.7-A(x): CONTINUE OPTIMIZING THE MBTA ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

Improvements to MBTA online analysis that reduce latency of alerts and allow for BNS alerts $\sim$ 30 seconds before merger. FTE-months: 24.0

TASK Op-3.7-A(xi): DEVELOPMENT OF A 4-DETECTOR SEARCH FOR SPIIR

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA. FTE-months: 6.0

TASK Op-3.7-A(xii): CONTINUE OPTIMIZING THE SPIIR SEARCH SENSITIVITY IN PREPARATION OF O4

Incremental improvements to the SPIIR pipeline's search sensitivity in preparation of the O4 run. FTE-months: 8.0

TASK Op-3.7-A(xiii): CONTINUE OPTIMIZING THE SPIIR COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the SPIIR pipeline's computational performance for the O4 run. FTE-months: 3.0

TASK Op-3.7-A(xiv): CONTINUE OPTIMIZING THE SPIIR ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

FTE-months: 24.0

Improvements to SPIIR online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

TASK Op-3.7-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-3.7-A(xvi): CONTINUE OPTIMIZING THE PYCBC SEARCH SENSITIVITY FOR FINAL O3 RESULTS

FTE-months: 12.0

Incremental improvements to the PyCBC pipeline's search sensitivity for final O3 results run.

TASK Op-3.7-A(xvii): CONTINUE OPTIMIZING THE PYCBC SEARCH SENSITIVITY FOR O4

FTE-months: 12.0

Incremental improvements to the PyCBC pipeline's search sensitivity in preparation of the O4 run.

TASK Op-3.7-A(xviii): CONTINUE OPTIMIZING THE PYCBC COMPUTATIONAL PERFORMANCE FOR O4

FTE-months: 4.0

Incremental improvements to the PyCBC pipeline's computational performance for the O4 run.

TASK Op-3.7-A(xix): CONTINUE OPTIMIZING THE PYCBC ONLINE LATENCY AND ENABLE EARLY WARNING PIPELINE

FTE-months: 24.0

Improvements to PyCBC online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

ACTIVITY Op-3.7-B: O3 PIPELINE DEPLOYMENT

Search pipelines must be deployed and maintained on collaboration computer clusters for remaining O3 offline analyses.

TASK Op-3.7-B(i): DEPLOYMENT OF GSTLAL PIPELINE FOR OFFLINE RUNNING

FTE-months: 24.0

Deploy and maintain the GstLAL pipeline for deeper offline searches.

TASK Op-3.7-B(ii): DEPLOYMENT OF MBTA PIPELINE FOR OFFLINE RUNNING

FTE-months: 8.0

Deploy and maintain the MBTA pipeline for deeper offline searches.

TASK Op-3.7-B(iii): DEPLOYMENT OF PYCBC PIPELINE FOR OFFLINE RUNNING

FTE-months: 8.0

Deploy and maintain the PyCBC pipeline for deeper offline searches.

ACTIVITY Op-3.7-C: O3 PIPELINE REVIEW

Review of remaining changes to offline O3 pipelines and to configuration changes.

TASK Op-3.7-C(i): REVIEW OF GSTLAL PIPELINE

FTE-months: 2.0

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

TASK Op-3.7-C(ii): REVIEW OF MBTA PIPELINE

FTE-months: 2.0

Review of changes to the MBTA offline pipeline. Both changes to code and to configurations will be reviewed.

TASK Op-3.7-C(iii): REVIEW OF PYCBC PIPELINE FTE-months: 2.0

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

ACTIVITY Op-3.7-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, this is largely considered Rates/Pop. work, Sec. Op-3.5. But running the injections through pipelines is in scope here.

TASK Op-3.7-D(i): RUN RATES INJECTIONS IN MBTA, PYCBC AND GSTLAL PIPELINES FTE-months: 12.0

Run requested rates injection files through offline pipelines.

ACTIVITY Op-3.7-E: SUBTHRESHOLD SEARCHES FOR GRAVITATIONALLY LENSED COUNTERPARTS

Subthreshold searches with reduced template banks based on both GstLAL or PyCBC are promised in O3 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.

ACTIVITY Op-3.7-F: SUBGROUP ADMINISTRATION

Management of the all-sky pipelines subgroup.

TASK Op-3.7-F(i): SUBGROUP LEADERSHIP FTE-months: 2.0

Administrative and managerial tasks associated with subgroup leadership.

LT-3.7 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-3.7-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-3.7-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-3.7-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-3.7-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.

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

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.

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 O3b 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-3.8-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 FOR BROAD SEARCH — FTE-months: 6.0

Offline running of the PyCBC broad parameter search over O3b data chunks.

TASK Op-3.8-A(iii): PYCBC PIPELINE OPERATION FOR BBH-FOCUSED SEARCH — FTE-months: 6.0

Offline running of the PyCBC BBH-focused search over O3b data chunks.

TASK Op-3.8-A(iv): MBTA PIPELINE OPERATION — FTE-months: 6.0

Offline running of the MBTA search over O3b data chunks.

TASK Op-3.8-A(v): 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: SENSITIVITY ESTIMATION

Provide high-level sensitivity statement for various source categories (BNS, NSBH, BBH, etc.).

TASK Op-3.8-D(i): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR GSTLAL — FTE-months: 1.0

Using injection sets for different categories of signals (BNS, NSBH, BBH, etc.), estimate the spacetime volume sensitivity of the GstLAL search at a fiducial false-alarm-rate threshold.

TASK Op-3.8-D(ii): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR PYCBC — FTE-months: 1.0

Using injection sets for different categories of signals (BNS, NSBH, BBH, etc.), estimate the spacetime volume sensitivity of the PyCBC search at a fiducial false-alarm-rate threshold.

TASK Op-3.8-D(iii): ESTIMATE SPACETIME VOLUME SENSITIVITY FOR MBTA — FTE-months: 1.0

Using injection sets for different categories of signals (BNS, NSBH, BBH, etc.), estimate the spacetime volume sensitivity of the MBTA search at a fiducial false-alarm-rate threshold.

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: 1.0

- 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): TECHNICAL REVIEW COORDINATION — FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.8-F(ii): 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(iii): 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(iv): REVIEW OF MBTA PIPELINE SEARCH RESULTS — FTE-months: 1.0

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

TASK Op-3.8-F(v): 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(vi): 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.
- Strain data release surrounding catalog events in O3b.
- Posterior samples for catalog events in O3b.
- Data behind the figures appearing in O3b Catalog.

Op-3.9 O3b Astrophysical Distribution of Compact Binaries

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

Motivation and goals

With the addition of new detections during O3b, stronger constraints on the BBH, BNS, and NSBH populations are possible. This paper is an update to the O3a Astrophysical Distribution of Compact Binaries work.

Major aspects and methods for this activity

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

Inference on the binary neutron star merger rate.

TASK Op-3.9-A(i): PARAMETRIC BNS MERGER RATE ESTIMATE — FTE-months: 1.0

Estimate the rate of BNS mergers using FGMC or a fixed threshold, with a parametric mass model.

TASK Op-3.9-A(ii): NON-PARAMETRIC BNS MERGER RATE ESTIMATE — FTE-months: 1.0

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

ACTIVITY Op-3.9-B: NEUTRON STAR-BLACK HOLE MERGER RATE

Inference on neutron star-black hole merger rate.

TASK Op-3.9-B(i): PARAMETRIC NS-BH MERGER RATE CONSTRAINTS — FTE-months: 1.0

Constrain the rate of NS-BH mergers, assuming a parameterised mass distribution or distributions.

ACTIVITY Op-3.9-C: BLACK HOLE MASS DISTRIBUTION

Inference on the mass distribution of binary black holes observed.

TASK Op-3.9-C(i): PARAMETRIC HIERARCHICAL INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS — FTE-months: 6.0

Perform parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3b Catalog, using a variety of phenomenological models to extract different physical features.

TASK Op-3.9-C(ii): NON-PARAMETRIC INFERENCE OF MASS DISTRIBUTION USING OBSERVED BBH EVENTS — FTE-months: 2.0

Produce non-parametric estimates of the BBH mass distribution using PE posteriors for the collection of BBH events in the O3b Catalog.

ACTIVITY Op-3.9-D: REDSHIFT AND SPATIAL DEPENDENCE OF BLACK HOLE MERGER RATES

Estimate the merger rate of binary black holes as a function of redshift and test for spatial isotropy of mergers.

TASK Op-3.9-D(i): NON-EVOLVING RATE ESTIMATION — FTE-months: 2.0

Estimate the merger rates under the different mass and spin models, assuming that the rate does not evolve with redshift.

TASK Op-3.9-D(ii): INFERENCE ON REDSHIFT EVOLUTION — FTE-months: 3.0

Obtain the merger rate as a function of redshift, marginalizing over uncertainty in the mass distribution.

TASK Op-3.9-D(iii): MEASUREMENT AND BOUNDS ON ANISOTROPY — FTE-months: 2.0

Constrain the spatial (direction) dependence of BBH mergers and quantify any possible anisotropy.

ACTIVITY Op-3.9-E: BLACK HOLE SPIN DISTRIBUTION

Inference on the spin distributions of binary black holes observed.

TASK Op-3.9-E(i): PARAMETRIC HIERARCHICAL INFERENCE OF SPINS FROM OBSERVED BBH EVENTS — FTE-months: 6.0

Perform parametric hierarchical inference using PE posteriors for the collection of BBH events in the O3b Catalog, using a variety of phenomenological models to extract different physical features.

ACTIVITY Op-3.9-F: MODEL CHECKING AND OUTLIER TESTS

Evaluate the goodness-of-fit of the mass, spin and redshift distribution models and identify potential outliers in the set of events.

TASK Op-3.9-F(i): COMPARE POSTERIOR PREDICTIVE DISTRIBUTIONS TO OBSERVATIONS — FTE-months: 4.0

Check the consistency of the parameterized models with the observations and look for potential tensions between the model and the data.

TASK Op-3.9-F(ii): OUTLIER IDENTIFICATION — FTE-months: 4.0

Identify outliers in the population by various methods including leave-one-out analyses to test the robusntess of the population results against the targeted exclusion of individual events.

ACTIVITY Op-3.9-G: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.9-G(i): PROJECT MANAGEMENT — FTE-months: 1.0

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

TASK Op-3.9-G(ii): PAPER WRITING COORDINATION — FTE-months: 1.0

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

TASK Op-3.9-G(iii): FIGURE PREPARATION FTE-months: 2.0

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

TASK Op-3.9-G(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-H: TECHNICAL REVIEW

TASK Op-3.9-H(i): TECHNICAL REVIEW COORDINATION FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.9-H(ii): 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-H(iii): 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-H(iv): 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-H(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-H(vi): 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-H(vii): REVIEW OF BBH REDSHIFT EVOLUTION RESULTS FTE-months: 0.5

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

TASK Op-3.9-H(viii): REVIEW OF MODEL CHECKING RESULTS FTE-months: 0.5

Review of the posterior predictive checks and outlier analyses, including data behind figures.

ACTIVITY Op-3.9-I: PAPER REVIEW

TASK Op-3.9-I(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 0.5

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

TASK Op-3.9-I(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.
- Posterior samples from posterior distributions.
- Data products describing the detector sensitivity that can be used for independent population analyses.
- Data behind the figures appearing in the O3b Astrophysical Distributions paper.

Op-3.10 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.

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 [23, 24]. 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 [24, 18, 25].

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 [26]. 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 [27].

In O3, we have also observed events that require descriptions beyond the dominant quadrupole moment [28]. This has broadened the scope for us to test fundamental aspects of gravitational-wave generation, including the consistency between the dominant and higher-order moments.

In O4, 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-3.10-A: CONSISTENCY TESTS OF GR

Look for inconsistency between observed results and GR predictions for the events in O3b Catalog.

TASK Op-3.10-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-3.10-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-3.10-B: GRAVITATIONAL-WAVE PROPERTIES

Testing gravitational-wave properties, including generation and propagation, in O3b Catalog.

TASK Op-3.10-B(i): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN INSPIRAL AND POST-INSPIRAL

FTE-months: 2.0

Perform parameter estimation for each event while including a parameterized set of deviations from GR in the inspiral, merger and ringdown stages.

TASK Op-3.10-B(ii): PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN THE MULTIPOLAR STRUCTURE

FTE-months: 2.0

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

TASK Op-3.10-B(iii): 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.

TASK Op-3.10-B(iv): 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.

TASK Op-3.10-B(v): SPEED OF GRAVITY

FTE-months: 1.0

Constrain the speed of gravity by comparing the arrival time of signals between a network of detectors, or through comparison of the arrival time of a counterpart.

TASK Op-3.10-B(vi): EXTRA DIMENSIONS

FTE-months: 1.0

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

ACTIVITY Op-3.10-C: TESTING THE REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS

Probe the immediate environment of compact objects in O3b.

TASK Op-3.10-C(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 quasi-normal modes.

TASK Op-3.10-C(ii): ECHO SEARCHES

FTE-months: 2.0

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

ACTIVITY Op-3.10-D: EDITORIAL TEAM

Paper project management and writing.

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

FTE-months: 2.0

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

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

FTE-months: 0.5

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

TASK Op-3.10-D(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-E: TECHNICAL REVIEW

TASK Op-3.10-E(i): TECHNICAL REVIEW COORDINATION

FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.10-E(ii): REVIEW OF RESIDUALS TEST

FTE-months: 0.5

Review of the residuals consistency test results.

TASK Op-3.10-E(iii): REVIEW OF IMR TEST

FTE-months: 0.5

Review of the IMR consistency test results.

TASK Op-3.10-E(iv): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE GENERATION

FTE-months: 0.5

Review of the parameterized test of gravitational wave generation results.

TASK Op-3.10-E(v): REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE PROPAGATION

FTE-months: 0.5

Review of the Lorentz-invariance violation test results.

TASK Op-3.10-E(vi): REVIEW OF POLARIZATION TEST

FTE-months: 0.5

Review of the polarization test results.

TASK Op-3.10-E(vii): REVIEW OF QUASI-NORMAL MODES TESTS

FTE-months: 0.5

Review of the quasi-normal modes tests results.

TASK Op-3.10-E(viii): REVIEW OF SEARCH FOR LATE TIME ECHOES

FTE-months: 0.5

Review of the search for late time echoes results.

TASK Op-3.10-E(ix): REVIEW OF COMPARE GRAVITATIONAL WAVES WITH ELECTROMAGNETIC WAVES

FTE-months: 0.5

Review of the comparison of gravitational waves with electromagnetic waves.

TASK Op-3.10-E(x): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE

FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY Op-3.10-F: PAPER REVIEW

TASK Op-3.10-F(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 0.5

Publications & Presentations review of scientific content in O3b Testing GR paper.

TASK Op-3.10-F(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.
- Posterior samples from posterior distributions.
- Data behind the figures appearing in O3b Testing GR paper.

Op-3.11 O3 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.

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-3.11-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-3.11-A(i): COUNTERPART ONLY MEASUREMENT OF H_0

FTE-months: 0.5

Analyze events with electromagnetic counterparts to obtain a joint measurement on the Hubble constant.

TASK Op-3.11-A(ii): STATISTICAL ONLY MEASUREMENT OF H_0

FTE-months: 6.0

Analyze events without electromagnetic counterparts to obtain a joint statistical measurement on the Hubble constant.

TASK Op-3.11-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-3.11-A(iv): ASSESSMENT OF SYSTEMATIC UNCERTAINTIES

FTE-months: 6.0

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-3.11-B: EDITORIAL TEAM

Paper project management and writing.

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

FTE-months: 2.0

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

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

FTE-months: 2.0

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

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

FTE-months: 2.0

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

ACTIVITY Op-3.11-C: TECHNICAL REVIEW

TASK Op-3.11-C(i): TECHNICAL REVIEW COORDINATION

FTE-months: 2.0

Coordinate technical review activities.

TASK Op-3.11-C(ii): REVIEW OF COUNTERPART ONLY MEASUREMENT OF H_0

FTE-months: 0.5

Review of the counterpart only Hubble constant measurement results.

TASK Op-3.11-C(iii): REVIEW OF STATISTICAL ONLY MEASUREMENT OF H_0

FTE-months: 6.0

Review of the statistical only Hubble constant measurement results.

TASK Op-3.11-C(iv): REVIEW OF COMBINED MEASUREMENT OF H_0

FTE-months: 6.0

Review of the combined Hubble constant measurement results.

TASK Op-3.11-C(v): REVIEW OF ASSESSMENT OF SYSTEMATIC UNCERTAINTIES FTE-months: 6.0

Review of the systematic uncertainty study results.

TASK Op-3.11-C(vi): REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE FTE-months: 0.5

Review of posterior sample chains to be released.

ACTIVITY Op-3.11-D: PAPER REVIEW

TASK Op-3.11-D(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 0.5

Publications & Presentations review of scientific content in H_0 paper.

TASK Op-3.11-D(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in H_0 paper.

Expected products and/or outcomes

- O3 H_0 companion paper.
- Posterior samples from posterior distributions.
- Data behind the figures appearing in the O3 H_0 paper.

Op-3.12 O3 Search for Lensed Gravitational Waves

Search for gravitational-wave lensing signatures following LIGO/Virgo run O3

Motivation and goals

Gravitational waves can be gravitationally lensed by intervening galaxies, galaxy clusters, or microlenses. Lensing can result in magnified images, multiple images (separated in time), and modifications to the waveform due to microlensing. Here we will look for signatures of lensing in O3 data. The analyses will include I) Lensing statistics, II) Lensing magnification studies for chosen events, III) Multiple images (posterior analysis, joint-PE analysis, sub-threshold search), IV) Microlensing (if time allows).

Major aspects and methods for this activity

ACTIVITY Op-3.12-A: LENSING STATISTICS

Gravitational-wave lensing is a phenomenon that occurs when a gravitational wave propagates near a massive object such as a galaxy or a galaxy cluster. The objective is to derive the rate of observable strong gravitational-wave lensing for joint parameter estimation and to derive constraints on the lensed event rates and populations based on the (non-)detection of gravitational-wave lensing.

TASK Op-3.12-A(i): GRAVITATIONAL-WAVE LENSING RATES BASED ON KNOWN MODELS FTE-months: 1.0

Estimate the gravitational-wave lensing rate and multi-image time-delays based on the current population of binary black holes and lenses. This will enable us to estimate the prior odds of gravitational-wave lensing useful for the joint parameter estimation methodologies.

TASK Op-3.12-A(ii): DERIVE BOUNDS ON GRAVITATIONAL-WAVE LENSING FTE-months: 1.0

Use the (non-)detection of lensed gravitational waves to set limits on the gravitational-wave lensing rate and the population of lensed binaries.

ACTIVITY Op-3.12-B: LENSING MAGNIFICATION STUDIES

If a gravitational wave is strongly lensed, it will receive a magnification μ defined such that the gravitational-wave amplitude is increased by a factor $\mu^{1/2}$. If unaccounted for, the magnification will bias the measurement of luminosity distance and source-frame mass such that the binary appears more massive and closer to us than it actually is.

TASK Op-3.12-B(i): PERFORM MAGNIFICATION ESTIMATES ON THE MASSIVE OBSERVATION RUN O3 EVENTS

FTE-months: 1.0

Analyze O3 events that are outliers with respect to an expected unlensed mass distribution and estimate the required magnification under the lensing hypothesis.

TASK Op-3.12-B(ii): SEARCH FOR EVIDENCE OF LENSING MAGNIFICATION THROUGH TIDAL MEASUREMENTS

FTE-months: 1.0

Perform parameter estimation on O3 events with tidal measurements to search for evidence of gravitational-wave lensing magnification. Lensing magnification is fully degenerate with the measurement of the luminosity distance, and biases the source-frame masses. However, when combined with the neutron star equation-of-state, measurement of the tidal effects can break this degeneracy.

ACTIVITY Op-3.12-C: MULTIPLE IMAGE ANALYSES

Search for evidence that two or more gravitational wave observations might have a common lensed source.

TASK Op-3.12-C(i): POSTERIOR OVERLAP ANALYSIS

FTE-months: 1.0

Analyze all the O3 events to identify lensed multi-image candidate pairs using a fast posterior-overlap-based method. We can further analyze the lensed candidates using targeted joint parameter estimation.

TASK Op-3.12-C(ii): JOINT PARAMETER ESTIMATION ANALYSES

FTE-months: 3.0

Perform joint parameter estimation on event pairs to compute the Bayes factor of lensed vs. unlensed hypotheses.

TASK Op-3.12-C(iii): SUB-THRESHOLD SEARCH

FTE-months: 3.0

Search for sub-threshold candidates that could be lensed images associated with other, confidently detected events.

TASK Op-3.12-C(iv): TESTS OF GRAVITATIONAL-WAVE POLARIZATION

FTE-months: 1.0

If a lensed gravitational wave candidate is discovered, perform follow-up analysis of its gravitational-wave polarization content.

TASK Op-3.12-C(v): ASSESSMENT OF UNCERTAINTIES

FTE-months: 1.0

Investigate the systematic uncertainties of the posterior-based and joint parameter estimation methodologies through an injection campaign.

ACTIVITY Op-3.12-D: MICROLENSING

Search for evidence of wave-optics distortion of signals that could arise from microlensing.

TASK Op-3.12-D(i): SEARCH FOR WAVE OPTICS EFFECTS — FTE-months: 3.0

Perform parameter estimation on events to determine if there is evidence of microlensing distortions by a point mass lens.

ACTIVITY Op-3.12-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.12-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-3.12-E(ii): PAPER WRITING COORDINATION — FTE-months: 2.0

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

TASK Op-3.12-E(iii): FIGURE PREPARATION — FTE-months: 0.5

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

TASK Op-3.12-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-3.12-F: TECHNICAL REVIEW

TASK Op-3.12-F(i): TECHNICAL REVIEW COORDINATION — FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.12-F(ii): REVIEW OF LENSING STATISTICS STUDIES — FTE-months: 0.5

Review of the studies of lensing statistics.

TASK Op-3.12-F(iii): REVIEW OF LENSING MAGNIFICATION STUDIES — FTE-months: 0.5

Review of the studies of lensing magnification.

TASK Op-3.12-F(iv): REVIEW OF POSTERIOR OVERLAP ANALYSIS — FTE-months: 0.5

Review of the posteror overlap analysis study.

TASK Op-3.12-F(v): REVIEW OF JOINT PARAMETER ESTIMATION ANALYSES — FTE-months: 0.5

Review of the joint parameter estimation analyses.

TASK Op-3.12-F(vi): REVIEW OF JOINT PARAMETER ESTIMATION POSTERIOR SAMPLES — FTE-months: 0.5

Review of the posterior samples from the joint parameter estimation analyses.

TASK Op-3.12-F(vii): REVIEW OF SUB-THRESHOLD SEARCH FTE-months: 1.0

Review of the sub-threshold search for lensed images.

TASK Op-3.12-F(viii): REVIEW OF SEARCH FOR WAVE OPTICS EFFECTS FTE-months: 0.5

Review of the search for wave optics effects.

ACTIVITY Op-3.12-G: PAPER REVIEW

TASK Op-3.12-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 0.5

Publications & Presentations review of scientific content in the lensing paper.

TASK Op-3.12-G(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in the lensing paper.

Expected products and/or outcomes

- O3 Lensing companion paper.
- Posterior samples from joint parameter estimation analyses.
- Data behind the figures appearing in the O3 Lensing paper.

Op-3.13 O3a Sub-Threshold Search for Compact Binaries

Update a catalog of compact binary coalescence candidate with a deeper search for subthreshold signals observed during O3a along with parameter estimates and rate estimates.

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. Sub-threshold candidates can be used in statistical analyses with other astrophysical datasets. Pipeline improvements subsequent to initial catalog results can result in new detections.

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 update our catalog of detections made during O3a and release a detailed description of all new detected systems, covering their detection and physical parameters, inferred using the best available waveform models, as well as provide a list of subthreshold triggers recovered by the pipelines.

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.

For each event, both clear and marginal detections (but not subthreshold), 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 as well as a list of subthreshold triggers.

ACTIVITY Op-3.13-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-3.13-A(i): GSTLAL PIPELINE OPERATION — FTE-months: 12.0

Offline running of the GstLAL search over O3a data chunks.

TASK Op-3.13-A(ii): PYCBC PIPELINE OPERATION — FTE-months: 6.0

Offline running of the PyCBC search over O3a data chunks.

ACTIVITY Op-3.13-B: DATA QUALITY

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

TASK Op-3.13-B(i): DETECTOR CHARACTERIZATION ROTA — FTE-months: 2.0

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

ACTIVITY Op-3.13-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-3.13-C(i): PARAMETER ESTIMATION EVENT ROTA — FTE-months: 12.0

Run parameter estimation pipeline on each new significant candidate event.

TASK Op-3.13-C(ii): PARAMETER ESTIMATION EXPERT ROTA — FTE-months: 6.0

Supervise parameter estimation event rota efforts.

Certify validity of sample chains.

TASK Op-3.13-C(iii): POSTERIOR SAMPLE CURATION — FTE-months: 2.0

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

TASK Op-3.13-C(iv): WAVEFORM RECONSTRUCTION — FTE-months: 1.0

Perform waveform reconstruction estimation.

ACTIVITY Op-3.13-D: RATE ESTIMATION

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

TASK Op-3.13-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-3.13-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-3.13-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.13-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-3.13-E(ii): PAPER WRITING COORDINATION FTE-months: 6.0

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

TASK Op-3.13-E(iii): FIGURE PREPARATION FTE-months: 3.0

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

TASK Op-3.13-E(iv): SCIENCE SUMMARY AND DATA RELEASE FTE-months: 1.0

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

ACTIVITY Op-3.13-F: TECHNICAL REVIEW

TASK Op-3.13-F(i): TECHNICAL REVIEW COORDINATION FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.13-F(ii): REVIEW OF GSTLAL PIPELINE SEARCH RESULTS FTE-months: 1.0

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

TASK Op-3.13-F(iii): REVIEW OF PYCBC PIPELINE SEARCH RESULTS FTE-months: 1.0

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

TASK Op-3.13-F(iv): REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES FTE-months: 1.0

Review of Parameter Estimation posterior sample chains.

ACTIVITY Op-3.13-G: PAPER REVIEW

TASK Op-3.13-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT

FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK Op-3.13-G(ii): EDITING

FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

Expected products and/or outcomes

- Catalog update publication of new events in O3a: April, 2020 (submit to arXiv and journal).
- Full trigger list including sub-threshold events: April, 2020 (DCC).
- Posterior samples for new significant catalog events in O3a: April, 2020 (GWOSC).
- Data behind the figures appearing in O3a sub-threshold catalog update: April, 2020 (DCC).

Op-3.14 O3b Sub-Threshold Search for Compact Binaries

Update a catalog of compact binary coalescence candidate with a deeper search for subthreshold signals observed during O3b along with parameter estimates and rate estimates.

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. Sub-threshold candidates can be used in statistical analyses with other astrophysical datasets. Pipeline improvements subsequent to initial catalog results can result in new detections.

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 update our catalog of detections made during O3b and release a detailed description of all new detected systems, covering their detection and physical parameters, inferred using the best available waveform models, as well as provide a list of subthreshold triggers recovered by the pipelines.

In O3b 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.

For each event, both clear and marginal detections (but not subthreshold), 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 O3b, 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 as well as a list of subthreshold triggers.

ACTIVITY Op-3.14-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-3.14-A(i): GSTLAL PIPELINE OPERATION — FTE-months: 12.0

Offline running of the GstLAL search over O3b data chunks.

TASK Op-3.14-A(ii): PYCBC PIPELINE OPERATION — FTE-months: 6.0

Offline running of the PyCBC search over O3b data chunks.

ACTIVITY Op-3.14-B: DATA QUALITY

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

TASK Op-3.14-B(i): DETECTOR CHARACTERIZATION ROTA — FTE-months: 2.0

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

ACTIVITY Op-3.14-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-3.14-C(i): PARAMETER ESTIMATION EVENT ROTA — FTE-months: 12.0

Run parameter estimation pipeline on each new significant candidate event.

TASK Op-3.14-C(ii): PARAMETER ESTIMATION EXPERT ROTA — FTE-months: 6.0

Supervise parameter estimation event rota efforts.

Certify validity of sample chains.

TASK Op-3.14-C(iii): POSTERIOR SAMPLE CURATION — FTE-months: 2.0

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

TASK Op-3.14-C(iv): WAVEFORM RECONSTRUCTION — FTE-months: 1.0

Perform waveform reconstruction estimation.

ACTIVITY Op-3.14-D: RATE ESTIMATION

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

TASK Op-3.14-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-3.14-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-3.14-E: Editorial Team

Paper project management and writing.

Task Op-3.14-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-3.14-E(ii): Paper Writing Coordination

FTE-months: 6.0

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

Task Op-3.14-E(iii): Figure Preparation

FTE-months: 3.0

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

Task Op-3.14-E(iv): Science Summary and Data Release

FTE-months: 1.0

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

Activity Op-3.14-F: Technical Review

Task Op-3.14-F(i): Technical Review Coordination

FTE-months: 1.0

Coordinate technical review activities.

Task Op-3.14-F(ii): Review of GstLAL Pipeline Search Results

FTE-months: 1.0

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

Task Op-3.14-F(iii): Review of PyCBC Pipeline Search Results

FTE-months: 1.0

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

Task Op-3.14-F(iv): Review of Parameter Estimation Posterior Samples

FTE-months: 1.0

Review of Parameter Estimation posterior sample chains.

Activity Op-3.14-G: Paper Review

Task Op-3.14-G(i): Review of Paper Scientific Content

FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

Task Op-3.14-G(ii): Editing

FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

Expected products and/or outcomes

- Catalog update publication of new events in O3b: October, 2020 (submit to arXiv and journal).
- Full trigger list including sub-threshold events: October, 2020 (DCC).
- Posterior samples for new significant catalog events in O3b: October, 2020 (GWOSC).
- Data behind the figures appearing in O3b sub-threshold catalog update: 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 [29] less the gravitational binding energy. Current models and observations place the minimum neutron star mass near $\sim 1.15\ M_{\odot}$ [30, 31, 32]. The lightest black holes are constrained by the maximum non-rotating neutron star mass, which is currently believed to be $\sim 2\ M_{\odot}$ [33].

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 [34]. The size and abundance of primordial black holes is closely related to the early universe equation of state and the scale of the primordial perturbations [35, 36, 37, 38]. Another class of models links sub-solar mass black holes to particulate dark matter, either via a complex particle spectrum [39] or nuclear interactions with neutron stars [40, 41, 42, 43, 44, 45, 46].

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: INTERPRETATIONS OF SEARCH RESULTS

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(i): RATE ESTIMATION — FTE-months: 2.0

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): PARAMETER ESTIMATION FTE-months: 2.0 ((only for detection))

In the event of a detection, we will perform parameter estimation.

ACTIVITY Op-3.15-C: EDITORIAL TEAM

Paper project management and writing.

TASK Op-3.15-C(i): PROJECT MANAGEMENT FTE-months: 3.0

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

TASK Op-3.15-C(ii): PAPER WRITING COORDINATION FTE-months: 2.0

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

TASK Op-3.15-C(iii): FIGURE PREPARATION FTE-months: 1.0

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

TASK Op-3.15-C(iv): SCIENCE SUMMARY AND DATA RELEASE FTE-months: 1.0

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

ACTIVITY Op-3.15-D: TECHNICAL REVIEW

TASK Op-3.15-D(i): TECHNICAL REVIEW COORDINATION FTE-months: 1.0

Coordinate technical review activities.

TASK Op-3.15-D(ii): REVIEW OF SEARCH RESULTS FTE-months: 1.0

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

TASK Op-3.15-D(iii): REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES FTE-months: 1.0

Review of Parameter Estimation posterior sample chains.

ACTIVITY Op-3.15-E: PAPER REVIEW

TASK Op-3.15-E(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 1.0

Publications & Presentations review of scientific content in Catalog paper.

TASK Op-3.15-E(ii): EDITING FTE-months: 0.2

Editorial Board review of paper quality in Catalog paper.

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. 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;
- measurement of a high-spin system;
- measurement of black hole quasi-normal 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: 12.0 (12 months per exceptional event paper)

Expected products and/or outcomes

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

4 CW Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Stochastic group in section 10.

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 [47]).

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 [48]. 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 [49], the 5-vector method [50], and the time-domain $\mathcal{F}/\mathcal{G}$-statistic method [47]. 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 [51, 52]. 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. [53]), 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 all the 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.

ACTIVITY Op-4.1-C: FULL O3 TARGETED J0537-6910 PAPER

The large spin-down luminosity and observed phase evolution of this pulsar mean that it stands out as a high value target compared to many other pulsars that will be included in a full O3 targeted search. The upcoming release of a NICER ephemeris for the pulsar means that a quick and timely analysis of this source is possible. A standalone paper would highlight the astrophysical importance of this source and allow a quick turnaround time.

TASK Op-4.1-C(i): OBTAIN PULSAR EPHEMERIDES

FTE-months: 3.0

Obtain timing ephemerides from electromagnetic observers for J0537-6910.

TASK Op-4.1-C(ii): RUN TIME-DOMAIN BAYESIAN PIPELINE

FTE-months: 3.0

Run the time-domain Bayesian pipeline on J0537-6910.

TASK Op-4.1-C(iii): 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 [54]. 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 [55] used in target searches, and one based on the $\mathcal{F}$-statistic [51], 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 [56].

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 [57, 58].

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 [49] 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 [59], either as fully coherent [60, 61, 62] or semi-coherent [63] 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 [64], 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 [65].

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 [66]. 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 FTE-months: 3.0

Select a list of sources for directed searches.

TASK Op-4.4-A(ii): RUN SEARCH AND POST-PROCESSING FTE-months: 3.0

Run directed searches using multiple pipelines, identify and follow up candidates, and veto outliers caused by instrumental artifacts.

TASK Op-4.4-A(iii): SET UPPER LIMITS FTE-months: 3.0

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK Op-4.4-A(iv): REVIEW SEARCH RESULTS FTE-months: 3.0

Review the search procedure and results.

TASK Op-4.4-A(v): PUBLICATION FTE-months: 3.0

Produce a publication presenting the results.

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 [67]. 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 [68, 69, 70], doubly-Fourier transformed data (TwoSpect; [71]), hidden Markov models (Viterbi; [72, 73, 74]), coherent summation of matched-filter sidebands (Sideband; [75]), and a resampling procedure, which is a generalization of the 5-vector method [76]. 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 [77].

Activities for O3

ACTIVITY Op-4.5-A: FULL O3 SCORPIUS X-1 PAPER

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 INCREMENTAL VITERBI SEARCHES FTE-months: 1.0

Run Viterbi search to analyze data as soon as calibrated, cleaned, and gated data becomes available – even if these products are only subsets of the full run – to generate a list of candidates to follow up.

TASK Op-4.5-A(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-A(iii): 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(iv): 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(v): 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(vi): 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(vii): 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

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 [78, 79, 80, 81, 82].

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 [83] 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 [66]. 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

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 — FTE-months: 3.0

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK Op-4.6-A(iii): REVIEW SEARCH RESULTS — FTE-months: 3.0

Review the search procedure and results.

TASK Op-4.6-A(iv): PUBLICATION — FTE-months: 3.0

Produce a publication presenting the results.

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 [84] 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 [85] is capable of improved sensitivity at greater computational cost. FrequencyHough [86] and SkyHough [87] are based on different implementations of the Hough transform algorithm and inherit its resilience to contaminated data. The time-domain $\mathcal{F}$-statistic pipeline [88] 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 — FTE-months: 3.0

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.

TASK Op-4.7-A(ii): RUN TIME-DOMAIN $\mathcal{F}$-STATISTIC PIPELINE — FTE-months: 3.0

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.

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

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 [89], which relies on doubly-Fourier transformed data, was the first method applied to LIGO and Virgo data to perform an all-sky search for unknown sources in binaries [90]. TwoSpect allows for a broad range of parameter space to covered while maintaining computational efficiency.

The BinarySkyHough is a new pipeline [91] 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 was employed to analyse O2 open data [92].

Activities for O3

ACTIVITY Op-4.8-A: EARLY O3 ALL-SKY BINARY PAPER

With the use of expernal computational GPU resources (Spanish Supercomputing Network), we run the existing BinarySkyHough code for unknown CW signals using early O3 data. The parameter space covered a broad frequency band 50-300 Hz, zero spin-down and three binary parameters. The all-sky search used the two stage approach with the same detection statistics (weighted Hough and weighed powers). The search was divided into a low frequency band (50-100Hz) and a high frequency band (100-300Hz). Different binary parameter regions were covered in those bands. Tops lists of candidates have been produced for each 0.125Hz band and sky-patch.

TASK Op-4.8-A(i): IMPROVEMENTS ON POST-PROCESSING — FTE-months: 2.0

Establish an improved clustering procedure and tuning will be set according to theoretical and signal injection studies in a number of frequency bands using both O2 and O3a data, as well as strategies for the determination of the volume in parater to be followed up to minimize computational cost.

TASK Op-4.8-A(ii): POST-PROCESSING AND VETOES — FTE-months: 2.0

Selection of clusters, application of lines veto, multi-detector significance veto, binary modulation "DMOff" veto, and χ^2 veto.

TASK Op-4.8-A(iii): FOLLOW-UP CANDIDATES — FTE-months: 2.0

Follow-up candidates with an adaptation of MCMC Follow-up F-statistic method.

TASK Op-4.8-A(iv): REVIEW — FTE-months: 3.0

This will include code review as well as reviewing search results.

TASK Op-4.8-A(v): 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

CW-derived analysis methods can be used to search for a long-lived neutron star remnant from nearby binary neutron star (BNS) mergers such as GW170817 [26]. 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 [93], longer signals associated with the rapid spindown of a young massive neutron star are well suited for CW-derived methods [94]. 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 [95, 96].

Methods

The parameter space [97, 98], signal morphology and data quality requirements are quite different from other CW searches. Available methods include adaptations of the hidden-Markov-model Viterbi tracking algorithm [99, 100] and the two semi-coherent Hough algorithms [87, 101, 102, 103] to the rapid-spindown waveform model from [104]. It is also possible to combine some of these methods, with a cheaper, more generic method as a first-stage search and a semi-coherent 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 FTE-mo listed 2019-20)

During O3 and future observing runs, CW post-merger experts will be on standby to coordinate, in the event of an interesting nearby BNS detection, 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-DURATION 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 FTE-mo listed 2019-20)

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 FTE-mo listed 2019-20)

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 FTE-mo listed 2019-20)

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 FTE-mo listed 2019-20)

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 FTE-mo listed 2019-20)

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 FTE-mo listed 2019-20)

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 FTE-mo listed 2019-20)

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-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 [105]. The mechanisms behind pulsar glitches are still poorly understood [106] 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 [105, 107] is an efficient method with demonstrated performance on real data [108]. A simple search based on the transient $\mathcal{F}$-statistic method and a setup similar to [108] can be cheaply run for several such targets, with additional development and/or the use of GPUs [107, 109] allowing for either deeper or more searches. For shorter signals with nontrivial frequency evolution, more immediately associated with the glitch event itself, methods similar to those for post-merger searches [99, 100, 101, 103] or from the burst and stochastic domains [6, 110, 16] could also be employed.

Similar to post-merger searches, post-glitch searches face unusual 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 instrumental 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 [111].

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 the 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 in nearby pulsars, beating the indirect energy upper limit may be possible.

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. If the number of promising targets turns out to be limited, inclusion of search results in one of the targeted or narrow-band papers is also an option.

Op-4.11 Searches for continuous emission from ultra-light boson clouds around black holes

Motivation

Ultra-light boson clouds forming around BH are expected to emit continuous wave (CW) signals over long times. According to theoretical predictions, which are based on several approximations, the emitted signal is monochromatic with a small spin-up. The actual signal could be more complicated due to matter accretion, presence of a binary companion, unpredicted physics, etc. For this reason it is important to develop robust methods that are able to detect long-lasting signals, with (small) spin-up and a finite unknown coherence time. While we have in mind BH/ultra-light boson 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 thousands seconds, has been developed. The procedure is computationally cheap (relative to standard all-sky CW searches) and is designed for an all-sky search [112]. 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 [113]. The first observational constraints on the mass of ultra-light scalar bosons have been set in all-sky [114] and directed [115] searches carried out on LIGO O2 data.

Activities for O3

We will run two searches on O3 data, one all-sky for scalar boson clouds and a directed for vector boson clouds, targeting a few potentially interesting galactic black holes. A directed search for scalar boson clouds around post-merger black holes will be also carried out on, pending person power and identification of interesting targets. These analyses will be collectively described in a single observational paper.

ACTIVITY Op-4.11-A: FULL O3 ULTRA-LIGHT SCALAR BOSON CLOUD ALL-SKY SEARCH

We will run an all-sky search for scalar boson cloud continuous signals, relying on the semi-coherent all-sky pipeline method described above [112], as well as further developments. Candidate follow-up will be based on the Viterbi tracking [113].

TASK Op-4.11-A(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-A(ii): SET CONSTRAINTS FTE-months: 1.0

In the event of no detection, interpret results and set constraints on scalar ultra-light boson mass and other properties.

TASK Op-4.11-A(iii): REVIEW SEARCH RESULTS

FTE-months: 2.0

Review some portions of the analysis pipeline and search results.

TASK Op-4.11-A(iv): PUBLICATION

FTE-months: 1.0

Produce a publication presenting the results.

ACTIVITY Op-4.11-B: FULL O3 ULTRA-LIGHT BOSON CLOUD DIRECTED SEARCH

We are planning to run a directed search for vector boson clouds using the same semi-coherent method of a collection of FFTs [112]. The best targets for this search are Cygnus X-1, LMC X-1 and GRO J1665-40, where a detection or constraint in the region spanning $\sim 30-100$ Hz is possible. In contrast to the all-sky search for scalar bosons, we know the sky position and the orbital parameters of these X-ray binaries, which means that we are able to correct for the expected frequency modulations. We can therefore create a collection of FFTs that are overall longer than those for the all-sky scalar boson search, thus providing (in principle) better sensitivity.

Pending on person power and identification of interesting sources, we will also run a directed search for scalar bosons from selected CBC merger remnants, which are well localized and close in distance, using the Viterbi pipeline [113].

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: 1.0

In the event of no detection, interpret results and set constraints on ultra-light boson mass and other properties.

TASK Op-4.11-B(iii): REVIEW SEARCH RESULTS

FTE-months: 1.0

Review some portions of the analysis pipeline and search results. Note that for the vector boson search the core analysis code is the same as for the all-sky search. Note also that the Viterbi pipeline has been reviewed in previous CW analyses.

In addition to the outlined person power budget, we consider 2 FTE-months for paper writing.

Scientific motivations for a separate search/paper w.r.t. "standard" CW searches

The search for CW signals from boson clouds around spinning black holes is conceptually similar to "standard" searches of CWs from asymmetric spinning neutron stars. Therefore the core data analysis techniques can be shared among them. There are, however, some specificities that we can take into account to improve the boson cloud search. The following points support performing the searches for boson clouds and asymmetrically rotating neutron stars separately. a) In all-sky searches,the simple idea of working with FFT databases of different length allows us to deal with non-monochromatic signals, potentially providing a significant gain in sensitivity, with respect to the standard choice of a fixed FFT duration, as shown in [112]. The feasibility of this approach for boson cloud searches is guaranteed by the small range of frequency derivative values we need to consider. For standard CW searches for spinning neutron stars, the large spin-down range we need to cover prevents us from using this methodology, due to computational cost constraints. b) In all-sky searches, candidates are selected with a "top list" criterion according to which for every frequency band (e.g 0.1 Hz), and every sky position, the two most significant candidates, across the whole spin-down/up range, are chosen. Now, if we should consider the boson cloud search as a particular case of a standard all-sky search, we would select candidates over a spin-down/up range much larger than needed. As a result, there would be a very high probability to select candidates much stronger than those we could choose by running the search only on the restricted spin-up range suitable for boson clouds. This, clearly, implies a net loss in sensitivity: by running a search specifically for bosons we can select weaker candidates, i.e. go "deeper". c) For directed searches, the targets are of course different from those of CW searches for spinning neutron stars.

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 [116] was found to be more effective for candidate follow-up compared to other implementations [117]. Other methods have been developed more specifically for candidate follow-up. A general-purpose follow-up tool has been described recently in [111]. A long-transient add-on to semi-coherent analyses is also available for intermediate follow-up steps [118].

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.

ACTIVITY Op-4.12-C: EXPANDED PARAMETER ESTIMATION FOR NEWLY-DISCOVERED CW SOURCES

If a known radio or X-ray pulsar is seen to be a continuously emitting gravitational wave source, its mass quadruple can be readily estimated from the signal strain and the distance to the pulsar. This distance is usually known reasonably well from dispersion or parallax measurements. If however the source of the gravitational waves is not radio or X-ray loud we need another way to determine its distance if we are to progress further than a simple strain and frequency measurement. For close, bright GW sources we can apply the same annual parallax method used in radio to gravitation observations.

The current targeted parameter estimation code can be adapted to include frequency and its derivative, sky position and parallax (or distance) as constrained parameters, returning estimates of the neutron star's mass quadruple and distance. Of course this process is sensitive to the signal-to-noise ratio and will become increasingly important in A+ and beyond.

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, data folding on integer-second intervals, and self-gating strain data) 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. Identified artifacts are also provided to the open data science center for the benefit of the entire GW community.

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.

Frequent, large transient glitches seen beginning in the O3 Observing Run has motivated data cleaning to excise the loud glitches. Run-averaged strain spectra are strongly degraded below 500 Hz caused by the loud transients. The data must be cleaned in order to prevent degrading search sensitivity and results for CW sources.

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): SPECTRAL ARTIFACT INVESTIGATION AND MITIGATION

FTE-months: - (3 FTE-mo listed under OPS)

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. See OPS O.C.1.4 and O.C.1.7.

TASK Op-4.13-A(ii): GENERATE LIST OF SPECTRAL ARTIFACTS

FTE-months: - (3 FTE-mo listed under OPS)

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. See OPS O.C.1.4.

TASK Op-4.13-A(iii): OUTLIER FOLLOW UP INVESTIGATIONS

FTE-months: - (3 FTE-mo listed under OPS)

Outliers from CW search pipelines may need additional, manual investigation to check for any spectral artifacts as part of CW follow up strategies. See O.C.1.4

ACTIVITY Op-4.13-B: SELF-GATED DATA SET GENERATION

TASK Op-4.13-B(i): GENERATING O3B DATA SET

FTE-months: - (3 FTE-mo listed under OPS)

O3b self-gated strain data set to be generated using final calibrated and cleaned data set. The procedure and methods will be reviewed and documented in a DCC technical note to be publicly available once bulk data is released. See OPS O.C.1.8

TASK Op-4.13-B(ii): AUTOMATED NEAR-REALTIME SELF-GATING

FTE-months: - (3 FTE-mo listed under OPS)

In preparation for the next observing run, a near-realtime automated method must be developed and implemented. This is essential for more rapid investigation of detector characterization. See OPS O.RD.1

ACTIVITY Op-4.13-C: 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-D: 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. See OPS O.C.1.4

ACTIVITY Op-4.13-E: UPGRADING SPECTRAL ARTIFACT IDENTIFICATION/INVESTIGATION SOFTWARE

FTE-months: - (3 FTE-mo listed under OPS)

Software that supports spectral artifact identification and investigation needs to be updated to the latest version of python and supported to be more widely deployed. The software should be stored in the git version control repository. See OPS O.C.1.5

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. In addition, self-gating of $h(t)$ may be required to deal with very loud glitches which contaminate the spectrum when Fourier-transformed. 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 [49] and $\mathcal{F}/\mathcal{G}$-statistic [47] 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 [119]. 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 FTE-months: 3.0

TASK Op-4.14-B(i): VET GATED $h(t)$ FRAMES

Vet gated $h(t)$ frames for any issues before starting SFT/SFDB production.

TASK Op-4.14-B(ii): PRODUCE SFTS

SFT files will be produced for a variety of coherence times and at least two windowing choices (Tukey, Hann). Vet produced SFT files for any issues.

TASK Op-4.14-B(iii): PRODUCE SFDB

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(iv): DISTRIBUTE DATA PRODUCTS

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

FTE-months: 3.0

TASK Op-4.14-C(i): PRODUCE BSD

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

The narrowband heterodyned time series will be produced for a range of pulsars with rotation frequencies $\gtrsim 10$ 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 [120], 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 LVK 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.

[2] https://git.ligo.org/lscsoft/lalsuite
[3] contact+lscsoft-lalsuite-1438-issue-@support.ligo.org

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/LVK 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.

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 [121, 122, 123]. 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 [105, 107] 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 [108]. The method itself can easily support generic transient amplitude evolutions [105], e.g. exponential decay, but the LALSuite code [120] is very slow for these. A much faster GPU implementation is available [107, 109] 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 [124] 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: IMPROVEMENTS TO PYFSTAT FOLLOW-UP TOOLKIT

PyFstat [109] is a package for $\mathcal{F}$-statistic-based data analysis, aimed mostly at candidate followup (see (Section Op-4.12)) and long-duration transients (see (Section Op-4.10)). Ongoing and planned development includes closer interfacing with existing LALPulsar functionality, better support for CW sources in binaries, and possibly migration of the MCMC-based followup methods [111] to the flexible Bilby parameter estimation package [125].

ACTIVITY LT-4.16-H: IMPACTS OF CALIBRATION SYSTEMATIC ERROR AND UNCERTAINTY ON CW SEARCHES

Improved understanding of calibration systematic error and uncertainty is increasingly important, especially when performing parameter estimation on a source signal. It is also important to understand how time- and frequency- dependent errors impact results from CW search pipelines, especially when systematic error may be poorly quantified. As a pilot study, we intend to research the impact of current understanding of calibration error and uncertainty in the O3 era impacts the Viterbi/HMM pipeline. We expect this kind of study could be expanded to include other pipelines. The conclusions of such studies will enable better understanding on usage of different calibration versions and impacts on CW analysis results.

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.

ACTIVITY LT-4.17-B: DEVELOP AND IMPLEMENT THE SOAP PIPELINE.

SOAP [126] is a non-parametric search pipeline which is computationally cheap, returning results within $\mathcal{O}$(hours) after SFTs are generated. The non-parametric nature of the search allows it to identify many different signal types which may not follow the standard CW frequency evolution. We aim to have the code for this pipeline reviewed and apply it to the advanced LIGO observing runs. Further developments include improving the robustness to instrumental lines by using convolutional neural networks to classify the outputs of the search. SOAP can also be applied in detector characterisation, where it can be used to identify instrumental lines. We aim to run this search on advanced LIGO observing runs and integrate this tool into existing instrumental line searches.

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 [127] 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 [53] 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 [128, 129], to veto likely false candidates, etc. We plan to continue efforts to use machine learning to run searches [130], perform parameter estimate [131, 132], and to apply it in new ways.

ACTIVITY LT-4.18-E: NEW SEMI-COHERENT METHOD FOR DIRECTED SEARCHES FOR CONTINUOUS WAVES FROM NEUTRON STARS IN BINARY SYSTEMS

Accreting neutron stars in low-mass X-ray binary systems (LMXB), particularly Sco X-1, are one of the strongest candidates for the future detection of CW signals. A new detection pipeline, namely BinaryWeave, is being developed that is suitable for searching for CW signals from spinning neutron stars in binary systems with known sky position over a wide parameter space. Development and characterization of the pipeline is ongoing. Depending upon its performance, the pipeline would be used in production searches for Sco X-1 and other targets.

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 [133] and all-sky searches for isolated sources [134].

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, DetChar and CW groups in sections 7, 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 [135], phase transitions in the early universe [136, 137], and cosmic (super)strings [138, 139, 140, 141]. 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 [142], binary black holes [143], or black-hole–neutron stars. 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 [143, 142, 144].

General relativity allows only for two gravitational-wave polarizations – the tensor plus and cross modes. Alternative theories, such as scalar-tensor theories [145, 146], $f(R)$ gravity [147, 148], bimetric [149] and massive [150] 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 [151, 152], which has served as the basis for all previous LIGO/Virgo stochastic searches [153, 154, 155, 156, 157, 158]. 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

FTE-months: 22.0 (includes all aspects of the search, review, and paper writing)

(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 neutron star-black hole binaries, (iii) Implement a method to mitigate loud glitches in O3. (iv) Constrain the presence of magnetic noise.

TASK Op-5.1-A(ii): PREPARATIONS FOR O4

FTE-months: 15.0 (includes all aspects of the preparations listed)

Develop and review infrastructure that will support O4 analyses. This includes (i) developing and reviewing a general parameter estimation infrastructure that can support O4 analyses, which can be used for inference of stochastic backgrounds of any spectral shape, and for magnetic noise. (i) performing mock data challenges to verify the detection capabilities of the stochastic search; and (ii) developing statistical techniques to infer properties of the underlying sources in an astrophysical or cosmological background.

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 [159, 142, 160], 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. We will develop methods to infer properties of the underlying compact binary population from a detection of an astrophysical stochastic background, such as the merger rate as a function of redshift. We will also develop methods and carry out a program to compute implications of our observations for models of interest in cosmology, such as phase transitions, cosmic strings, primordial black holes, 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 [161]. 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 such as broken power laws. 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 [162] 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 [163]. 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 [1]. 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 [141, 164, 165, 166, 167, 168, 169]. For example, a confusion background may arise from binary mergers [159, 170, 171], core-collapse supernovae [172, 173], neutron-star excitations [174, 175], persistent emission from neutron stars [176, 177], and compact objects around supermassive black holes [178, 179]. 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 [180]); 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 [181]:

$$\Omega_{\rm GW}(f,\Theta) \equiv \frac{1}{\rho_c}\,\frac{d^3\rho_{\rm GW}}{d\ln f d^2\Theta} = \frac{2\pi^2 f^3}{3H_0^2}\,H(f)P(\Theta), \quad \Omega_{\rm GW}(f) = \int d\Theta\Omega_{\rm GW}(f,\Theta), \tag{2}$$

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 [182, 181, 183] 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

FTE-months: 30.0 (includes all aspects of the search, review, and paper writing)

(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.

TASK Op-5.2-A(ii): ALL-SKY ALL-FREQUENCY (ASAF) SEARCH FOR UNMODELED SOURCES

FTE-months: 22.0 (includes all aspects of the search, review, and paper writing)

Recent work [184] demonstrates that data compression using sidereal folding [185] 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 [186]. 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` [187]. Building on these developments, we plan to perform an all-sky, all-frequency radiometer search using O3 data. The maps can be used to identify patches on the sky to follow up with CW searches [See Section Op-10.1].

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: 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-B: IMPLICATIONS AND PARAMETER ESTIMATION FOR MODELS OF 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 [165, 167], and have applied the formalism to specific cases of the models due to BBH mergers [166, 168, 169, 188, 189, 190, 190, 191] and due to cosmic string networks [167]. We will develop a method of using 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 [164] or in the galactic center [180].

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. [192], 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) [59, 193, 194]. 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 [195], 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 $\Omega_{\rm gw}$ [151] due to transient phenomena. As a baseline, the transient searches are carried out using the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) [196, 197, 198, 199, 200]. STAMP works by cross-correlating data from two detectors to produce cross-power spectrograms [196]. Gravitational-wave signals appear as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [196, 201, 199, 200, 202]) in order to identify statistically significant clusters of pixels. More recently, a highly-parallel seedless clustering algorithm [199, 200] was implemented, and recent work [200] 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 [7, 8].

We will analyze data on timescales of $\approx$ 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 [203]. 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 [94], 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 [204, 205] and follow-up/visualization of CBC triggers [202]. 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.

LT-5.3 Search for very-long transient gravitational-wave signals (Long Term)

TASK LT-5.3-(i): MACHINE LEARNING APPROACH TO IDENTIFYING LONG TRANSIENTS

Explore the use of modern Machine Learning algorithms to parse the cross-power spectrograms with the goal of improving the sensitivity computational efficiency of the search.

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 [185]. 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 [185] 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, `PyStoch`, 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 incorporating data quality cuts

Expected products and/or outcomes

- Folded data for different stochastic analyses for O3
- Data and codes for GWOSC release

6 Burst+CBC Joint Activity Plans

Op-6.1 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

The GW190521 discovery [206] in O3a, representing the first black hole with mass in the pair instability mass gap and the first definitive IMBH, promises to revolutionize this topic. Previously, 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 $\mathrm{M}_\odot$. Meanwhile, massive black holes, exceeding $10^5\ \mathrm{M}_\odot$, appear to be generic in galactic centers. Intermediate-mass black holes (IMBHs) occupy the mass range between these two. IMBHs 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 [207, 208, 209]. These IMBHs may then form binaries and merge with stellar-mass black holses in dense environments. Several channels for IMBH formation were explored in the GW190521 "implications" paper [210].

IMBHs with a mass of a few hundred solar masses may generically exist in globular clusters [211, 212]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [213], or as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [214]. 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 [215]. Binaries including two IMBHs could also form as a result of evolution of isolated binaries with very high initial stellar masses [216].

Detections of additional IMBH systems will serve as probes of globular cluster dynamics, and, potentially, as probes of structure formation and growth of super-massive black holes.

The searches are carried out 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 mis-match 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-6.1-A: O3 SEARCHES AND PUBLICATIONS

In addition to the GW190521 papers, the plan is to publish one paper on IMBHB results for all of O3.

TASK Op-6.1-A(i): NR WAVEFORMS — FTE-months: 5.0

In collaboration with numerical relativity (NR) community, continue development and refinement of the IMBHB NR waveforms for interpretation of the results.

TASK Op-6.1-A(ii): RUN THE OFFLINE PIPELINES — FTE-months: 2.0

Run the IMBH-specific pipelines on the O3 data. Report results regularly.

TASK Op-6.1-A(iii): INTERFACE WITH CBC CATALOGS — FTE-months: 2.0

Report results and contribute to the O3b CBC catalogs and catalog papers.

TASK Op-6.1-A(iv): REVIEW AND PUBLISH RESULTS

FTE-months: 5.0

Collect results and write paper for O3.

TASK Op-6.1-A(v): EXCEPTIONAL EVENTS

FTE-months: 2.0

Follow up any IMBHB candidates. Make the case for or against a single-event LVC/LVK publication. Collect results and write paper.

ACTIVITY Op-6.1-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-6.1-C: SUBGROUP ADMINISTRATION

Management of the IMBHB subgroup.

TASK Op-6.1-C(i): SUBGROUP LEADERSHIP

FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-6.1 Search for GWs from intermediate mass black hole binaries R&D

ACTIVITY LT-6.1-A: NR WAVEFORMS

Continue to work with the numerical relativity (NR) community to develop waveforms for interpretation of IMBHB results.

ACTIVITY LT-6.1-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-6.1-C: SEARCH ALGORITHM UPGRADE

Improve and upgrade CBC/Burst IMBHB search algorithms for upcoming observing runs.

ACTIVITY LT-6.1-D: SENSITIVITY STUDIES

Study the sensitivity of current CBC/Burst searches to precessing IMBHBs using Numerical Relativity Injections.

Op-6.2 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 [217]: 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 [218, 219, 220, 221, 222]. The joint observation of GRB 170817A and GW170817 has confirmed that NS-NS coalescences are the progenitors of at least some short GRBs [223]. Any future coincident observations of GWs and short GRBs would also be a major scientific result, demanding a rapid publication. A possible association should be communicated with low latency to enable follow-up observations of the GRB of interest. Finally, the nature of the post-merger remnant (hypermassive/supramassive NS or BH) can be investigated via searches for post-merger GWs similar to those carried out for the case of GW170817/GRB 170817A [93].

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 [224] in the case of short GRBs, or generic GW burst signals [10] 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 [225] to search online (minutes latency) for coincidences between low-latency, all-sky GW triggers and GRBs. These methods were applied to the full sample of GRBs which occurred during O2[226].

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].

An offline cross-correlation algorithm[227] targeting long-duration GWs from the remnants of exceptional short or long GRBs, potentially in association with EM plateaus, will be used for opportunistic searches.

O3 deliverables

ACTIVITY Op-6.2-A: TRIGGERED GRB SEARCH AND PUBLICATIONS - OFFLINE

The following tasks are necessary for implementing the standard offline, triggered GRB search and to report results. The analysis and publication of results have been carried out separately for O3a and O3b. The work for O3b is in progress.

TASK Op-6.2-A(i): CATALOG THE GRBS FTE-months: 2.0

Collect and catalog the GRBs from Swift, Fermi, and IPN to be used in the triggered searches.

TASK Op-6.2-A(ii): RUN THE SEARCH PIPELINES FTE-months: 3.0

Run the Burst and CBC pipelines on the appropriate GRB triggers, as catalogued above.

TASK Op-6.2-A(iii): COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW FTE-months: 3.0

Report results and prepare publications separately for O3a and O3b.

TASK Op-6.2-A(iv): EXCEPTIONAL EVENTS FTE-months: 4.0

Follow up any exceptional event candidates identified in O3b in the all-sky Burst or CBC searches, or resulting from the above triggered searches. Follow-up will include consideration of any opportunistic search for long duration GWs from GRB remnants. Make the case for or against a single-event publication.

ACTIVITY Op-6.2-B: 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-6.2-B(i): TARGETED SEARCHES FTE-months: 3.0

Define methods and goals for an O3 search.

TASK Op-6.2-B(ii): UNTARGETED SEARCHES FTE-months: 3.0

Define methods and goals for an O3 search.

ACTIVITY Op-6.2-C: PIPELINE DEVELOPMENT FOR O4

A few pipeline development activities are needed well in advance of O4 in order to allow time for testing and review by the start of the run.

TASK Op-6.2-C(i): PYGRB PIPELINE FTE-months: 3.0

Complete development and review of a targeted, coherent matched-filter CBC search which is consistent with the pyCBC framework.

TASK Op-6.2-C(ii): MEDIUM LATENCY FTE-months: 2.0

Prepare and update the online GRB pipeline infrastructure for O4, including any necessary reviews.

ACTIVITY Op-6.2-D: SUBGROUP ADMINISTRATION

Management of the GRB subgroup.

TASK Op-6.2-D(i): SUBGROUP LEADERSHIP FTE-months: 3.0

Administrative and managerial tasks associated with subgroup leadership.

LT-6.2 Multimessenger search for GWs and GRBs R&D

ACTIVITY LT-6.2-A: CBC-GRB PIPELINE

Continue improvements of the pyGRB pipeline, especially to speed up execution times and to improve sensitivity by background reduction.

ACTIVITY LT-6.2-B: MEDIUM LATENCY GRB PIPELINE

Continue development and updating of the infrastructure to run the GRB pipelines online.

ACTIVITY LT-6.2-C: RAVEN

This task is complete for O3. The next task is preparation for O4. FTE contributions are to be included in the OPS White Paper.

ACTIVITY LT-6.2-D: 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-6.2-E: LONG-DURATION SEARCH

For the cross-correlation search, test the feasibility of parameter estimation analyses aimed at ensuring understanding of any parameter correlations, and establishing appropriate probability coverage.

ACTIVITY LT-6.2-F: SUB-THRESHOLD SEARCHES

Continue development of methods to exploit sub-threshold GRBs (from Fermi, Swift) and/or sub-threshold GW triggers.

Op-6.3 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 mostly 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[232]. It is expected that an MOU agreement between LIGO/Virgo and CHIME will become active in time to provide additional FRB triggers which occurred during the O3 run and can be used for the triggered GW analses.

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 [233] 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.

Recently, there was potentially an important clue in the FRB story. In April 2020, galactic magnetar SGR 1935+2154 became very active in x-ray emission. And on April 28 an FRB was observed[234] from this source. The observed fluence provided an estimate for the intrinsic FRB energy which was 1 to 6 orders of magnitude less energetic than previously observed (cosmological) FRBs, but otherwise closely resembled previous FRBs. While this provides credence to the magnetar model of FRBs, it is still unclear how many FRB progenitor classes actually exist in nature.

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-6.3-A: OFFLINE TRIGGERED SEARCH AND PUBLICATION

The following tasks are necessary for implementing the O3 FRB-GW search.

TASK Op-6.3-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-6.3-A(ii): RECONFIGURE, TEST AND RUN THE SEARCH PIPELINES — FTE-months: 5.0

Reconfigure, test, and run the modified GRB Burst and CBC pipelines over the above triggers.

TASK Op-6.3-A(iii): COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW — FTE-months: 5.0

Report results and prepare a publication for O3.

TASK Op-6.3-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-6.4 Search for GW transients from magnetar flares and neutron star glitches

Motivation and methods

Violent phenomena associated with neutron stars, such as flaring activity in magnetars [235, 236, 237] 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 neutron star oscillations holds the potential for GW neutron star asteroseismology, whereby neutron star oscillation mode identification and characterization leads to constraints on the equation of state. Our goals for science deliverables are focused on the improvement of O1-O2 GW emission upper limits [238], 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 [239, 240, 241, 242, 238]. The methods employed overlap with the long-duration burst searches (Section Op-2.2) and the GRB group (Section Op-6.2).

Major deliverables and critical tasks for O3

ACTIVITY Op-6.4-A: MAGNETAR FLARES

TASK Op-6.4-A(i): MONITOR FLARES DATA FTE-months: 1.0

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

TASK Op-6.4-A(ii): RUN TRIGGERED SEARCHES FTE-months: 2.0

Run an unmodeled search for galactic flares or any giant flares in O3. The search should include both short duration (less than about 1 s) and long duration algorithms.

TASK Op-6.4-A(iii): REPORTING RESULTS AND REVIEW FTE-months: 2.0

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 GRB group and periodically to the Burst group.

TASK Op-6.4-A(iv): PUBLISHING RESULTS FTE-months: 2.0

If there is an extraordinary event – e.g. a giant galactic flare or a very nearby ($\sim$ 1 kpc) normal flare – or a significant improvement in upper limits compared to O1-O2 publish a collaboration paper reporting any signals found by the search.

LT-6.4 Search for GW transients from isolated neutron stars R&D (Long Term)

ACTIVITY LT-6.4-A: DEVELOPMENT OF NEW AND IMPROVED METHODS

TASK LT-6.4-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 neutron star observations.

Op-6.5 O3GK Observation Paper

Search for compact binary coalescences, short duration GW bursts, and targeted search for GRBs in GEO and KAGRA data during the O3GK data taking period.

Motivation and goals

This represents the first multi-detector search for gravitational wave signals with the KAGRA detector in a joint GEO and KAGRA data run O3GK. Following the conclusion of the O3b data taking period, KAGRA and GEO operated for two weeks of simultaneous data taking with sensitivities of approximately 1 Mpc and 0.6 Mpc binary neutron star range for GEO and KAGRA. Although it is difficult to derive significant astrophysical results with this sensitivity, since this observation is a milestone for KAGRA, we describe the joint observation and analysis tasks together.

Major aspects and methods for this activity

The search for compact binary coalescences and short duration gravitational wave bursts are done. There are several long and short GRBs occurred during the O3Gk period. The targeted searches for these GRBs are also done.

ACTIVITY Op-6.5-A: OFFLINE SEARCHES

Perform searches of gravitational wave data for compact binary coalescences and unmodeled burst signals using multiple search pipelines.

Note: requires calibrated data and detector characterization.

TASK Op-6.5-A(i): GSTLAL PIPELINE OPERATION — FTE-months: 2.0

Offline running of the GstLAL search over O3GK data chunks.

TASK Op-6.5-A(ii): CWB PIPELINE OPERATION — FTE-months: 2.0

Offline running of the cWB search over O3GK data chunks.

TASK Op-6.5-A(iii): TARGETED GRB SEARCH PIPELINES OPERATION — FTE-months: 2.0

Offline running of the pyGRB and X-Pipeline searches over O3GK data chunks.

ACTIVITY Op-6.5-B: DATA QUALITY

Perform data quality analyses of GEO and KAGRA data.

TASK Op-6.5-B(i): DETECTOR CHARACTERIZATION OF GEO — FTE-months: 0.5

Datector characterization of GEO data during O3GK.

TASK Op-6.5-B(ii): DETECTOR CHARACTERIZATION OF KAGRA — FTE-months: 0.5

Datector characterization of KAGRA data during O3GK.

ACTIVITY Op-6.5-C: OFFLINE PARAMETER ESTIMATION

Perform parameter estimation on most significant event(s) identified by the offline searches.

TASK Op-6.5-C(i): PARAMETER ESTIMATION — FTE-months: 1.0

Run parameter estimation pipeline on most significant event(s).

ACTIVITY Op-6.5-D: SENSITIVITY ESTIMATION

Provide high-level sensitivity statment for source categories (BNS, NSBH, BBH, etc.).

TASK Op-6.5-D(i): SUMMARY OF SURVEYED SPACETIME VOLUME — FTE-months: 6.0

Estimate the surveyed spacetime volume at the significance of the most significant event.

ACTIVITY Op-6.5-E: EDITORIAL TEAM

Paper project management and writing.

TASK Op-6.5-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-6.5-E(ii): PAPER WRITING COORDINATION — FTE-months: 2.0

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

TASK Op-6.5-E(iii): FIGURE PREPARATION FTE-months: 1.0

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

TASK Op-6.5-E(iv): SCIENCE SUMMARY FTE-months: 0.2

- Write science summary.

ACTIVITY Op-6.5-F: TECHNICAL REVIEW

TASK Op-6.5-F(i): TECHNICAL REVIEW COORDINATION FTE-months: 1.0
Coordinate technical review activities.

TASK Op-6.5-F(ii): REVIEW OF GSTLAL PIPELINE SEARCH RESULTS FTE-months: 0.5
Review of GstLAL search results: candidate lists, background estimation, sensitivity.

TASK Op-6.5-F(iii): REVIEW OF CWB PIPELINE SEARCH RESULTS FTE-months: 0.5
Review of cWB search results: candidate lists, background estimation, sensitivity.

TASK Op-6.5-F(iv): REVIEW OF TARGETED GRB PIPELINE SEARCH RESULTS FTE-months: 0.5
Review of targeted search results: candidate lists, background estimation, sensitivity.

TASK Op-6.5-F(v): REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES FTE-months: 0.2
Review of Parameter Estimation posterior sample chains.

ACTIVITY Op-6.5-G: PAPER REVIEW

TASK Op-6.5-G(i): REVIEW OF PAPER SCIENTIFIC CONTENT FTE-months: 1.0
Publications & Presentations review of scientific content in Observation paper.

TASK Op-6.5-G(ii): EDITING FTE-months: 0.2
Editorial Board review of paper quality in Observation paper.

Expected products and/or outcomes

- Paper describing the O3GK run and search results. March, 2021 (submit to arXiv and journal).
- Data behind the figures appearing in O3GK paper: March, 2021 (DCC).

Op-6.6 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) [243, 244]. 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 [245], its surroundings [246], and the nature of relativistic outflows [247, 248]. 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 [249, 250].

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 [251], LVT151012 and GW151226 [252], and GW170817 [253]. 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-6.6-A: CARRY OUT O3 SEARCH

Perform the multimessenger search between GW events and high-energy neutrinos.

TASK Op-6.6-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-6.6-A(ii): 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-6.6-A(iii): EXCEPTIONAL EVENTS — FTE-months: 3.0

In the event of a GW-HEN detection or an astrophysically interesting upper limit, make the case for a single-event publication.

LT-6.6 Multimessenger search for GWs and high-energy neutrinos R&D

ACTIVITY LT-6.6-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.

7 Burst+Stochastic Joint Activity Plans

Op-7.1 Search for GWs from cosmic strings

Motivation and methods

Cosmic strings [254] are one-dimensional topological defects, formed after a spontaneous symmetry phase transition characterized by a vacuum manifold with non-contractible loops [255]. These objects are expected to be generically formed in the context of Grand Unified Theories [256]. Their obervational consequences offer a tool to probe particle physics beyond the Standard Model at energies far above the ones reached at accelerators. 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 [257, 258, 259, 260]. Cosmic strings produced in string-theory-motivated models (dubbed "cosmic superstrings") have received much attention since they could provide observational signatures of string theory [261, 262].

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational-wave emission from loops [263, 264] and long strings [265]. 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. They are transient and produce a beam along a single direction. Kinks are loop discontinuities that form every time intercommuting occurs. They propagate around the string, beaming over a fanlike range of directions. Since long (super-horizon) strings are not straight due to the existence of kinks, they also emit gravitational radiation [265]. Both cusps and kinks produce powerful bursts of gravitational waves [266]. In addition, left- and right-moving colliding kinks will produce a GW spectrum emitted in all directions, this is the dominant mechanism for fairly wiggly strings [267].

Cosmic string GW events are searched individually using matched-filtering techniques or as a stochastic background of all signals in the Universe [268, 156]. 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 bounds are then used to drive further theoretical developments and constrain particle physics beyond the Standard Model as well as early Universe cosmological models.

Major deliverables for this activity

ACTIVITY Op-7.1-A: O3 SEARCH FOR GW BURSTS

TASK Op-7.1-A(i): 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-7.1-A(ii): 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-7.1-B: O3 STOCHASTIC BACKGROUND SEARCH

TASK Op-7.1-B(i): DETERMINE MODEL PARAMATERS — FTE-months: 3.0

Consider the two models supported by numerical simulations for the loop distribution of Goto-Nambu strings. Follow also a (new) agnostic approach, interpolating between the theoretical models, based on [269]. Consider also the (new) kink-kink waveform.

TASK Op-7.1-B(ii): PARAMETER ESTIMATION

FTE-months: 3.0

For the chosen cosmic string models, perform the parameter estimation using the latest (O3) results of the stochastic searches to compute excluded or preferred regions of the parameter space (string tension and number of kinks).

ACTIVITY Op-7.1-C: PUBLICATION

TASK Op-7.1-C(i): DETERMINE PUBLICATION PRODUCT

FTE-months: 12.0

Write a collaboration paper for the O3 data.

LT-7.1 Search for GWs from cosmic strings R&D (Long Term)

ACTIVITY LT-7.1-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-7.1-B: COMPLETE DEVELOPMENT OF NEW SEARCH CODE

Update the pipeline code by implementing methods used in the GstLAL CBC pipeline. This potentially enables a more powerful noise rejection, as well as a better memory management and execution speed.

ACTIVITY LT-7.1-C: 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. It is expected that soon we will be able to improve considerably the cosmic string models we are using and include further effects.

8 Stochastic+CBC Joint Activity Plans

LT-8.1 Search for the stochastic background from unresolvable binary black hole mergers

LT-8.1.1 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 ∼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 [270]), which is optimally-suited to handle the non-stationarity of the expected background from BBH mergers.

LT-8.1.2 Methodology

The search methodology is based on Smith et al. [270] which applies Bayesian parameter estimation to all available data. The search uses the output of parameter estimation code (e.g., Bilby [271]) 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 Bilby. 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 Bilby and this particular glitch model was shown in [270] 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 [270] that the BBH background can be detected using around one day of design sensitivity data. Subsequent work has investigated how the signal from unresolved binaries is distributed in redshift [272]. The same study develops tools to extract the population parameters of unresolved binaries;

see also [273]. Meanwhile, in [274] it was shown that it will be necessary to marginalize over uncertainty in the noise power spectral density to avoid bias in the estimate of duty cycle. 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-8.1-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.
3. Develop the necessary computational tools to be able to search for weak BBH signals at cosmological distances (luminosity distances greater than ~ 15 Gpc).
4. 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-8.1-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.

9 Stochastic+DetChar Joint Activity Plans

Op-9.1 Data quality investigations for stochastic searches

Op-9.1.1 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 of the LSC-Virgo Operations White Paper (Section 4).

Op-9.1.2 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). 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 [275]. The primary sources of these correlated fields are geophysical Schumann resonances [275]. 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.2.7, F.C.3.3) . Noise subtraction techniques, especially with respect to the correlated electromagnetic noise, are being studied [276]. 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-9.1-A: DETECTOR CHARACTERIZATION FOR STOCHASTIC SEARCHES

TASK Op-9.1-A(i): INSTRUMENTAL CORRELATIONS BETWEEN DETECTORS FTE-months: 8.0

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-9.1-A(ii): SCHUMANN RESONANCES

FTE-months: 8.0

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-9.1-A(iii): STUDY OF NOISE IMPACT ON STOCHASTIC SEARCHES

FTE-months: 2.0

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.

LT-9.1 Data quality investigations for stochastic searches (long term)

In addition to the above, there are long-term activities that will be needed for long-term improvements in the sensitivity of the stochastic searches.

ACTIVITY LT-9.1-A: CALIBRATION UNCERTAINTY ASSESSMENT

Perform a set of analytical and numerical studies to understand the impacts of the frequency-dependent systematic error in the calibration estimate on the stochastic searches. This includes the isotropic and directional stochastic searches, as well as estimation of parameters in favored models of the stochastic background. Identify what level of calibration uncertainty starts to dominate the sensitivity of the stochastic searches and of the parameter estimation studies, and identify the frequency band(s) in which understanding the calibration errors is particularly important.

10 Stochastic+CW Joint Activity Plans

Op-10.1 Identification and follow-up of outliers in All-Sky All-Frequency (ASAF) skymaps

Motivation

Performing all-sky searches for continuous gravitational wave sources is an important goal of gravitational wave astronomy. Significant trade-offs between sensitivity against computational costs must be considered. Continuous wave analyses carry out optimal targeted searches for known sources or use a variety of different hierarchical search strategies, depending on the amount of information known for a putative source. Unmodeled, radiometer-style searches reaching maturity in stochastic gravitational wave searches are comparatively computationally inexpensive. A novel technique to aid rapid analysis of detector data is to combine CW and stochastic searches in a hierarchical search. This can be achieved by utilising the sky-maps produced by the ASAF analysis [184] on folded data [185].

Methodology

The goal is to perform fast ("quick-look") all-sky analysis for continuous wave signals, even though the expected sensitivity will be less than other, dedicated searches. The ASAF radiometer search is presently being carried out on folded O3 data using `PyStoch` [187] which produces a full sky- map at every frequency bin. Those regions of parameter space (sky locations and frequencies) that produce interesting outliers will be passed to continuous wave searches for follow up under the assumption that the outlier may be due to a rapidly rotating neutron star or possibly a boson cloud surrounding a black hole.

It is expected that model-agnostic continuous wave searches (such as the Viterbi/Hidden Markov Model searches) will be used to first confirm or reject the outliers, any remaining candidates would be subsequently followed up using analyses that place further constraints on the long duration waveform coherence.

Activities for O3

ACTIVITY Op-10.1-A: IMPLEMENTATION AND MOCK DATA CHALLENGE VALIDATION

TASK Op-10.1-A(i): IDENTIFICATION OF ASAF OUTLIERS — FTE-months: 8.0

Development of a reliable statistic to identify patches on the sky for follow up and share the coordinates of the patches in a readily usable format. This may depend on the parameters used for the searches. It may be possible make the information more robust by combining results of activities with similar goals.

TASK Op-10.1-A(ii): FOLLOW-UP OF ASAF OUTLIERS AND SET UPPER LIMITS — FTE-months: 12.0

Develop and implement a sensible strategy to follow up ASAF outliers using CW searches, especially to understand how much parameter space to explore around a given outlier. Explore methods to put more stringent upper limits on physical parameters. Understand the upper limit procedure.

ACTIVITY Op-10.1-B: O3 ANALYSIS

TASK Op-10.1-B(i): ANALYZE THE ASAF SEARCH FOR OUTLIERS — FTE-months: 3.0

Using the ranking statistic developed using mock data validation, identify outliers and parameter space to be passed to the CW stage for follow up

TASK Op-10.1-B(ii): FOLLOW UP OUTLIERS USING CW ANALYSES FTE-months: 3.0

Process the outliers using the follow up procedures developed using the mock data validation.

TASK Op-10.1-B(iii): SET UPPER LIMITS FTE-months: 3.0

In the event of no detection, set an averaged population based upper limit on the gravitational-wave strain amplitude and derive astrophysical implications.

TASK Op-10.1-B(iv): REVIEW FTE-months: 3.0

Review search set up, code, scripts, and results.

TASK Op-10.1-B(v): PUBLICATION FTE-months: 3.0

In the event of interesting results (such as a candidate signal) prepare a stand-alone publication with input from both the CW and Stochastic groups. Otherwise, prepare for inclusion into relevant publication, perhaps the full-O3 all-sky CW paper and/or an O3 all-sky radiometer paper.

A Total FTE Commitments

Activity Plan		FTE-months Op	FTE-months LT
Overview and Executive Summary		72.0	-
Op-2.1:	Search for short-duration GW bursts	18.5	-
LT-2.1:	Search for short-duration GW bursts R&D (Long Term)	-	-
Op-2.2:	Search for long-duration GW bursts	2.0	-
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	21.0	-
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	2.0	-
LT-2.4:	GW burst signal characterization R&D (Long Term)	-	-
Op-2.5:	Search for GWs from core-collapse supernova	3.5	-
LT-2.5:	Search for GWs from core-collapse supernova R&D (long term)	-	-
Subtotal for Burst Group Activity Plans		47.0	3.0
Op-3.1:	CBC Parameter Estimation R&D (Short Term)	55.0	-
LT-3.1:	CBC Parameter Estimation R&D (Long Term)	-	-
Op-3.2:	Tests of General Relativity R&D (Short Term)	28.0	-
LT-3.2:	Tests of General Relativity R&D (Long Term)	-	-
Op-3.3:	Studies of Extreme Matter R&D (Short Term)	2.0	-
LT-3.3:	Studies of Extreme Matter R&D (Long Term)	-	-
Op-3.4:	CBC Waveform Models R&D (Short Term)	267.0	-
LT-3.4:	CBC Waveform Models R&D (Long Term)	-	-
Op-3.5:	Binary Coalescence Rates and Population R&D (Short Term)	61.0	-
LT-3.5:	Binary Coalescence Rates and Population R&D (Long Term)	-	14.0
Op-3.6:	CBC Cosmology R&D (Short Term)	98.0	-
LT-3.6:	CBC Cosmology R&D (Long Term)	-	24.0
Op-3.7:	CBC All Sky Search InfraOps R&D	288.0	-
LT-3.7:	CBC All Sky Search R&D (Long Term)	-	-
Op-3.8:	O3b Catalog of Compact Binaries	83.2	-
Op-3.9:	O3b Astrophysical Distribution of Compact Binaries	41.7	-
Op-3.10:	O3b Strong-Field Tests of General Relativity	33.2	-
Op-3.11:	O3 Hubble Constant Measurements	48.2	-
Op-3.12:	O3 Search for Lensed Gravitational Waves	26.7	-
Op-3.13:	O3a Sub-Threshold Search for Compact Binaries	71.2	-
Op-3.14:	O3b Sub-Threshold Search for Compact Binaries	71.2	-
Op-3.15:	Search for sub-solar-mass compact binary coalescences	21.2	-
Op-3.16:	Characterizing exceptional CBC events	12.0	-
Subtotal for CBC Group Activity Plans		1207.6	38.0
Op-4.1:	Targeted searches for known pulsars	45.0	-
Op-4.2:	Narrow-band searches for known pulsars	30.0	-
Op-4.3:	Targeted searches for non-tensorial emission from known pulsars	9.0	-

Activity Plan		FTE-months Op	LT
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	31.0	-
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	15.0	-
Op-4.9:	Searches for long-transient emission from a post-merger neutron star	-	-
Op-4.10:	Searches for long-transient emission following a pulsar glitch	24.0	-
Op-4.11:	Searches for continuous emission from ultra-light boson clouds around black holes	12.0	-
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	6.0	-
Op-4.14:	Support for continuous wave searches: Data preparation	9.0	-
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		256.0	-
Op-5.1:	Search for an isotropic stochastic gravitational-wave background (short term)	37.0	-
LT-5.1:	Search for an isotropic stochastic gravitational-wave background (long term)	-	-
Op-5.2:	Directional searches for persistent gravitational waves (short term)	52.0	-
LT-5.2:	Directional searches for persistent gravitational waves (long term)	-	-
Op-5.3:	Search for very-long transient gravitational-wave signals	10.0	-
LT-5.3:	Search for very-long transient gravitational-wave signals (Long Term)	-	-
Op-5.4:	Data Folding for Efficient Searches of Stochastic Gravitational-Wave Background	2.0	-
Subtotal for Stochastic Group Activity Plans		101.0	-
Op-6.1:	Search for GWs from intermediate mass black hole binaries	19.0	-
LT-6.1:	Search for GWs from intermediate mass black hole binaries R&D	-	-
Op-6.2:	Multimessenger search for GWs and GRBs	26.0	-
LT-6.2:	Multimessenger search for GWs and GRBs R&D	-	-
Op-6.3:	Multimessenger search for GWs and fast radio bursts	16.0	-
Op-6.4:	Search for GW transients from magnetar flares and neutron star glitches	7.0	-
LT-6.4:	Search for GW transients from isolated neutron stars R&D (Long Term)	-	-
Op-6.5:	O3GK Observation Paper	23.1	-
Op-6.6:	Multimessenger search for GWs and high-energy neutrinos	11.0	-
LT-6.6:	Multimessenger search for GWs and high-energy neutrinos R&D	-	-
Subtotal for Burst+CBC Joint Activity Plans		102.1	-
Op-7.1:	Search for GWs from cosmic strings	26.0	-

Activity Plan		FTE-months Op	LT
LT-7.1:	Search for GWs from cosmic strings R&D (Long Term)	-	-
Subtotal for Burst+Stochastic Joint Activity Plans		26.0	-
LT-8.1:	Search for the stochastic background from unresolvable binary black hole mergers	-	-
Subtotal for Stochastic+CBC Joint Activity Plans		-	-
Op-9.1:	Data quality investigations for stochastic searches	18.0	-
LT-9.1:	Data quality investigations for stochastic searches (long term)	-	-
Subtotal for Stochastic+DetChar Joint Activity Plans		18.0	-
Op-10.1:	Identification and follow-up of outliers in All-Sky All-Frequency (ASAF) skymaps	35.0	-
Subtotal for Stochastic+CW Joint Activity Plans		35.0	-
Grand Total		1864.7	41.0

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