

LIGO SCIENTIFIC COLLABORATION  
VIRGO COLLABORATION

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<b>EXECUTIVE SUMMARY</b> <b>from the LSC-Virgo White Paper on</b> <b>Gravitational Wave Data Analysis and Astrophysics</b> <b>(Summer 2019 edition)</b>	
The LSC-Virgo Data Analysis Working Groups and Data Analysis Council	

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

## 1 Overview and Executive Summary

Gravitational wave (GW) searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo Collaboration are organized into four working groups. The **Compact Binary Coalescence (CBC)** group searches for and studies signals from merging neutron stars and black holes by filtering the data with waveform templates. The **Burst** group searches for generic gravitational wave transients with minimal assumption on the source or signal morphology. The **Continuous Waves (CW)** group targets periodic signatures from rotating neutron stars. The **Stochastic Gravitational-Wave Background (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin.

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

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

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

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

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

This document is the executive summary of the 2019 *LSC-Virgo White Paper on GW Data Analysis and Astrophysics*.

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

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

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

## Scientific Operations and Observational Results

LSC-Virgo scientific activities which we plan to implement in the production of observational results of the current Observing run 3 are summarized in Table 2, by search group, and prioritized in three categories:

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

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

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

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

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

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

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

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

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

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

## 1.1 Searches for Generic Transients, or Bursts

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

For example, the complexity of supernovae makes it difficult to reliably map the dynamics of a core-collapse into a gravitational-wave signal. The merger of precessing intermediate-mass black holes ( $\geq 100 M_{\odot}$ ) 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  $\gamma$ -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.
- **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.
- **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.
- **Searches without templates from GWs from binary black holes:** Although most expected BBH mergers will also be detected with CBC searches, burst algorithms are sensitive to a range of features not included in current template banks, including higher order modes, eccentricity, and spin precession. This is important to detect some classes of BBH events. Deliverables include the results of searches targeting both stellar mass and intermediate mass ( $M > 100 M_{\odot}$ ) black hole systems, with results to be included in papers written jointly with the CBC group.
- **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.

#### 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.
- **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.
- **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.

Several of these science targets – including binary black hole mergers, gamma-ray bursts, and low-latency trigger production – overlap with the CBC group, while others – including long transient and cosmic string

searches – overlap with the stochastic group. Joint teams are working together across the multiple groups on these targets.

### 1.1.2 *Advanced Analysis Methods for Advancing Frontiers*

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

#### 1. **Essential**

- **Improvement of existing pipelines and methods for GW burst searches:** The group will maintain and improve the pipelines employed in GW burst searches and the methods used to produce high-priority results. Deliverables include technical notes and papers describing these improvements.
- **Plans for the detection of exceptional multi-messenger sources:** In advance of an exceptional astrophysical event, the group will make plans for what types of statements to make in case of a multi-messenger detection, and develop software that will be used to produce the results.

#### 2. **Exploratory**

- **Development of new methods for GW burst searches:** The group will develop new methods and software to look for GW burst signals. Deliverables include technical notes and papers describing the algorithms and data analysis methods. Examples include searches for GW bursts with polarization states not allowed by General Relativity, GW memory effects and machine learning algorithms.

## 1.2 **Searches for Signals from Compact Binary Coalescences**

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

The range of scientific activities pursued by the CBC group requires us to prioritize our goals. In the regime of increasing detection frequency over the coming observing runs, we must strike a balance between exploitation of established classes of sources and preparing for detection of new source classes. Achieving these goals requires the group to prioritize the continued research and development of our tools and methods for source detection, estimation of parameters, inference of rates and populations, probing fundamental physics and modeling of waveforms with analytical and numerical relativity. We will continue to develop our search pipelines to improve their sensitivity to quiet sources by improvements in detection statistics,

understanding of the noise background and rigorous understanding of data quality. A tremendous human effort is required to develop, deploy, run and interpret the results of low-latency and offline searches in the context of evolving detector sensitivity and data quality. Additionally, the CBC group maintains an active collaboration with a broader community to enhance the impact of our discoveries on theoretical astrophysics and the electromagnetic and astroparticle observing communities.

### 1.2.1 *Scientific Operations and O3 Observational results*

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

#### 1. **Highest priority**

- **Responding to exceptional events.**

We must be prepared to detect and respond to novel sources of extraordinary scientific importance. We define these as sources that yield significant new astrophysics and would warrant a rapid stand-alone publication. These would naturally include new detections of binary neutron stars, the first detection of a neutron-star + black-hole binary, or intermediate-mass or sub-solar mass binary systems. We also anticipate examples in which measurement of a source's parameters (e.g., masses and spins) could provide significant constraints on its formation channel or our understanding of stellar evolution (e.g., the possible existence of gaps in the black hole mass distribution, minimum or maximum neutron star mass). Other examples could include sources which are exceptionally loud and allow us to measure the source physics with unprecedented precision, thereby providing exceptional constraints on general relativity, or, for binaries containing a neutron star, improved measurement of the nuclear equation of state. Binaries with observed electromagnetic counterparts can significantly improve our estimate of Hubble constant using the standard-siren distance estimate.

- **Producing a catalogue of detected compact binaries.**

We will produce a summary of all compact binaries detected during each observing run in order to provide a reference for the astrophysics community with details of the detected source's physical parameters, notable properties, and waveform estimates. This requires a good understanding of systematic errors, including waveform modelling errors. We will continue to reduce our sources of systematic errors by improving our waveform modeling with comparison to numerical relativity simulations. The catalog completeness will be improved by including uncertain signals along with their estimated significance.

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

- **Characterizing the astrophysical distributions of compact objects.**

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

- **Testing general relativity.**

The final stages of compact binary coalescence provide a unique window into the behavior of gravity in the strong-field, high-velocity regime. We will continue to develop the range of tests

we are able to perform on our detections, ensuring their robustness through comparison to numerical relativity simulations where possible. We will develop methods of combining multiple detections to place better constraints on the theory, and test specific predictions from general relativity such as the no-hair and area theorems, Lorentz violations of the graviton, and the speed of gravitational waves. As more detectors are added to the network we will also be able to make improved tests of the polarization states of gravitational waves.

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

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

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

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

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

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

- **Determination of the Hubble constant.**

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

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

## 2. High priority

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

- **Improved searches for intermediate mass black hole binaries & intermediate mass-ratio inspirals.**

A goal of the CBC group is to search for intermediate mass black hole binaries. Especially at the highest masses, the success of any search will be sensitive to the effects of higher order modes and precession in the waveforms. An extension of the intermediate mass black hole binaries research is the development of refined searches for intermediate-mass-ratio inspirals and waveforms to describe them.

- **Search for sub-solar mass compact binary coalescences.**

A speculative source is black hole binaries (or other compact object binaries) having component masses below one solar mass. Primordial black holes could be one channel by which such systems are formed, but there are other possibilities. Such systems might possibly constitute some fraction of the dark matter. A search for sub-solar mass binaries could reveal the existence of a new class of object, or place stronger constraints on the fraction of dark matter explained by sub-solar mass black hole binaries.

### 3. Additional priority

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

- **Multimessenger search for gravitational waves associated with fast radio bursts and high-energy neutrinos.**

It is possible that fast radio bursts and high-energy neutrinos are produced during compact binary coalescence. The method for performing deep searches for gravitational waves associated with gamma-ray bursts can be extended to explore periods of time around triggers produced by fast radio bursts or high-energy neutrinos. Though the methods are similar, the time window to be explored will need to be reassessed.

- **Stochastic background of gravitational waves from compact binary coalescences.**

The superposition of a large number of weak signals arising from compact binary coalescences in the distant universe will produce a stochastic background of gravitational radiation. Such a background produced by binary black hole mergers is not truly continuous, though, as it originates from discrete signals that are not fully overlapping in time, and an optimized statistical search for such sub-threshold signals will be pursued.

#### 1.2.2 Advanced Analysis Methods for Advancing Frontiers

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

##### 1. Essential

- **Parameter Estimation Acceleration.**

Parameter estimation engines need to be modernized and optimized to increase their utility, computational performance, and ease of use, in order to handle the future onslaught of events.

- **Essential Improvements to Waveform Models.**

With increasing sensitivity we will become increasingly dependent on highly accurate waveform models. Waveform models that capture sub-dominant modes of emission, improved models of precession, and eccentricity will be developed. In addition, inclusion of additional matter effects, e.g., during the merger and post-merger phases, will be needed for modeling neutron star binary systems. Additionally, the computational performance of waveform simulation will be improved to enable faster parameter estimation.

- **Improved Models of Population Inference.**

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

- **Improvements to Statistical Measurement of the Hubble Constant.**

There are a number of potentially biasing systematic effects present in the statistical method of measuring the Hubble constant. These effects will be studied and methods for mitigating them will be implemented in the cosmology code.

- **Essential Enhancements to All-Sky Searches.**

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

## 2. Exploratory

- **Research and Development in Parameter Estimation Methodology.**

Investigation of new algorithms and optimization has the potential to greatly improve the speed of the parameter estimation code and add scalability to allow for increasing number of parameters and more complex signal models.

- **New Tests for Exotic Black Hole Physics.**

Tests for exotic speculative physics such as black hole mimickers or late time gravitational wave echos from black holes will be explored.

- **Long Term Improvements to Waveform Models.**

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

- **Robust Population Inference with Marginal Events.**

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

- **Real-Time Cosmology Calculation.**

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

- **Exploratory Enhancements to All-Sky Searches.**

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

### 1.3 Searches for Continuous-Wave Signals

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

For known pulsars with measured spin frequencies, frequency derivatives (also known as *spindowns*) and distances, energy conservation sets an upper limit on gravitational wave strain amplitude, known as the *spindown limit*, albeit with significant uncertainties. Searches of LIGO and Virgo data have obtained high-confidence upper limits well below the spindown limits for many pulsars, including the Crab and Vela pulsars; as detector sensitivities improve the number of pulsars for which the spindown limit has been surpassed will continue to increase, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or estimated accretion rates can also be derived. Such indirect limits are more optimistic for non-accreting stars, but accreting neutron stars are more likely to be emitting near their limits.

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

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

*Searches for known pulsars* use known ephemerides from radio, X-ray or  $\gamma$ -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 than 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 built 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, then 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, could target emission from e.g. a remnant neutron star formed in a binary neutron star coalescence, or following a pulsar glitch. *Axion clouds around black holes* may also produce long-lived continuous wave signals.

### 1.3.1 Scientific Operations and O3 Observational Results

The CW group plans to undertake a comprehensive search program over the course of the O3 observing run, which is reflected in the following list of priority activities. The prioritization of each activity into different classes is arrived at by considering a number of factors: i) the prior likelihood of detecting a particular category of source; ii) the sensitivity achievable by searches targeting that source category, which in many cases is restricted by their computational cost; and iii) available human resources needed to produce 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 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 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 and Scorpius X-1.

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

## 2. High priority

- Targeted searches for known pulsars for which the spindown limit is unlikely to be surpassed.<sup>1</sup>
- Targeted searches for known pulsars sensitive to non-tensor polarizations.
- Directed searches for other point sources of interest, including but not limited to: galactic supernova remnants, sources in low-mass X-ray binaries, sources near the Galactic center, and sources in nearby globular clusters.
- Long-transient searches for emission from post-merger neutron stars at estimated distances larger than GW170817.

## 3. Additional priority

- Searches for long-lived transient emission following a pulsar glitch.
- Searches for continuous emission from axion clouds around black holes.

### 1.3.2 Advanced Analysis Methods for Advancing Frontiers

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

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

### 1. Essential

- Further improvement and optimization of existing data analysis pipelines.
- Development of model-robust/agnostic data analysis methods.

### 2. Exploratory

- Development of new and potentially more sensitive data analysis methods.
- Use mock data challenges to compare data analysis pipelines.

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<sup>1</sup>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.

## 1.4 Searches for Stochastic Backgrounds

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

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

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 interpreting 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  $\sim 100$ . This will facilitate the application of more computationally-expensive stochastic searches like the all-sky all-frequency radiometer and searches for parameterized anisotropy.

### 1.4.2 Advanced Analysis Methods for Advancing Frontiers

#### 1. Essential

- **Stochastic background from compact binary coalescences.** Implement and test an optimal Bayesian search for the nonstationary background produced by individually unresolvable CBC events (e.g., BBH mergers) throughout the universe.
- **Implications and astrophysical modeling.** Develop more accurate theoretical models of astrophysical and cosmological gravitational-wave backgrounds; perform mock data challenges to test the recovery of simulated backgrounds corresponding to different theoretical models, using Bayesian model selection or parameter estimation.
- **Component separation.** Implement frequentist or Bayesian component separation methods to determine the individual spectral contributions to an isotropic gravitational-wave background.
- **All-sky all-frequency search for unmodeled persistent sources.** Implement an all-sky, all-frequency extension of the narrow-band radiometer search that can look for unmodeled persistent GW point sources not conforming to the assumptions made by standard template-based searches.

#### 2. Exploratory

- **Fully Bayesian search.** Implement a fully Bayesian alternative to the standard cross-correlation statistic search for an isotropic stochastic background; compare the fully Bayesian and standard cross-correlation search to see if any information is lost by ignoring auto-correlated components in the covariance matrices.
- **Component separation using narrowband maps.** Develop and implement component separation methods for anisotropic gravitational-wave backgrounds.
- **Models for anisotropic backgrounds.** Develop theoretical models of astrophysical backgrounds; use the measured SGWB anisotropies to constrain such models; correlate SGWB sky maps with electromagnetic tracers of large-scale structure; and search for parametrized models of anisotropic backgrounds.
- **Dark Photon Search.** Develop the search for the dark photon dark matter. This signal is expected to be narrowband and correlated between GW detectors. Start from the existing analysis pipeline, refine it to use theoretical signal template, and apply it to O2 and O3 data.