LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION
KAGRA COLLABORATION

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EXECUTIVE SUMMARY from the LSC-Virgo-KAGRA Observational Science White Paper (Summer 2021 edition)

The LSC-Virgo-KAGRA Observational Science Working Groups

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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*** 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 complete the publication of results from the most recent observing run (O3), to prepare for the next observing run (O4) which is expected to begin in the second half of 2022, and to carry out analyses of the O4 data.
- 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-T2100304, VIR-0790A-21, JGW-T2113065).

This document is the executive summary of the 2021 *LSC-Virgo-KAGRA Observational Science White Paper*.

Achieving the 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 LVK observational science working groups have completed roughly half of the planned analyses from the O3 run and are expecting to complete most or all of the remaining ones before the end of 2021. Working group members will then focus on preparing for O4 data analysis until the O4 run begins, currently expected to be no earlier than June 2022.

Epoch	Run Name	Run Duration	Typical Binary Neutron Star (BNS) Range (Mpc)			$E_{\mathrm{GW}} = 10^{-2} M_\odot c^2$ 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	150–260	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, and published in Living Reviews in Relativity), curated by the LVK Joint Run Planning Committee.

Scientific Operations and Observational Results

LSC-Virgo data analysis activities for Observing run 4 (very similar to the activities for O3) 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-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	All-sky all-frequency search for unmodeled persistent sources
	GW burst signal characterization	Low-latency searches to enable multimessenger astronomy	Long-transient searches for emission from nearby post-merger neutron stars	SGWB implications and modeling
		Multimessenger search for CBC-GRB coincidences	Follow-up searches of any promising candidates found by other searches	Development of python SGWB search pipeline
		Measuring the properties of extreme matter, e.g. the neutron star equation of state	Detector characterization, data preparation, scientific software maintenance	
		Determination of the Hubble constant		
High priority	Multimessenger searches for GW bursts associated with GRBs, fast radio bursts, and high-energy neutrinos.	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	Targeted searches for CW signals with non-tensor polarizations	Data folding for efficient SGWB searches
	All-sky cosmic string search	Search for gravitationally lensed signals from compact binary coalescences	Directed searches for other point sources of interest	
	Optimized algorithms for binary black hole mergers with features well-suited to unmodeled searches.	Improved waveform models for signals expected during the O4 run	Long-transient searches for emission from distant post-merger neutron stars	
Additional priority		Multimessenger searches for binary mergers associated with fast radio bursts and high energy neutrinos	Searches for long-lived transient emission following a known pulsar glitch	Analysis to separate components of a stochastic GW backgroun
		Optimized search for stochastic background of gravitational waves from CBCs	Continuous emission from ultra-light boson clouds around black holes; direct detection of dark photon dark matter	Searching for SGWB-EM sky correlations

Table 2: **Scientific Operations and 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 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.

Depending on the course of development, these enhancements may be used in the analysis of the O4 data, or may be used farther in the future.

	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	Essential improvements to waveform models	Development of model-robust/agnostic data analysis methods	
		Improved models of population inference		
		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	Cross-correlation search for intermittent background
		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		
		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 GW 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 GW bursts typically do not require a well-known or accurate waveform model and are robust against uncertainties in the GW signature. Burst searches are, therefore, sensitive to GW transients from a wide range of progenitors, ranging from known sources such as binary black hole (BBH) mergers, in particular the most massive and loudest ones, to poorly-modeled signals such as core-collapse supernovae (CCSN) as well as gravitational-wave transients that are currently unknown to science such as cosmic strings, neutron star instabilities, fast radio burst and magnetars. 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 GW signal. The merger of precessing intermediate-mass black holes ($\geq 100\,\mathrm{M}_{\odot}$) produces GW transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts (GRBs) could be associated with a GW 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 GWs 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 GW 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 GW 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 GW burst detection. Most importantly, joint *multi-messenger* studies of complementary data enable scientific insight that cannot be accessed through GWs or other messengers alone. Therefore, in addition to searches using only the GW 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- and medium-latency, from 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 GW 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 (CBC, CCSN, cosmic strings, etc.) This information can then be used to learn about the nature of the astrophysical source and test different astrophysical scenarios.

1.1.1 Scientific Operations and O4 Observational Results

The Scientific Operations and O4 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, FRB, Magnetar Flare, Neutrino):** In the event of an exceptional GW burst or astrophysical event with a reasonable expectation for detecting GWs, 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 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.

    - **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**

    - **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. The group will pursue a number of searches, both triggered and untriggered. 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.

    - **Optimized algorithms for BBH mergers with features well-suited to unmodeled searches.** The group will optimize burst algorithms to search for new populations of non-vanilla BBH mergers, such as systems with high eccentricity, hyperbolic and parabolic encounters. Deliverables include offline searches for these systems and papers describing the search results.

Several of these science targets – including BBH 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, including the quantification of the significance of a candidate multi-messenger detection of cosmic events, and further 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.

1.2 Searches for Signals from Compact Binary Coalescences

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 coalescences 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 completed 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 reported the discovery of another binary neutron star merger as well as the detection of two coalescing systems comprising a neutron star and a black hole. During O4, we anticipate several detections 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 O4 Observational Results

The Scientific Operations and O4 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, 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.

     Along similar lines, the concrete possibility of detection of hyperbolic captures will require the development of models to be used in templated searches to be run in synergy with unmodeled searches.

- **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 behaviour 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, area theorems and the general nature of merger remnants, 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 searches 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 development 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. Lensing can also 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.

- **Improved waveform models**.

  The O4 run is likely to produce additional interesting CBC events, possibly with higher signal-to-noise ratio or in new regions of parameter space. Development and validation of improved waveform models may be needed to robustly interpret the detected signal or signals.

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 and Automation**.
     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. This will entail management, archiving and interfacing with workflows from other analyses as well as an increase in the level of automation of existing and future pipelines.

   - **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. A new and flexible interface for waveform models will be implemented to harvest the power of modern hardware, like GPUs, and software, such as Machine Learning methods. Such interface will help the need improvements in the computational performance of waveform simulations to enable faster parameter estimation on the scale necessary for O4.

   - **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

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 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 (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 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. *Ultra-light boson clouds around black holes* may also produce long-lived continuous wave signals. A direct detection of *dark photon dark matter* in interferometric gravitational wave detectors is being pursued in collaboration with the Stochastic working group.

1.3.1 Scientific Operations and O3/O4 Observational Results

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. Work on identification and mitigation of spectral noise artifacts (lines or combs) coupling into the calibrated $h(t)$ channel benefits from a close interaction with the detector characterization working group and the site commissioning staff. 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. Frequent, large transient glitches seen beginning in the O3 observing run have motivated the use of data cleaning methods to excise them. The detector response is also validated 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. A set of such signals are monitored daily, weekly and cumulatively during observational runs, and are essential to validate the detector calibration, data cleaning, and other post-processing steps.

The CW group is undertaking a comprehensive search program using data from the O3 and O4 observing runs, 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: the prior likelihood of detecting a particular category of source; the sensitivity achievable by searches targeting that source category, which in many cases is restricted by their computational cost; and 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 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 resources 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 (see the Operations White Paper), data preparation, and scientific software maintenance.

2. **High priority**
    - Targeted searches for known pulsars for which the spindown limit is unlikely to be surpassed. [1]
    - 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 ultra-light boson clouds around black holes.
    - Searches for a direct detection of dark photon dark matter, in collaboration with the Stochastic working group.

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 *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.

[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.

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 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, O2 and O3, results from the isotropic search constrain the energy density of the stochastic background to be $\Omega_0 < 1.7 \times 10^{-8}$ 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, search pipelines targeting popcorn backgrounds are being developed using both the traditional cross-correlation approach as well as the fully Bayesian techniques.

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. We note that collecting information from unresolved binaries at large luminosity distance will also help test the Primordial Black Hole scenario, whose merger rate evolution with redshift is expected to be significantly different from the one of astrophysical black holes.

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 O4 Observational Results

The Scientific Operations and O4 Observational Results priorities of the Stochastic group are:

1. **Highest priority**

   - **Search for an isotropic background.** Analyze the O4 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 O4 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; optimize the search sensitivity in terms of angular resolution, regularization bias, and frequency band used in search; 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 O4 data on the stochastic searches, and pursue approaches to mitigate these sources of noise.
- **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.
- **Development of python-based pipeline for isotropic stochastic background search.** Implement and vet the cross-correlation based search algorithm for the isotropic stochastic gravitational-wave background in python, taking advantage of the existing infrastructure.
- **Implications and gravitational-wave background 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.

2. **High priority**
   - **Search for very long transients.** Analyze the O4 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 O4 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.
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).
   - **Dark matter searches.** Searches for dark photon dark matter in collaboration with Continuous Wave working group.

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**

- **Cross-Correlation Based Search for Intermittent Gravitational-wave Backgrounds.** Develop a search for intermittent (i.e., popcorn-like) stochastic GW backgrounds by modifying the standard cross-correlation search for a stationary-Gaussian background to target short intermittent “bursts" of correlated GW signals.
- **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.

1.5 Working Group Leadership Roles

Each of the four observational science working groups (CBC, Burst, CW, SGWB) is led by Co-Chairs, with at least one from each collaboration. As the collaborations complete analyses from the full O3 data run and prepare to analyze O4 data when it is collected, KAGRA working group chairs will expand their role to lead the joint groups on a more equal basis with the LSC and Virgo co-chairs, and to help all LVK members contribute to a unified science program.

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.