LIGO SCIENTIFIC COLLABORATION

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LIGO Scientific Collaboration Program (2024 Edition)

The LSC Program Committee

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1 Overview

1.1 The LIGO Scientific Collaboration's Scientific Mission

The charter approved in 2020 [1] describes briefly our mission: "The LIGO Scientific Collaboration (LSC) is a self-governing collaboration using gravitational wave detectors to explore the fundamental physics of gravity and observe the universe, as a multimessenger astronomical tool of discovery. The LSC works toward this goal through development, commissioning and operation of gravitational wave detectors; through the development and deployment of techniques for gravitational wave observation; and through interpretation of gravitational wave data."

Member groups of the LSC, specifically the LIGO Laboratory and the GEO Collaboration, operate the Advanced LIGO gravitational wave detectors at Hanford, WA and Livingston, LA, and the GEO 600 detector in Hannover, Germany, respectively. The detectors are laser interferometric gravitational wave interferometers with suspended mirrors, with laser beams traveling 4 km (600 m in the case of GEO 600) in perpendicular arms in each detector, above ground and in vacuum [2, 3]. The LSC works closely with the Virgo Collaboration and KAGRA Scientific Collaboration (together: the LVK), operating gravitational wave detectors to ensure the coordinated operation of the global network of ground-based detectors.

The LSC is engaged in bringing its advanced detectors to their design sensitivity, maintaining their performance, undertaking observing runs, and collecting calibrated gravitational wave data. The Collaboration identifies instrumental artefacts impacting data quality and times of good data quality, develops, maintains and optimizes complex software to perform searches for gravitational wave signals in the LIGO data, and uses analytical calculations or numerical simulations that provide models of the expected signals. Searches for gravitational waves are performed, some in near real time, and alerts are issued to the broader astronomical community to enable multimessenger observations of gravitational wave events. The LSC extracts the details of the gravitational wave signals from the data and presents in publications the measured signal properties and their scientific implications. Following a proprietary period, LIGO strain data from observing runs are made public, enabling other scientists to independently search the data. The Collaboration is engaged in activities aimed at making gravitational wave science accessible to the broader community, including resources for educating school children.

The LSC works to develop new instrumental techniques to improve the sensitivity of the LIGO detectors beyond the Advanced LIGO design, to bring them to the best sensitivity possible within the limits of the LIGO facilities. Among other research, this includes reducing the thermal noise due to optical coating of mirrors, improving the control of the interferometers, manipulating the quantum nature of the light in the interferometers to reduce the quantum noise in the measurement, and further attenuating the effect of environmental noise. The LSC will assist the LIGO India project team to construct the detector at the LIGO Aundha Observatory (LAO) in India and bring it to a comparable sensitivity to the other LIGO detectors to expand the global network. Additionally, the gravitational-wave community, including many LSC members, is planning a future generation of gravitational wave detectors, and many related investigations have goals in common with the LSC mission.

The LSC has more than 1,600 members from over 140 institutions worldwide so significant infrastructure is required to ensure that the Collaboration operates smoothly. This includes collaboration leadership and management, provision of the communications resources enabling the Collaboration to work across multiple time-zones, provision of computing hardware and software to enable gravitational wave searches, and long-term planning for gravitational wave astronomy.

The LSC presents in this program details of its goals, the activities it intends to perform in 2024 and beyond, and the results it intends to deliver to the broader scientific community in pursuit of its mission. More complete details, and a more exhaustive list of activities pursued by LSC working groups can be found in the Collaboration white papers [4, 5, 6, 7, 8].

1.2 LSC Science Goals: Gravitational Wave Targets

The Advanced LIGO detectors have completed three successful observing runs, with O2 and O3 joint with the Virgo detector and the KAGRA detector operational at the end of O3. Over the past year, the detectors have finished a number of upgrades. Observing run O4 started on May 24, 2023 with the two LIGO observatories, and is expected to last until June 9, 2025 including short commissioning breaks [9, 10]. In the beginning months of O4, the observatories were operating with binary neutron star (BNS) inspiral ranges of 140–150 Mpc (LIGO Hanford) and 150–160 Mpc (LIGO Livingston). During the second part of the run (O4b) the inspiral ranges have increased to 140–160 Mpc and 160–180 Mpc, respectively, with Virgo joining the run at 40-60 Mpc. Public alerts are being issued at a rate higher than one event candidate per week. Catalogs of binary coalescence events have been published [11, 12, 13, 14], along with numerous other scientific results. At the time of writing, most results from the first three observing runs (O1–O3), as well as the first results from a joint run of KAGRA and GEO 600 (O3GK), have been published. A large number of binary black hole (BBH) coalescences, as well as several BNS and neutron star–black hole (NSBH) events have been observed. Notably, the BNS GW170817 was observed in coincidence with a short gamma-ray burst (GRB) and other transients across a wide range of electromagnetic (EM) frequencies.

We describe below the gravitational wave targets, as well as dark matter targets, for which we will publish results using the O4 LIGO, Virgo and KAGRA data.

(A) **Gravitational waves emitted during the coalescence of compact binaries**. We will search for coalescences of compact binaries that produce gravitational waves in the sensitive frequency range of the LIGO detectors, including binary systems with neutron stars and black holes. These searches have been developed over the history of the Collaboration. They are run in low latency to provide alerts to electromagnetic observers, and offline to produce the final catalog of observed binary coalescences. The searches will further benefit from incorporating more accurate waveforms reflecting the presence of matter (in coalescences of neutron stars), higher harmonics, eccentricity and precession. The analyses must also deal, at times, with poor data quality, which can impact detection. Upgrading the software to handle these complications can improve search sensitivity and the reliability of inferences about source properties.

(B) **Searches for unmodelled transient gravitational wave signals.** We will search for transients with durations from a few milliseconds up to hours or days. Expected sources include core-collapse supernovae, soft gamma repeaters, neutron star glitches, proto-neutron stars and accretion disks, and cosmic string cusps and kinks. These searches may also allow the discovery of previously unknown sources. Searches for short transients will also be run in low latency, and produce alerts to electromagnetic observers. Searches for unmodelled transients are hampered by noise transients and non-stationarities in the LIGO data, for which detector characterization is critical.

(C) **Gravitational waves associated with known astronomical transients.** We will search for transient gravitational wave signals around the time of known electromagnetic transients such as GRBs, fast radio bursts, supernovae, magnetar flares and exceptional astrophysical neutrino events. By using the known times and sky locations of these electromagnetic transients and, where applicable, the expected gravitational wave signals, we will perform targeted gravitational wave searches with improved sensitivity over blind all-sky searches. Some of these searches will be also performed in low-latency mode to allow for alerts to be issued to the broader community.

(D) **Continuous gravitational waves emitted by previously unknown non-axisymmetric neutron stars and other unknown sources.** We will search for continuous gravitational wave emission from fast-spinning Galactic neutron stars, both isolated and in binary systems, and more exotic sources such as boson clouds around spinning black holes. These searches are the most computationally demanding we carry out and necessarily require sensitivity trade-offs for tractability. Improving computational efficiency to improve sensitivity is an active research area.

(E) **Continuous gravitational waves emitted by known pulsars and other promising sources.** We will search in greater depth for continuous gravitational waves from sources for which we can exploit astrophysical measurements, such as the frequency evolution of known pulsars and/or the locations of other promising sources, such as recent supernovae and known X-ray binaries.

(F) **Searches for astrophysical and cosmological gravitational wave backgrounds.** We will search for an isotropic, stochastic gravitational wave background from unresolved binary coalescences, cosmic string cusps and kinks, and of cosmological origin. We will also search for an anisotropic background, where the anisotropy may be correlated with structure in the Universe.

(G) **Searches for dark matter candidates.** We will perform searches for dark matter candidates which can be directly observed via their interactions with the LIGO and GEO interferometers. Examples include dark photons and scalar-field dark matter, directly affecting the motion of the detector test masses.

1.3 LSC Science Goals: Gravitational Wave Astronomy, Astrophysics and Fundamental Physics

The following list describes the measurements to be carried out for gravitational wave detections and potential conclusions to be drawn from non-detections, with the expectation to publish high impact results with O4 data.

(A) **Public alerts.** During an observing run we will issue prompt and public alerts of significant as well as subthreshold gravitational wave events in newly recorded data to allow for follow-up observations with electromagnetic and neutrino observatories.

(B) **Signal characterization.** We will extract the physical properties of the observed gravitational wave signals. When the source is well modelled, such as a binary coalescence, we will extract the physical parameters of the source. Where the signal morphology is not well modelled, we will reconstruct the waveforms. Where possible, we will determine probabilistic maps of sky position and distance. Finally, where possible, we will improve the understanding of detector noise, as this will reduce parameter estimate biases and uncertainties.

(C) **Astrophysical rates and populations.** We will use the observed individual events, primarily compact binary coalescences of black holes and neutron stars, to determine the underlying population of sources in the universe, taking into account selection effects. We will interpret the detected populations in terms of models of compact binary formation and evolution. This can be done both with detections and non-detections as the latter can set upper limits on the rates of sources, and more generally constrain astrophysical population properties. We will also determine the implications of stochastic background search results for various cosmological and astrophysical models, including models based on cosmic string cusps and kinks, inflationary models, and models due to coalescences of compact object binaries.

(D) **Testing gravitational wave properties.** In general relativity (GR), gravitational waves propagate at a constant speed, independent of frequency, equal to the speed of light, and in two transverse polarizations. Using gravitational wave observations, both with and without electromagnetic counterparts, we will look for variations of the speed of gravity (either from the speed of light or as a function of gravitational wave frequency). Through observations of gravitational wave transients or stochastic gravitational waves in a network of detectors, or of continuous gravitational waves in one or more detectors, we will probe the polarization content of the signal and look for the existence of additional polarizations.

(E) **Strong-field tests of GR.** Precise predictions of gravitational waveforms from binary coalescences are obtained by solving Einstein's equations, numerically and analytically. We will use gravitational wave observations to look for deviations from GR's predictions during the inspiral, merger and ringdown.

We will search for these effects in individual signals and by coherently analyzing the population of observed signals.

(F) **Probing extremes of matter.** Through the observations of neutron stars, either in binary coalescences or through continuous gravitational wave emission, we will probe the underlying structure of neutron stars, often parametrized via the neutron-star equation of state. The neutron star structure affects the waveform emitted during the inspiral and the post-merger waveform. Since the coalescences of binary systems involving neutron stars produce electromagnetic waves, combining electromagnetic and gravitational wave observations can yield insight into the mechanisms for prompt and post-merger electromagnetic burst generation. In the fortunate event of a nearby supernova, combining neutrino and gravitational wave observations can yield insight into the explosion mechanism. Observations of continuous gravitational wave signals from neutron stars can also constrain the equation of state. Electromagnetic observations of the star could be especially helpful in establishing distance (and hence absolute signal strength) and in relating potential electromagnetic pulse phase to gravitational wave signal phase (relevant to interpreting the neutron star non-axisymmetry).

(G) **Gravitational wave cosmology.** We will use the gravitational waveform emitted during a binary coalescence to obtain a measurement of the luminosity distance to the binary. Such gravitational wave observations provide a new cosmic distance ladder. Given an accurate measurement of the source redshift, it is possible to probe the expansion history of the universe and measure the Hubble constant and other cosmological parameters, as well as test the standard cosmology model. The redshift measurement can either be from an electromagnetic observation, directly from the properties of the gravitational wave signal (e.g., merger physics in neutron star coalescences) or statistically derived from overlaying a galaxy catalog on the source localization. We will furthermore use limits on, and measurements of, a stochastic gravitational-wave background to probe the early universe physics and constrain multiple cosmological models whose signatures will be accessible in upcoming observing runs. Similarly, we will also study gravitational lensing effects on gravitational waves.

(H) **Implications for dark matter.** We will use gravitational wave observations and observational limits to place bounds on the properties of dark matter candidates. In addition to dark matter directly coupling to test masses, this for example includes ultra-light boson clouds formed around black holes that are expected to emit continuous gravitational wave signature.

2 LIGO Scientific Operations and Scientific Results

This section describes operations and infrastructure (InfraOps) activities and tasks referenced in paragraph 1.5.3 of the LSC Bylaws [15]. These activities are generalized service contributions to the Collaboration. A detailed work breakdown of InfraOps activities is provided in the white paper of each Division of the LSC.

LIGO Scientific Operations enable gravitational wave science by ensuring a stable and ever-improving LIGO detector, and producing good quality and calibrated data to be combed for astrophysical signals. Data are taken in Observing runs. The latest run, O4, started on May 24, 2023 and is expected to last until June 9, 2025, including multiple commissioning breaks. The LSC commissions the detectors in between runs to improve the sensitivity, plans the dates of observing runs in consultation with Virgo and KAGRA, and operates the detectors during the runs. For the first six-months following data taking, the primary effort is on low-latency analysis, release of public alerts and data vetting. During this period the LSC also ensures that the acquired gravitational wave data is properly calibrated and characterized to be used in analysis algorithms.

The success of the LSC in exploiting the LIGO data depends directly upon the use and development of specialized data analysis tools (detection and reconstruction methods, search algorithms and waveform simulation software) for identifying gravitational waves in the LVK data and producing scientific results. These tools are used to search in the data for the astrophysical targets and to achieve gravitational wave astronomy objectives listed in Section 1. All software developed as part of the LSC Program must be made available under an open-source license and reviewed as described in §2.2.1.6 of the LSC Policies and Procedures [16]. In general, software should also be packaged for easy inclusion in standard Collaboration software environments.

This section describes the activities carried out for operations at the observatories, commissioning and detector improvements, as well as activities needed for the data calibration and characterization. We describe activities needed to exploit the LIGO data, the use or operation of analysis tools to obtain scientific results from the data and the dissemination of results to both scientific and public audiences. This also includes development and upgrades of existing tools to successfully complete ongoing analyses and preparations for the next run. Analysis activities are performed jointly with the Virgo Collaboration and use data from LIGO and Virgo detectors. Starting in Spring 2020, the KAGRA Scientific Collaboration was also integrated.

In defining the LSC Infrastructure and Operations (InfraOps) program as defined in the LSC Bylaws [15], we use the following criterion: *Work needed to be done by the LSC to enable a given paper to be written on open data outside the Collaboration is defined as InfraOps.* Thus, for example, detector calibration and characterization work, low-latency analysis code development and running, as well as paper/code review service on behalf of the collaboration qualify as InfraOps, regardless of which paper the work is used for. Furthermore observational science papers are prioritized into two groups:

1. **Key collaboration papers** report on key observational science objectives that shall be completed before the end of the data proprietary period, or very soon afterwards, to maximize their scientific impact. Papers that report on the observation of exceptional events shall be included on this list. Activities and tasks directly impacting these papers are considered operations and infrastructure activities (InfraOps). This includes all related work, explicitly including code development, code maintenance, paper writing and editing.

2. **Other collaboration papers** report on other observational science goals of the LSC. These papers are part of the LSC Program. However, to discern which activities and tasks impacting these papers are considered InfraOps, the InfraOps criterion listed above should be applied as if they were external papers. Thus, explicitly, data characterisation, calibration, code maintenance and paper review work does count as InfraOps, while analysis and paper editing does not.

The future, long term, development activities beyond this time-frame are discussed in Sections 3 and 4.

2.1 Observatory Operations

The LIGO Laboratory has primary responsibility for the operation and maintenance of the LIGO Hanford and Livingston Observatories through a Cooperative Agreement with the US National Science Foundation.

There are many detector-related activities at the LIGO Hanford and Livingston Observatories that support Observatory Scientific Operations. Facilities operations comprise a large number of ongoing maintenance activities throughout the year. In preparation for the O4 run, the LIGO Laboratory has carried out the detector improvements that were identified as targets for sensitivity improvement, has successfully executed the Phase 1 A+ upgrades for O4, and has begun O4 observations on 24 May 2023.

The LIGO Laboratory will plan all activities related to the detectors and vacuum refurbishment efforts. Additional activities that will be undertaken will include the following: continuing test mass point absorber R&D, including further R&D on coatings for O5; improving particulate contamination control; improving automation of detector operation; continued work on the LIGO vacuum system refurbishment program; in concert with its A+ partners, carrying out the planning, procurement and fabrication, and assembly of the remaining Phase 2 A+ subsystems necessary for O5.

The LIGO Laboratory personnel will also continue to maintain and update the Control and Data Systems (CDS) suite of software [17] used in real-time control and data acquisition systems deployed to the LIGO sites and R&D facilities. This includes introducing updates to the software suite based primarily on changes in software packages not developed in-house and computer technologies (software improvement) and providing general support in the area of electronics design, fabrication, test and maintenance (electronics improvements). As part of the O4–O5 upgrade CDS will be upgrading and updating the real-time control infrastructure for both Hanford and Livingston.

The LIGO Laboratory Annual Work Plan (AWP) presents a detailed list of LIGO Laboratory tasks planned for the fiscal year. A detailed list of detector improvements can be found in the Bi-Monthly Commissioning and Detector Improvement (DI) Status Reports. The GEO Collaboration is responsible for the operation and maintenance of the GEO 600 Observatory, taking data in AstroWatch mode while the LIGO detectors are being commissioned, and testing new technology developments to be implemented later in the LIGO detectors.

2.2 Detector Commissioning and Detector Improvement activities

Detector Commissioning includes all activities involved in bringing the detectors to their target design sensitivity and operating robustly. Examples include diagnosing and reducing technical noise sources, improving the interferometer controls, characterizing the optical behavior of the system, and improving the duty cycle for low-noise operation. Most commissioning work is performed at the observatories, but remote contributions are also made by analyzing test and performance data, or modeling the interferometer behavior, in preparation for observation runs. Careful observations of the detector while running also give valuable information on possible detector improvements. Detector characterization activities (described below) contribute to the commissioning described here.

While LIGO Detector Commissioning and Detector Improvements at the Observatories are the responsibility of the LIGO Laboratory, there are also important contributions from other LSC institutions. Commissioning activities are managed by the LIGO Laboratory Chief Detector Scientist and the local LIGO Hanford and LIGO Livingston Commissioning Leaders.

During a run, the commissioning effort focuses mainly on maintaining detector performance; in addition, limited time (nominally six hours per week) is permitted for performing diagnostics, making tests that could produce incremental sensitivity and data quality improvements, and performing preventative maintenance activities. Longer breaks for commissioning or implementing detector improvements are possible with the approval of the LIGO Operations Management Team and are coordinated with the Joint Run Planning

Committee.

Detector Improvements involve new hardware or software that is intended to improve detector performance; as such, they support the commissioning effort. Detector Improvements are managed by the LIGO Detector Project Manager and Chief Detector Scientist, and any proposed improvement projects must follow the processes for approval and implementation defined by LIGO Laboratory. Contributions in this category are in the form of the development, fabrication, or integration of approved Detector Improvement projects. The list of Detector Improvement projects is maintained in the LIGO Detector Improvements Work Packages document. Although many contributions are from LIGO Laboratory personnel, other LSC institutions make important contributions as well. Commissioning activities will be interleaved with the detector improvement and A+ upgrade program (described in Section 2.3) as detector improvements are carried out in preparation for the O5 run.

With the increased sensitivity, observations are sometimes made when one or more detector is not in observing mode, resulting in requests from inside and outside the Collaboration for the release of the non-observing data from the additional detector(s). Depending on the status of the detector a significant amount of work can be required to calibrate and validate this data. While it is not possible to perform this work for all such events, the scientific gain might justify it for some exceptional events, if needed for full author-list LVK publications, following procedures agreed between the operations and observational science divisions.

2.3 A+ Upgrade Project

The A+ detector project is a major upgrade to the existing Advanced LIGO detectors. Formal project activities began in 2019 and will continue through September 2025, followed by installation of A+ and other detector improvement upgrades and the commencement of O5 in mid 2027. The key goals of A+ are frequency dependent squeezing with a 300 m filter cavity, balanced homodyne readout, implementation of lower mechanical loss coatings (when developed), and installation of new test masses from upgraded pulling and welding systems for fused silica fibers. The installation of some of the A+ improvements, notably the 300 m filter cavity, were completed before the O4 run, while other upgrades are planned for after the O4 run.

Activities related to A+ operations are: testing frequency dependent squeezing at 1064 nm; designing measurement and implementation methods for Newtonian noise reduction; testing low noise control of the homodyne readout; reliability testing for higher stress silica fibers; active wave front control sensing and actuation; and studying production of fused silica suspension fibers to ensure that frequencies of violin modes are sufficiently matched. Substantial efforts are underway to develop new optical coatings for A+ with improved mechanical loss. These coatings are expected to be amorphous oxide coatings deposited with ion-beam-sputtering techniques, such as titania-doped germania coatings. Parallel efforts are underway to understand the fundamental loss mechanisms for these coatings, and to improve the loss with different compositions, nano-layered coatings, and modified deposition and annealing processes. Details on A+ can be found in the LSC Instrument white paper [4].

2.4 LIGO-India

LIGO-India received approval from the Government of India on April 6th, 2023. Funding of Rs 2600 Crore (approximately $315 million), was approved for construction of a LIGO interferometer at the Aundha site in the Hingoli district of Maharashtra state. Major construction is expected to begin in early 2025.

Prior to final approval pre-project activities included acquisition of the site, construction of the first on-site building, baseline seismic survey for a period of 14 months, installation of a weather station and the building prototype HAM and BSC chambers. Fabrication of two 10 m sections of vacuum tubes and a 80 K long-cryopump are in progress and near completion. Construction of vacuum equipment is overseen by

LIGO members from the Institute of Plasma Research (IPR) in Ahmedabad. A dedicated test and training building has been constructed at the Raja Ramanna Center for Advanced Technology (RRCAT) in Indore. Work has begun on a 10-m prototype at this facility. In addition the prototype BSC and HAM chambers will be tested at RRCAT. The Pre-Stabilized Laser, currently in storage at LIGO Hanford, will be shipped to RRCAT for use in training and testing prior to installation at the LIGO-Aundha Observatory.

IPR and RRCAT are joined by the Inter-University Center for Astronomy and Astrophysics (IUCAA), located in Pune, and the Directorate of Construction Services and Estate Management (DCSEM), located in Mumbai, to form the four core institutes responsible for construction, installation, and operation of the LIGO India detector. RRCAT, which is an R&D Centre of the Department of Atomic Energy, has the key role in construction, installation and commissioning after which operation of the Observatory will be handled by IUCAA.

A robust training program has been developed in laboratories at IUCAA over the past several years. This program introduces students to various aspects of detector technology and continues to expand. Several graduates have already moved on to graduate studies at other LSC institutions. LIGO-India scientists and engineers will work with the LIGO Lab to upgrade the stored detector components to the A+ configuration. Pathfinder shipments of some core components will be made to the RRCAT facility in the next twelve months. The bulk of the detector will be shipped directly to the Aundha site once there are facilities in place to receive it.

We anticipate increased participation in the LSC Fellows program by scientists and engineers from LIGO India, as well as increased visits to other LSC institutions for the purposes of training and knowledge transfer. LSC Fellows will contribute to assembly, installation and commissioning of the current detectors. LIGO-India continues to provide high-throughput computing resources for LSC data analysis activities. It is expected to expand that facility by adding more disk-space and processors.

2.5 $A^{\#}$ Technology Development

Formal A+ upgrade project activities are scheduled to complete by September 2025. Installation of A+ and other detector upgrades will result in the crowning O5 observation run (scheduled to end in 2029). The current planning for third-generation detectors will not have them online before the mid-2030s, leaving a decade of opportunities for detector improvements and observation runs. Detector improvements that can increase sensitivity, improve stable operation, and reduce the technology risk for third-generation detectors are of particular interest. A post-O5 study group has conducted a study of available options and has developed a planing document for this period [18]. This report identifies improvement options for the post-O5 period, identifying two main design options, currently named $A^{\#}$ (A-sharp) and Voyager, each with possible sub-variants. The report assesses the technology readiness of the $A^{\#}$ design as further advanced, and identifies a variant of the $A^{\#}$ design as the baseline choice for a Post-O5 upgrade.

Activities and research directly related to developing the technology for an $A^{\#}$ upgrade are thus considered operations and infrastructure (InfraOps) activities as defined in LSC Bylaws [15] Specifically, these include: R&D towards alternatives for mirror substrates and coatings, amorphous or crystalline; improvements to suspension and isolation systems, including higher stress fibers, methods to reduce thermal noise, reduce control-system-related noise and improve sensor performance; systems to suppress Newtonian noise; research into lasers with higher power and improved modal stability intended for current observatories; research into systems to handle increased circulating power including parametric instability suppression and thermal aberration correction; improvements to squeezed light source detector integration; and research aimed at improving auxiliary optics components in the current interferometers. This list is possibly not complete, but any activities considered as InfraOps have to aim at integrating the technology into the $A^{\#}$ design.

Activities aimed at a possible later upgrade (e.g., Voyager) and new observatories (e.g., Cosmic Explorer) are not considered InfraOps unless they also have a direct impact on the post-O5 upgrade.

2.6 LSC Fellows Program

LSC Fellows are scientists and engineers who are resident at the LIGO observatories for extended periods of time [16]. LSC Fellows work with observatory scientists who serve as mentors or liaisons depending on their initial level of expertise and the nature of their project.

The LSC Fellows program continues to be both popular and a major success, enabling LIGO Laboratory to host scientists at all levels of experience for at least three months, and sometimes longer. The Fellows conduct critical LSC activities supporting LIGO Laboratory commissioning and scientific operations, and engage in a variety of activities, including: detection coordination efforts during observing runs; detector commissioning; installation of detector improvements; detector calibration; and detector characterization. For junior scientists this has provided a learning opportunity to gain hands-on experience at one or both of the LIGO observatories. Their hands-on experience at the observatories contributes to their development as scientists at the beginning of their careers, whether they later pursue experimental physics or data analysis.

During the 2024–2025 period the observatories will be completing the O4 observing run, and will initiate the A+ commissioning mid 2025. LSC Fellows will have opportunities to take part in hardware installation, and participate in investigations with the commissioning and detector characterization groups.

2.7 Detector Calibration and Data Timing

Timely, accurate calibration of each detector's differential arm length channels into equivalent strain time series is essential to extracting gravitational wave science from the LIGO detectors' data. The task involves producing a calibrated data stream for each detector, called $h(t)$, of sufficient quality to support both the online and offline analyses, including both searches for new signals and the detailed analysis of detections and null results. Analyzing and providing uncertainty estimates are also part of the calibration task.

The data calibration uses the known displacement produced by radiation pressure (photon calibrator) to track time-varying calibration at certain frequencies and a model for the detector's frequency-dependent response to produce time-dependent, frequency-dependent calibration and estimated uncertainties. The model is vetted with measurements before, during, and after collecting observational data [19].

The activities required for calibration are:

(i) Maintenance and improvement (as necessary) of the photon calibrator system, the calibration model code, and the code for determining calibration uncertainties,

(ii) Measurement of transfer functions required for the calibration model,

(iii) Maintenance and operation of the low- and high-latency $h(t)$ data production software, and

(iv) Maintenance of calibration monitoring tools used for reviewing and diagnosing calibration issues.

The near-real-time calibration provided by the front-end system is most helpful for commissioning and is not used for astrophysical analysis. The low-latency (on the order of $\sim$ 10s delay) calibrated strain data, accompanied by a frequency-dependent, time-dependent estimate of the calibration uncertainty, are used as the main products for astrophysical analyses. The high-latency offline re-calibration is only produced (with associated uncertainty estimates) for time periods when the low-latency calibration is deemed to have significant systematics, which prevents its use for scientific analyses and publications.

The calibration accuracy of low-latency strain data is assessed at certain selected frequencies in low-latency to enable faster publication decisions. It is highly recommended that parameter-estimation analyses and their interpretation start as soon as possible using the low-latency calibration (unless significant systematics are identified in the low-latency data) so that results are available quickly and can be used to inform the scientific scope of the papers and facilitate their swift completion. The final time-dependent, frequency-dependent uncertainty estimates of the low-latency data are delivered on a best-effort basis at the moment ($\sim$ months after data collection); improvements are needed to achieve delivery on a shorter time scale.

In order to assess the required level of calibration accuracy and precision, the impact of calibration error on data analyses, including detection pipelines, parameter estimation, source localization, and population inferences (such as cosmological measurements), needs to be quantified. Hence, all follow-up analyses and searches to be run on O4 data need to document the impact of calibration errors on the analysis results and communicate this information to the calibration group to establish an acceptable level of calibration accuracy and precision.

Since improved calibration can improve gravitational wave science, some development projects are now underway. Improved calibration modeling and a more unified, efficient calibration pipeline are being developed, along with the new data/computing infrastructure being implemented for O5. Improved NIST-traceable power monitoring for the photon-calibrator subsystem and alternative fiducial references, e.g., Newtonian calibrators, are being studied.

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

2.8 Detector Characterization

Robust detection of signals, the vetting of candidate signals and the accuracy of parameter estimation are crucially dependent on the quality of the data searched. The LSC's knowledge of the LIGO detectors and their environment is essential to deliver data quality information to the astrophysical searches which will avoid data with known issues, veto false positives, and allow candidate follow up. Characterization of the LIGO detectors themselves help to identify data quality issues that can be addressed at the instrument to improve instrument and search performance.

The LSC will perform the following critical tasks:

(i) Characterize the LIGO detector subsystems, with the aim to quantify their contribution to detector performance and identify strategies to mitigate instrumental issues as they arise, by providing feedback to detector scientists and engineers to eliminate or mitigate hardware sources of corrupt data;
(ii) Provide timely data quality information to the astrophysical searches to designate what data should be analyzed, remove untrustworthy data due to quality issues, and identify periods/frequencies of poor data quality;
(iii) Identify sources of data defects that limit sensitivity to transient and continuous gravitational wave sources;
(iv) Provide gating and conditioning of data impacted by instrumental artefacts, to be used internally and for public release;
(v) Develop improved methods to uncover the causes of noise which most impact astrophysical search performance, with the goal of mitigating these causes in the instrument;
(vi) Undertake vetting of event candidates for potential instrumental origins; and
(vii) Maintain and extend the software infrastructure required to provide needed data quality information to the astrophysical searches and monitoring of the LIGO detectors.

Automation of these tasks will continue to be a focus and this work will require expertise in both the astrophysical searches and instrumentation.

2.9 Computing Systems and Services for Modeling, Analysis and Interpretation

The timely production of LSC results requires significant computing resources, and dedicated, expert computing personnel. Turnover in computing support personnel working on these services is of particular concern. The prioritization and review of needs across Computing and Software activities identified ~ 11 full-time employee (FTE) deficit from the LSC (~ 8 additional FTEs from Virgo and KAGRA). It is essential that the collaboration identifies people to reduce this deficit through proportional support for personnel and computational resources by the LIGO-Virgo-KAGRA Collaboration.

The LSC will perform the following critical work:

(A) **Computing systems** Several large-scale computing clusters are provided within the LSC for gravitational wave analyses. The computing clusters must remain secure, have the appropriate gravitational wave software installed, provide access for LSC, Virgo, and KAGRA members, and provide storage and web space for posting results. Computing usage must be tracked accurately to ensure efficient use of computing resources and guide code-optimization efforts. Estimates of computational requirements must be updated as scientific targets, detector sensitivity, network size and rate of observed signals increase.

The LSC, in coordination with Virgo and KAGRA, is transitioning to a joint computing environment based on the Open Science Grid Platform, i.e. the IGWN Grid, with shared responsibility for provisioning computing resources and computing personnel. This unified environment will enable more efficient use of collaboration-wide computing resources, as well as facilitate access to shared resources. This transition will require increasing integration of LSC computing with the wider physics and astronomy communities.

Seamless and efficient access to computing resources and services must be provided for LSC users. Furthermore, a coherent, high-quality and well-managed suite of tools and infrastructure for development and production work has to be maintained.

As described in the LIGO Data Management Plan [20] LIGO maintains a copy of all LIGO gravitational wave interferometer data taken during observational runs in the central data archive at Caltech with remote backups at the observatories. Copies of data from future runs will be similarly stored.

Other activities include system provisioning and maintenance; operating and maintaining automated build and test tools and systems; providing gateways to use external computing resources for LSC science; monitoring the globally distributed computing systems and accounting of usage; optimization of the most computationally costly LSC analyses to enable more efficient use of resources and more timely results.

(B) **Data analysis and handling services.** Each LIGO observatory generates 25 MB/s of data from a combination of instrumental and environmental monitors. Data handling services include: automated data transfer infrastructure to support both low-latency analysis and batch processing for less time-sensitive analyses; data discovery services; remote data access services; databases (and associated web services) to store and access metadata about the instruments, the data, and gravitational wave signals; and, finally, a summary service that presents an overview of important information about the instrument and data that can be viewed by date.

There is also a need to develop tools to automate and coordinate analyses, including development of pipelines that can integrate different steps of the analysis, from calibrating the data to producing population inferences with a large number of detections. The collaboration also needs improved archiving tools that can organise catalogs of results for use in LSC analyses and for distribution to the wider public.

(C) **Collaboration operations services.** The LSC requires tools to effectively collaborate and communicate including: mailing lists, wikis, web pages, document preparation and management systems, version control repositories, a messaging system, a voting system, problem reporting systems, interfaces with needed non-LSC documentation services, and teleconference systems.

(D) **Security, identity and access management.** The LSC must ensure that LSC cyberinfrastructure is used in accordance with basic security principles. This includes: communicating with members about security concerns they experience and providing general guidance on secure practices; recommending security enhancements to LSC management and to LSC facilities administrators; performing security reviews of LSC software and systems, especially those that are critical to the LIGO/IGWN science mission; and organizing and participating in incident response for LSC facilities. LSC security is coordinated with LIGO Lab security as well as with security efforts in Virgo and KAGRA, and also with institutional security offices on campuses that have a substantial LSC computing presence or that host critical systems.

Identity and access management services underpin the ability of the LSC to interact and operate efficiently across the globe. Users require services to manage their LIGO.ORG identity and their access to LIGO.ORG resources; these range from a user enrollment and group management platform, through certificate management resources, to group membership management tools. Federated identity management and additional group management tools are needed to support collaborative relationships between the LSC, other collaborations, and other scientists.

(E) **Software.** The LSC supports the use of shared software across the collaboration, through either the support and maintenance of shared software common to many groups, or the integration of individual group's software into common distributions. This includes the support, maintenance and operation of: LALSuite and GWPy; software tools and libraries to distribute and read gravitational-wave frame files; general-purpose workflow management tools; IGWN designated software packaging; cyberinfrastructure and platforms that enable IGWN users to deploy their own software; cyberinfrastructure and documentation that facilitates IGWN users' ability to deploy continuous integration and automated testing. Specialized engineering to improve the hardware performance of other collaboration software, porting of such software to run on accelerators, and the testing and deployment of hardware-specific optimizations is also required.

(F) **Strategic and project management.** Development of tools and processes to ensure the efficient management of computing projects and tasks, including maintenance of the IGWN Computing WBS and Operations Division whitepaper; GitLab project and task management; scheduling; and communication of plans and project status between Observational Science and Operations Working Groups, the LSC Management Team, and other LVK management bodies. This should also include fostering and maintaining beneficial computing collaborations with external scientific projects and Cyberinfrastructure providers.

2.10 The Operation of Data Analysis Search, Simulation and Interpretation Pipelines

The main objective of the data analysis operations is the processing of the gravitational wave data with reviewed search pipelines, identification of gravitational wave signals in the data, and the production of scientific results and LSC publications. With the growing number of detectors participating in the global gravitational wave network and the increasing volume of gravitational wave data, the data analysis activities become increasingly time consuming and require significant human and computing resources. Specifically, the activities critical for the effective and timely analysis of the gravitational wave data are listed below. For items (E) through (G), when performed for papers in the Other category, the InfraOps criterion introduced at the beginning of this section applies.

(A) **Operation of the low latency searches.** Ensure continuous 24/7 operation of the low latency searches for transient gravitational wave signals during the data taking runs. Perform rapid parameter estimation of detected signals and calculation of the source localization. Provide input for public alerts for significant events, and rapidly update the details with any new pertinent information. Accommodate for changing run conditions, detector sensitivity and non-stationary detector noise.

(B) **Prompt response to the real-time events.** Run the follow-up analysis of candidate gravitational wave events for better estimation of the source categorization, signal parameters and refined source localization. Perform rapid analysis of exceptional gravitational wave events, followed by LSC publications on those events.

(C) **Data conditioning and validation.** Coordinate closely the data analysis work with the data quality and calibration efforts. Perform timely integration of the data quality information into the LSC searches. Using the search pipelines, perform monitoring and mitigation of the environmental and instrumental glitches affecting the search performance. Apply algorithms for subtraction of known noise contributions to improve detection and parameter estimation of observed gravitational wave signals.

(D) **Maintenance of production search software.** Although the search algorithms, analysis algorithms and waveform simulations should be reviewed and tested before use in production, there are often maintenance activities needed to address the review issues, critical bugs, security and unforeseen problems, which should be carried out promptly by the analysis groups. The software maintenance should not include major pipeline upgrades during the O4 data taking and analysis period that may result in a significant delay of the LSC publications.

(E) **Running the gravitational wave searches on archived data.** Define the methodology, data products, and results, beyond those obtained in low latency, to be used in LSC publications, including internal review of relevant algorithms and training of Collaboration members. Prepare and execute searches on vetted data, including updated calibration and data quality information as appropriate for each publication. Searches will be run on all collected data passing validity and quality checks from the LIGO, Virgo and KAGRA detectors. Processing of data from such a heterogeneous network of detectors with different sensitivity, duty cycle and varying run conditions is time consuming and requires significant computing resources and time. Following the LSC–Virgo multiple pipeline policy, we would generally expect to run no more than two analyses for a given source or a region of the parameter space, unless the additional pipeline runs are justified by discovery of potentially new GW sources and improved scientific results.

(F) **Production of the search results.** Final estimation of the detection significance for candidate events and the parameter estimation of detected signals. Processing of simulation data sets for estimation of the search sensitivity and interpretation of the search results with the astrophysical models. Estimation of the astrophysical rates and the source population properties. Careful indexing and archiving of candidates and associated data products.

(G) **Multimessenger searches.** Conduct multimessenger observations and interpretation of astrophysical events triggered by the gravitational wave detectors or by other electromagnetic or neutrino instruments. In most cases, this work requires observations and expertise outside the LSC, Virgo Collaboration and KAGRA Scientific Collaboration, and activities are regulated by the signed agreements with the external partners. Projects involving external partners will be proposed, reviewed, and then approved by the LSC Council.

2.11 Delivery of Analysis Tools to Search and Interpret the Gravitational Wave Data

The LSC has carried out gravitational wave searches on the data from previous runs to identify the targets listed in section 1.2, and to extract the gravitational wave science detailed in section 1.3. While existing analysis tools have performed well in past observing runs, further delivery, automation and review of these tools are required to ensure timely and effective searches on new data, and to characterize the increasing number of gravitational wave events. All work described below must lead to functional, documented, computationally efficient and reviewed tools which are available to the full Collaboration. Details of activities are available in the Observational Science white paper [5]. Examples of those required for completion of the upcoming O5 analysis (and, in some cases, also beneficial to increase the scientific output of the ongoing O4 analysis) include:

(A) **Automation of detector characterization, detection and parameter estimation pipelines.** With the increased LIGO sensitivity during the O4 run, the rate of gravitational wave detections is expected to approach one event per day. Therefore, any procedures to identify, vet and follow-up candidate gravitational wave events must be increasingly automated and optimized to allow for the analyses for key papers to keep up with the observations. Additionally, where possible, review tasks should be automated to enable high numbers of analyses to be checked efficiently. Similarly, repetitive tasks for updating science results, such as for example new limits on deviations from GR, should also be automated.

(B) **Deliver tools for issuing public alerts of gravitational wave events.** The LSC provides public alerts for significant event candidates observed by its low-latency pipelines, which need further development and updates. The infrastructure for public alerts should be developed, tested and reviewed before the beginning of each run. Required are improved methods for handling alerts from multiple searches and/or multiple versions of the same search algorithm, automated selection of the correctly prioritized source information and vetting of the alerts, and improved methods for the update and retraction of the active alerts.

Following the NSF review of LIGO Lab and the LSC in 2022, the LSC has been asked to carry out a high-level assessment of the low-latency architecture used in O4 with a view to improving system scalability, sustainability and reducing alert latency. The review should be completed and a report prepared for the 2025 NSF review of LIGO Lab and the LSC.

(C) **Implementing and testing operation plans**. This work includes efforts to optimize gravitational wave searches, parameter-extraction and population-inference analyses for computational efficiency and run-time. It also requires documenting the calibration error impact on analysis results, and communicating this information to the calibration group (see Section 2.7). Implementing and testing should be done ahead of each observation run, while the focus during an observation run is on executing the plans, as outlined in Section 2.10. This work is critical to enable sustainable use of both human and computational resources in delivering gravitational wave science from the data.

(D) **Prepare analyses for exceptional discoveries.** Observation runs are likely to provide exceptional events, and more broadly exceptional discoveries, which significantly expand the observed population of gravitational wave signals, lead to the observation of entirely new sources, enable significant improvements in the measurement of physical or astrophysical quantities, or open the possibility of deviations from general relativity or the existence of new fundamental particles. Observational Science groups have identified classes of potential events and discoveries, and have defined procedures to act upon them. Further work is needed to enable full exploitation of these discoveries, requiring continuous development of corresponding analysis tools.

(E) **Enhancements of existing analyses.** Development and upgrades of the existing analyses may be required to handle the improved detector sensitivity and enlarged network including Virgo and KAGRA. When multiple search pipelines (or different configurations of the same pipeline) are used to search for the same source, approaches should be developed to obtain an overall, robust, Collaboration statement about the candidates that are identified in our data. Results from the individual pipelines should be aggregated, combining all available information about pipeline sensitivity, and where possible, lead to a single quantitative statement about the confidence in each candidate or an upper limit in the event of a non-detection. In addition, refined methods for applying information on data quality and accounting for detector non-stationarity should be developed to maintain search sensitivity. Due to the increased event rate and improved detector bandwidth, parameter estimation is likely to become a bottleneck, and requires improvements in terms of computational efficiency and run time. Additional work is required to improve subthreshold analyses. Major enhancements should target O5, except for O4 analyses that are only planned to start late in the run or after the end of data taking and where there is no risk to significantly delay LSC publications.

(F) **Deliver infrastructure and tools to manage and characterize the gravitational wave catalog.** As the number of gravitational wave observations increases, it will become increasingly important and interesting to provide details of the underlying gravitational wave population, and to exploit the full event data set for scientific analysis. More efficient tools to manage the event data set, to monitor analyses, and to update rate and population information are required. Analyses to measure population properties, cosmological parameters, neutron star equation of state, and deviations from general relativity should, where possible, be blinded. Mock data challenges can be used to determine search configurations in advance of the actual analysis.

(G) **Improvements to existing waveform models.** With increased detector sensitivity, it is likely that signals will be observed with greater signal-to-noise ratio, and covering hitherto undetected parameters. Consequently, increasingly accurate gravitational waveforms, with wider parameter coverage (more extreme mass ratios, larger spins and stronger precessional effects, orbital eccentricity, tidal effects, etc.), are required to correctly interpret the gravitational wave source and ensure that any systematic uncertainties arising from discrepancies in model waveforms remain less significant than statistical uncertainties. Such waveforms need to be tested and validated against numerical relativity waveforms where available. In regions of the parameter space where numerical-relativity simulations are not available, one could estimate the accuracy by comparing different waveform models with each other. Finally, since waveform generation can be the computationally dominant part of parameter estimation routines, optimization work is required to speed up the analyses. In order to benefit the broader collaboration through accessible use, waveforms should be reviewed and made accessible for use in the standard LSC data analysis software.

For items (E) through (G), when performed for papers in the Other category, the InfraOps criterion introduced at the beginning of this section applies.

2.12 Development of Computational Resources

The content of this section has been included into Secs. 2.9 and 2.11.

2.13 Dissemination of LIGO Data and Scientific Results

LSC scientific results and data are disseminated to fellow scientists in a number of ways:

(A) **Gravitational-wave alerts.** During an observing run we will provide prompt and open public alerts for significant as well as subthreshold transient event candidates. These alerts will include the significance of the event and a localization on the sky. For compact binary coalescence candidates, the alert will contain the estimated probability of the event being a BBH, NSBH or BNS candidate, as well as a three-dimensional source localization. Alerts will be updated as further relevant information becomes available from follow-up studies.

(B) **Publication of scientific papers.** We aim to produce high-impact publications based upon our understanding of our data, instruments and the implications of our observations. The schedule of our papers is tied to our observing plans.

Key collaboration papers, as defined in the introduction of this section, shall be completed before the end of the proprietary period for the data, or very soon afterwards, to maximize their impact. Activities and tasks directly impacting these papers are considered as being within Infrastructure and Operations.

With the O4 data, we will fast-track publications that describe exceptional events or new types of discovery. Examples of exceptional discoveries are: a new class of binary systems; a binary with parameters definitely outside the previously observed region; a binary with well measured high spin magnitudes, spin precession, large/small component masses, etc.; observations leading to new insights about the neutron star equation of state; an observable post-merger signal; apparent deviations from general relativity; an exceptional unmodeled gravitational-wave transient (with or without associated multimessenger transient); continuous waves; or a stochastic background. Certain discoveries, such as events with multimessenger counterparts, might require a much shorter time-to-publication, while unexpected discoveries that do not fall into an anticipated category might require extra time. Therefore the appointed science team will promptly present details of the publication timeline and paper scope. We will target public release of papers that require the publication of a significant fraction of the data (e.g., catalog papers) to coincide with the bulk release of data as specified in the Data Management Plan [20], with the potential for the peer-review process to start at least one month earlier. Since the results of catalog papers are needed for multiple companion papers that perform further analyses using this, it will be necessary for catalog results to be complete up to several months in advance of the submission deadline, and production of these results should be prioritised.

(C) **Release of data at times of gravitational-wave transients:** As described in the LIGO Data Management Plan [20], at the time when the details of a new gravitational wave transient are first published in a scientific journal, the LSC commits to making the data containing the event public; a minimum of one hour of data around each event will be released. The LSC also commits to releasing other data products required to reproduce Collaboration analyses, most significantly the parameter estimation information for observed events.

(D) **Bulk release of LIGO data:** As described in the LIGO Data Management Plan [20], the LSC will make public the calibrated strain data taken in observation runs. The data from the O1, O2 and O3 run has been released. O4 data will be released as specified in the Data Management Plan [20].

The bulk data release will coincide, to the extent possible, with the data used for LSC analyses. In particular, we advocate releasing the same vetted data, data quality and segment information as used for LSC analyses, as this will reduce overall workload and require significantly less vetting for the open data. The released data will include the final parameter estimation, localization and population inference information described above, as well as folded data used for searches for stochastic backgrounds. In addition to data release, the LSC provides documented tools to allow the community to access and search the gravitational wave data.

(E) **Release of additional non-observing data upon request:** Requests from outside and inside the Collaboration for release of additional data outside of nominal observing times will be considered in cases where this may lead to an exceptional discovery. The cost and benefits of producing accurate, calibrated data around such events are evaluated following the same guidelines used internally as described in Section 2.2.

(F) **Release of LIGO auxiliary data:** The publication of a selection of auxiliary channels around some selected events will go forward. The LSC will further assess the usefulness of auxiliary data to outside researchers in order to decide whether to continue, expand or stop releasing auxiliary data in the future. The LSC will work towards making physical environment monitor data from the observatories publicly available as local laws permit.

Items (D) through (F) are functions of the Gravitational-Wave Open Science Center (GWOSC), which handles public access to gravitational-wave data products.

2.14 Communication, Education and Outreach to the Public and Scientific Community

The LSC aims to promote its science and to bring people into the field, including people from groups traditionally underrepresented in STEM. Activities that are important for the LSC to broadcast its mission and results are related to several aspects listed below. It is expected that contributions are readily available to the LSC (e.g., delivered to the Communication and Education (C&E) Division, posted to the DCC, and otherwise integrated into the broader LSC C&E program).

(A) **LIGO Observatory education and public outreach**: We will expand the LLO Science Education Center (SEC) and the LHO LIGO Exploration Center (LExC) capability for evaluating the impact it has on students participating in field trips, continuing to serve the local teacher community through summer workshops and collaborative teacher exchanges.

(B) **Formal and higher education**: We will develop new classroom units for high schools aligned with Next Generation Science Standards (NGSS) and other appropriate international school standards, including updates and revisions of existing classroom activities. We will develop high-school teacher training materials that can be tested and evaluated prior to use, conduct professional development with high school teachers at local, regional, national, and international venues, and develop new classroom and laboratory activities on LIGO-related data analysis, astrophysics, and experimental topics, suitable for use in high school and undergraduate introductory astronomy and physics classes.

(C) **Informal communication, education and outreach**: We will maintain, update and renovate the ligo.org website for informal users. We will continue worldwide outreach and communication through social media (in a variety of formats, e.g., text-based, image-based and video-based) and other informal educational materials that showcase our observational and instrument science and the importance of multimessenger astronomy. In particular, we will provide educational materials and social media support for exceptional event announcements. We will continue answering question@ligo.org and ask.igwn queries, developing efficient approaches to curate and organize them. Together with Virgo and KAGRA, we will develop printed material and multilingual resources including science summaries for Collaboration papers. We will promote development of innovative approaches that communicate LIGO science, such as audio, video, virtual reality, web and phone apps, video games and planetarium shows. We will develop and maintain tools to share, in low latency, public alerts of detection candidates and resources to explain the content of these alerts. We will explore innovative approaches to generating and disseminating this content that will be scalable to the candidate event rates expected for O4 and beyond. We will support the Humans of LIGO blog, Gravity Spy and other relevant community-science initiatives. We will support our LSC members communicating our science through public talks, writing popular articles, and communications on social media, podcasts or blogs. We will develop and curate a bank of approved graphics and multimedia on all aspects of gravitational wave science, suitable for LSC, Virgo, and KAGRA colleagues to use in public lectures, and support LSC presence at major science festivals, exhibitions, and other high-profile public events that attract large audiences both online and face-to-face.

(D) **Professional outreach**: We will maintain, update and renovate the ligo.org website for professional scientists, with an emphasis on renovating the website to improve the backend user interface. We will support the provision of information and materials for professional astronomers, including updates on observation run schedule, public alerts during observing time, organization and promotion of LVK webinars, and communication with the astronomy community as described in the Operations Analysis white paper [6].

We will promote outreach to scientists and policy makers at professional conferences and meetings, both online and face-to-face, working in collaboration with other gravitational wave communities where appropriate. We will develop flexible and easily portable resources that can be used at exhibitions as well as other informal education and outreach events. We will aim to enable our Collaboration members to present the science of our latest results at conferences in talks and panel discussions, through online presentations, and at seminars and colloquiums at individual institutions.

(E) **Public relations and communication**: We will continue to support communication with media contacts, to provide media guidance and training for Collaboration members, and to coordinate regular communication liaison for LVK public announcement of scientific results, particularly (but not only) O4 exceptional event papers and webinars. We will investigate avenues for professionalization of LSC public relations and press releases. We will also develop a framework (appropriate for the event rates anticipated in O4) for deciding when LSC papers are worthy of public announcement, as, e.g., exceptional events and/or webinars, and for effective and efficient management of these public announcements. We will maintain and produce public materials such as the LIGO Magazine.

(F) **Gravitational Wave Open Science Center support**: In order to encourage and facilitate the use of public strain data and other analysis data products, such as posterior samples from parameter estimation and population inferences, by the public, in educational settings, and by professional scientists, the LSC will provide services including curating and documenting analysis results for public release; documenting software; creating online tutorials and associated notebooks to demonstrate analysis techniques, plot making, etc.; coordinating Gravitational Wave Open Data Workshops, and responding to Gravitational Wave Open Science Center tickets asking for help with public data or software.

2.15 Reviewing Detector Upgrade Designs, Analysis Pipelines and Papers

Review of LSC methods, results and publications is a critical task that must be done to ensure that credible scientific results are produced and shared in a timely manner. Some review tasks require expert insights, whereas others only require a general background understanding and provide an opportunity to become expert in the area. Currently, there is often a shortage of reviewers, and hence there exists a need to increase active engagement in reviews and ensure that new reviewers are given appropriate mentoring. While often seen as thankless work, involvement in these tasks can give LSC members the opportunity to expand their knowledge and increase their exposure in other areas of the LSC. Therefore, it a priority for the LSC not only to perform reviews, but to investigate procedures that properly reward this work. All LSC related reviewing work is therefore considered InfraOps.

2.16 Roles in LSC Organization

The LSC has a complex organizational structure, with many members serving different roles, such as leadership and management of working groups, participation in committees, execution of non-scientific but necessary activities, etc.

There is a wide range of activities undertaken by Collaboration members that are organizational roles. Some of these have scientific elements, and some are simply necessary to maintain and propel the Collaboration. The activities listed below are critical to the smooth running of the Collaboration:

(i) Chairing or co-chairing an LSC governance body, as described in Section 2 of the Bylaws (on Governance) [15];

(ii) Participating in committees or chairing subgroups as detailed in the LSC organizational chart LIGO-M1200248 [21] as well as in ad-hoc Study Teams charged by the Spokespersons;

(iii) Participation in reviews of the LSC activities, e.g., reviews of LSC groups agreements (MoUs), reviews by funding agencies, presentations to LIGO's Program Advisory Committee;

(iv) Administrative support to the LSC organization (setting up, e.g., MoU meetings, maintaining spreadsheets and LSC activity documentation, LSC Activities accounting and invoicing);

(v) Management (by group leaders or their delegates) of LSC member groups.

Below, we highlight two new activities which will improve the long-term running of the Collaboration:

(A) **Professional support of the collaboration.** There is an increasing need for professional support for various aspects of Collaboration work. This includes support and maintenance of Collaboration websites and web services (wikis, version control repositories, etc); co-ordination of Collaboration press releases and media coverage; administrative support for leadership roles in the Collaboration, notably the Spokesperson and also leaders of large working groups and divisions; increased project management oversight of complex analyses and workflows. The Collaboration will track the need for professional support across the Collaboration and assess potential scenarios to fund this work.

(B) **Collection of demographic data.** The LSC recognizes the importance of diversity, equity, and inclusion in carrying out its scientific mission. The collection of demographic data is necessary in order to establish a baseline for determining progress in achieving diversity goals in the LSC, to monitor the diversity of our leadership positions, and to track the opportunities afforded our members for external recognition. The LSC DEI Committee will capture demographic data through regular surveys of the collaboration. The data will be analysed and results reported to the Collaboration. Trend data will be archived for comparison with future survey results.

3 Advancing frontiers of Gravitational-Wave Astrophysics, Astronomy and Fundamental Physics: Improved Gravitational Wave Detectors

The LSC, as part of the international gravitational wave detector network, has begun to plan for next generation detectors (3G) with longer baselines and improved detector technology [22]. Although this document is focused on the LSC program, research to enable improved detectors is a world-wide effort and the LSC works closely with Virgo, KAGRA, and other partners. As we move towards 3G detectors, the community envisages detector operation in three epochs spread over the next 25 years. The first (and current) epoch is defined by enhancements to the existing Advanced LIGO detectors, first to enable stable operation at the Advanced LIGO design sensitivity (see sections 2.1-2.4), and then to go beyond the Advanced LIGO design with the A+ upgrade which is described in Section 2.5. The second epoch will be devoted to maximizing the scientific benefits of the current facilities once the A+ project is complete. After A+ is implemented and the LAO detector in India is online, there will be five long-baseline detectors in operation. Similar to Enhanced LIGO, strategic implementation of 3G technology in the existing facilities can both improve their scientific reach while demonstrating key technologies for 3G detectors. Much of this work will be at room temperature; we are also exploring the potential of low-temperature Voyager technology.

A third epoch is planned starting in the 2030s with installation and operation of 3G detectors in new facilities, such as Cosmic Explorer in the US and Einstein Telescope in Europe. The research and development for new technologies to be implemented in such facilities needs to be done in the next several years to allow the design and timely funding and construction of these projects.

R&D is required to improve the performance of the ground based, suspended mass, laser interferometer subsystems, improve their integration into more and more sensitive instruments, develop new control architectures and explore new topologies. Beyond A+, upgrades to interferometric detectors' sensitivities require pushing the limits of all interferometer technologies with the possibility of operation at low temperatures.

R&D activities in the LSC program must have a clear vision for how such developments can be applied in, and/or improve the performance of, suspended-mass interferometric gravitational wave detectors. Important R&D studies and activities include those listed below; more details can be found in the LSC Instrument White Paper [4].

3.1 Substrates

For future detectors, fused silica continues to be the substrate material of choice for interferometric detectors operating at room temperature. Larger diameter and heavier test masses are needed to facilitate larger diameter beams to reduce thermal noise and to reduce radiation pressure noise.

Further improvement to the detectors through cryogenics requires substrates with excellent optical and mechanical properties at low temperature. The most promising candidate is single-crystal silicon.

(A) **Silica substrates:** Research across a range of areas is required to develop larger fused silica test masses which may be as large as 320 kg [23] and 80 cm in diameter. For example, such larger substrates require an improved surface figure error over the larger mirror face, controlling the residual substrate static lens, and maintaining the figure error despite elastic distortion when suspended. In addition research to mitigate the effects of charging noise and parametric instabilities on detector operation is necessary.

(B) **Crystalline substrates:** Critical R&D activities include the study and optimization of the optical and thermo-mechanical material properties of crystalline (silicon or sapphire) substrates, and the scaling of those substrates to the diameter required by future detectors (on the order of 80 cm). For example, techniques for super-polishing and surface figuring large silicon substrates need to be developed. Significant improvements in birefringence, optical absorption and scatter in these materials are needed for them to viable candidates for the substrates of future gravitational wave detectors. The multiple propagation directions through a beam splitter make the substrates for these optics particularly challenging.

3.2 Suspensions and Seismic Isolation

Test mass suspensions need to provide adequate seismic isolation and maintain low thermal noise levels while allowing alignment and control of the interferometer optics.

(A) **Suspension thermal noise reduction:** The final stages of the suspended optics require suspension elements of appropriate design to give improved levels of thermal noise, which in turn influence the specific geometry and intrinsic dissipation levels of such elements. Required research includes R&D on room temperature fused silica suspensions operating at higher fiber stress, able to support heavier test masses (perhaps up to 320 kg), as well as R&D to improve the thermal noise performance of other portions of the suspension system, including lower thermal noise cantilever springs and bonds with the low mechanical loss, strength and vacuum-compatibility properties appropriate for new suspensions. Moving to cryogenic temperatures as envisaged for future developments requires development of crystalline suspension fibers (ribbons/fibers) with associated characterization of the thermo-mechanical properties of cryogenic materials (thermal expansion, thermal conductivity) and equivalent R&D as mentioned for silica suspensions, but translated to the cryogenic regime. In addition, studies are required of the application of techniques for cooling the optics via radiative and/or conductive processes.

(B) **Isolation, alignment and control:** Operation of interferometric detectors requires appropriate levels of isolation of the interferometer components from mechanical disturbance, necessitating research on mechanical design and active control systems. This includes increasing the robustness of the detector systems to external disturbances such as high winds or seismic events, and the use of enhanced sensing and control systems to improve stable observatory operations. Heavier test masses will require studies to optimise overall suspension performance, enabling seismic isolation and suspension control improvements that extend the detection band to below 10 Hz. These upgrades have to respect the load limits of the seismic isolation tables. Furthermore sensors, actuators and a mechanical design capable of providing low-noise seismic isolation in both the room temperature and cryogenic regime need to be developed.

Current detectors are not directly limited by seismic motion in the detection band, but rather by noise from sources such as scattered light and interferometer control. Many of these sources have strong interactions with seismic motion, and coordinated, systematic efforts is required to improve the in-band performance.

(C) **Newtonian noise reduction:** Finally, to benefit from improved seismic and thermal noise levels, the LSC will perform R&D targeted at methods of seismic and atmospheric Newtonian noise estimation and cancellation, and the design of a low-noise infrastructure.

3.3 Optical Coatings

Studies of the properties of the optical coatings applied to the test masses of ground-based, suspended mass gravitational wave detectors are required to enable sensitivities beyond that of current detectors, notably in the most sensitive frequency range of the instruments. This topic covers a wide range of optical and materials R&D, from atomistic simulation of coating materials, through development of techniques for enhanced coating deposition and creation of new materials to characterization of the macroscopic properties of coatings (both optical and thermo-mechanical) in the laboratory and in situ, at room and cryogenic temperatures.

Examples of where these R&D areas are required include:

(A) **Continued development of improved amorphous coatings:** R&D is required to understand the sources of, and further reduce, mechanical loss of coatings materials while achieving suitably low levels of optical absorption and scatter. This includes materials modeling, design, development, deposition and characterization of properties of coatings (optical and thermo-mechanical). The LSC is working intensely to finalise the recipe, and support the Pathfinder process, regarding the oxide materials for use at 1064 nm and room temperature to be implemented in A+ (see Section 2.3). Further improvements in coating thermal noise would be attractive for intermediate enhancements beyond A+, which could include moving to longer wavelength at room temperature to exploit the benefits of amorphous silicon-based coatings. Improved coatings will be required for Cosmic Explorer, and additional effort is needed to explore operation at longer wavelengths and lower temperatures for the second phase of Cosmic Explorer. Overcoming coating defects such as scatter, optical absorption, and delamination remains a key challenge, particularly as we attempt to increase the optical power in interferometers.

(B) **Technology challenges for manufacturing coatings for large diameter optics:** The larger size test mass substrates being studied elsewhere in the program will require appropriate coatings with uniformity of thickness and homogeneity of properties across large diameters. Thus research is needed to understand the relevant tolerances on coating properties and develop deposition techniques meeting required tolerances.

(C) **Development of large crystalline multi-layer coatings:** Crystalline GaAs/AlGaAs coatings have demonstrated excellent optical properties and thermal noise that is $\approx 10\times$ lower than that of the Advanced LIGO coatings. Additional investigations are needed on the impact of birefringence variations and crystal defects. R&D efforts should continue to develop techniques for scaling production from the current 20 cm to 30 cm for A#, and greater sizes for 3G detectors.

3.4 Cryogenics

Cryogenic interferometers are an attractive approach to lower substrate, coating, and suspension thermal noise and potentially reduce the impact of thermal aberrations, but require a whole spectrum of new technological developments, from seismically quiet cooling systems, to new substrates and coatings, stable sensing and control systems, and different laser wavelength. R&D on testing the implementation of these in cryogenic interferometer technology in prototypes is therefore essential.

The LSC is taking major steps in developing cryogenic technologies. This includes work with cryogenic silicon around its null in thermal expansion near 120 K using radiative cooling, as well as silicon, sapphire and other materials below 10 K using conductive cooling.

3.5 Lasers and Squeezers

Advanced LIGO sensitivity will ultimately be limited in a broad band of frequencies by quantum noise (shot noise and radiation pressure). In O4 and A+, higher laser power and the quantum manipulation of the light (squeezing) will be used to improve the astrophysical reach. Lasers and squeezed light sources are critical subsystems in current and future detectors, where higher laser powers, enhanced levels of stabilization and sub-standard-quantum-limit sensing are required. Further, material choices for core optics components and coatings currently suggest that a change of operating wavelength will be desirable or even essential to achieve improved sensitivity levels. Areas of required research and development include:

(A) **Laser development**: It is still necessary to achieve a high power (200 W) pre-stabilized laser with understood noise coupling into the interferometer in Advanced LIGO, including alternatives such as power fiber amplifiers or coherently combined solid state amplifiers. For future detectors, pre-stabilized lasers at longer wavelength (1.5 or 2 microns) operating at 200 W and above are needed.

The use of low-noise, high power handling and high quantum efficiency photodiodes will improve the sensitivity of detectors, especially if using squeezed light.

(B) **Squeezed light sources**: Development and optimization of crystal squeezers is needed at longer wavelengths, as well as methods to reduce losses in the injection and internal coupling of squeezed states. The application of squeezing to reduce the broadband noise currently requires filter cavities; frequency-dependent squeezing without such cavities would make implementation more practical. There are novel squeezed state generation concepts (e.g. ponderomotive squeezing) that require investigation for possible use in detectors.

(C) **Squeezed light integration**: To gain the most benefit from squeezing, exquisite control of the optical properties of the interferometer is required. The benefits of squeezing can be significantly degraded through small amounts of optical loss and mode matching errors. Improving the realized squeezing on as built interferometers is an important part of the quantum noise improvement effort. Squeezing levels of up to 6dB were realized, which is significantly less than the 10 dB of quantum noise suppression often specified for third generation detectors. Ongoing efforts to understand and develop techniques to reduce optical loss and improve modematching are an important part of this effort. These efforts have significant overlap and synergy with auxiliary system development (Section 3.6).

3.6 Auxiliary Systems

Auxiliary systems are those technologies used in the interferometer not described in previous sections, such as Faraday isolators, electro-optics modulators, auxiliary lasers, and auxiliary cavities (input and output mode cleaners). The requirements for such systems often change in response to other design choices, such as cryogenic operation, test mass substrate materials, laser wavelength and squeezing operation. R&D activities include high power modulators, low-loss and high power isolators, arm length stabilization using a non-harmonically related laser wavelength, thermal correction systems for use at high power operation, and active wavefront control.

3.7 Topologies, Readout, and Controls

While subsystem improvements can separately enhance interferometer performance, interferometer topologies can combine these subsystems together in ways that further increase signal (or signal bandwidth) or reduce noise coupling. The integration of novel topologies will be limited by controls, and parallel research into controls systems, including deep learning optimization, is necessary to manage the complexity of proposed systems.

Research is ongoing into technologies that use different modes of action to improve interferometer performance. Topologies that reduce quantum back-action noise fall under a class of experiments known as quantum non-demolition (QND). Areas of focus include speedmeters, enhancing the test masses mechanical response to the gravitational waves using dynamical back-action of light, intra-cavity nonlinear devices for internal modification of quantum states, and high-frequency sensitivity improvement using negative-dispersion medium in the interferometer, with controls systems and deep learning optimization as required for their implementation.

Proof of concept requires the development of prototype interferometers of appropriate scale.

3.8 Large Scale Facilities

The very large scale of the facilities envisioned for Cosmic Explorer poses significant challenges, particularly for their cost and siting difficulty. Research on ways to build the vacuum system more cost effectively and to explore ways to deal with the civil engineering challenges of building 40 km long interferometer arms will help enable 3G detectors. A preliminary search for sites adequate to house a 40 km detector is required, including a survey assessing topography, geology, seismicity, as well as cultural and environmental impact.

4 Advancing frontiers of Gravitational-Wave Astrophysics, Astronomy and Fundamental Physics: Enhanced Analysis Methods

The LSC has, over the years, developed a diverse suite of detector characterization tools, gravitational wave searches, and parameter estimation routines and tools to interpret gravitational wave observations. In the future, as gravitational wave detectors become more sensitive, as the global network expands, and as our understanding of gravitational waveforms and gravitational astrophysics improves, significant effort will be required to enhance the existing analyses and to develop improved methods to identify and interpret signals in the LIGO data. In this section, we outline the LIGO Scientific Collaboration's plans for longer-term development of analyses.

4.1 Development of calibration resources

As stronger signals are observed and the gravitational wave detector network grows, improved detector calibration is required to accurately obtain parameter estimates, sky location and perform precision tests of general relativity. Details on these activities are found in the LSC white papers [5, 4]. Examples of planned calibration research and development activities include:

(A) **Improvement of the detector calibration above 1 kHz.** Investigate and accurately model the response of the detectors above 1 kHz which will benefit studies of the post merger signal and high-frequency burst-like signals;

(B) **Integration of LIGO calibration uncertainty estimates into astrophysical analyses.** Incorporate the calibration uncertainty at the time of a gravitational wave event into the astrophysical analyses to accurately accommodate for the changing response of the detector over time;

(C) **Improvement of LIGO calibration precision and accuracy.** Resolve any potential systematic error in the overall scale of the calibration and augment the precision and accuracy;

(D) **Automation of standard calibration precision and accuracy checks.** Automate the current methods to track and report the calibration precision and accuracy for more constant and effortless review;

(E) **Improvement of the calibration software.** Advance and augment the low- and high-latency production calibration pipeline and front-end based calibration software.

4.2 Development of detector characterization resources

Detector characterization remains vital to accurate identification and interpretation of signals in the gravitational wave data. During commissioning breaks and upgrade intervals, the focus of the group is on development and improvement of noise mitigation methods, as well as characterization of the performance of the LIGO instruments as their configuration evolves. During and following an observing run, the focus of the group is on improving the performance of the LIGO detectors and the quality of the data from the perspective of the astrophysical analyses. Examples of planned detector characterization activities, with details found in the LVK white papers [6], include:

(A) **Characterization of the components and subsystems of the LIGO detectors.** This is an important activity during commissioning efforts and instrument upgrades;

(B) **Investigation of the search background.** Study how instrumental artifacts affect the sensitivity of a specific search or method and develop search-specific techniques for noise mitigation;

(C) **Mitigation of noise artifacts.** Develop generic data cleaning and conditioning techniques for removal of noise artifacts (transient or persistent) from the strain channel as part of mainstream data analysis;

(D) **Machine learning and community science.** Research and development of machine learning, community science and/or new methods to identify and/or mitigate instrumental causes of noise;

(E) **Improvements to production trigger generators.** Enhance the performance of production trigger generators to more accurately report timing, frequency and signal-to-noise ratio of excess power;

(F) **Integration of key tools to be cross-compatible.** Ensure all essential tools, triggers and data products share the same well-maintained, well-documented and accessible codebase;

(G) **Quantification of the impact of transient noise on parameter estimation.** Evaluate the effects of transient noise on recovered source parameters and develop methods to reconstruct and remove transient noise from the strain channel without the use of auxiliary witnesses.

4.3 Development of searches and parameter estimation methods for future runs and improved detectors

Future development activities include new R&D projects, major search program upgrades and the optimization of existing tools. Future development must account for the evolving gravitational wave network with additional detectors and improving sensitivity, along with advances in the gravitational wave source modeling and inclusion of the latest astrophysical models. It should also keep up with the fast development of computing and artificial intelligence.

The development of new projects, or major upgrades to existing searches, take a significant amount of human and computing resources. Currently proposed development activities are listed in the LVK white paper [5]. The LSC will prioritize projects taking into account the scientific scope of the proposed development, potential applications, relevance to the LSC publications, the human and computing resources required, and the necessary support and review needed for new tools. Development of a new search algorithm, or a major upgrade to an existing analysis, will be considered part of the LSC program if at least one of the following requirements is met:

(A) **A new gravitational wave target.** The new algorithm targets a specific astrophysical source or phenomena from the list of the LSC gravitational wave target classes (see Section 1.2) not covered by the existing pipelines;

(B) **Improved scientific output.** The new algorithm has the potential to do significantly better science with the LSC gravitational wave target classes than algorithms in operation;

(C) **Second, independent pipeline.** The new algorithm searches for a particular gravitational wave target class with a second, independent pipeline of comparable sensitivity when only one pipeline exists;

(D) **Computational efficiency.** The new algorithm is computationally more efficient, and permits computationally limited searches to achieve significantly improved detection or characterization of gravitational wave sources, or the new algorithm makes more optimal use of computing resources, for example using GPUs or allowing the use of non-LSC resources like the Open Science Grid, maximizing the scientific return possible given finite LSC resources.

When independent pipelines (or different configurations of the same pipeline) are being developed to address the same astrophysical source, a composite pipeline should also be developed, where possible, in which results from the individual pipelines are combined leading to a single quantitative statement such as the confidence in each candidate or an appropriate upper limit in the event of a non-detection. Tools and methodologies are also required to quantify the scientific benefits of multiple pipelines.

4.4 Development of tools for scientific interpretation of gravitational wave observations

The gravitational wave astronomical measurements discussed in Section 1.3 require interpreting the results of searches and parameter estimation in light of current gravitational, astrophysical, cosmological or subatomic theory. Ensuring that our publications are well informed by current theory is important, as is incorporating relevant models driven by theory into LSC algorithms. The primary goal of the LSC is to make well grounded interpretations from new gravitational wave signals, guided by published theory, especially where gravitational waveforms, including signal times of arrival, are critical to interpretation. The LSC currently plans to further develop and exploit tools for interpretation in the following topics:

(A) **Populations of merging compact binary systems.** The LSC will develop tools to interpret the results of gravitational wave searches to make statements about the source population, using the properties of single events, the ensemble of a population of detections, and information from the observation of the stochastic background (or lack thereof). This will include parametric and non-parametric modeling of the merger rate density as a function of mass, spin and redshift for black holes and neutron stars. Interpretation of results will be done with reference to existing literature on binary evolution, complementary observations, and predictions for gravitational wave source properties.

(B) **Tests of GR and searches for deviations from GR predictions for well understood sources.** The LSC will maintain a suite of tests for both gravitational wave data alone (e.g., deviations of waveforms from GR predictions for inspiral, merger and ringdown phases of binary systems; evidence of dispersion in the waveform), and where possible, when electromagnetic signals are seen, tests of the speed of gravitational radiation relative to that of light. Polarization measurements can be carried out from multi-detector compact binary coalescence detections, and in the event of a continuous-wave signal detection, it should be possible to extract highly precise polarization measurements of the signal, allowing tests for deviations from GR predictions.

(C) **Measurements of matter effects in merging binary systems and properties of neutron star matter.** The LSC will establish a systematic program of testing inspiral waveforms for evidence of tidal effects, along with seeking and interpreting gravitational wave signals from potential postmerger remnants (e.g., hypermassive neutron stars). We will use published multimessenger observations and upper limits of gravitational wave sources to interpret the properties of binary coalescences. For detections of coalescing binary systems coincident with GRBs, we will work with gamma-ray observers to interpret the burst phenomenology. Similarly, in the event of a nearby supernova, we will work with neutrino observers to interpret the collapse and explosion phenomenology. Further, the LSC will establish systematic interpretation of any detected continuous-wave signal (ideally, also using electromagnetic signals) to constrain the structure of the source star and hence the equation of state.

(D) **Measurements of the expansion history of the Universe.** The LSC will work to improve measurements of counterpart standard siren cosmology from multimessenger observations of binary coalescences. This will require developing tools to improve measurements including potential sources of systematic error, and collaborating with electromagnetic observers and modelers to incorporate available follow-up observations that inform inclination determination. For binaries without an counterpart the LSC will work with astronomers to incorporate improved galaxy catalogs into the analyses.

(E) **Gravitational lensing of gravitational waves.** The LSC will develop tools to exploit the diverse astrophysical insights that could be gained from gravitational wave signals lensed by intervening matter, e.g., for improved source parameter estimation and population inference, studies of lens profiles and populations, cosmography, and additional tests of general relativity.

(F) **Interpretation of potential new physics effects beyond the Standard Model of particle physics.** It is possible that gravitational wave interferometer signals will bring evidence of entirely new physics beyond the Standard Model of elementary particles. Examples include cosmic string cusps (detected individually or stochastically from an ensemble), stochastic gravitational radiation from the early Universe processes such as inflation and phase transitions, direct dark matter detection (clumped or background field, primordial black holes), or superradiance induced by a condensate of new, ultralight bosons, such as axions created by extracting energy from a fast-spinning black hole. The LSC will develop tools to interpret detected signals, or lack thereof, in light of such predictions from the literature.

4.5 Analytical and computational research supporting gravitational wave analysis software

The search and interpretation of coalescing binary signals benefit directly from accurate analytical and numerical models of the gravitational waveform emitted by those sources. Searches for coalescence of binary systems use template waveforms to separate astrophysical signals from noise. Estimating source parameters and their uncertainties is based on comparing the data with millions of modeled signals, and testing the strong-field gravitational wave regime relies profoundly on accurate predictions of the expected gravitational wave signature. Research in the areas of improved analytical and numerical modeling, carried out by researchers inside and outside the LSC, is an important building block towards improved analyses of gravitational wave data.

The LSC will ensure in a collaborative effort that modeling advances supporting the LSC's science goals (as described in Section 1 and presented in detail in [5]) are appropriately implemented and tested in its analyses. Here, modeling is taken to include both analytical and numerical predictions of the gravitational waveform. In particular, this includes:

(i) The implementation of new waveform models, and optimizations or incremental model improvements in LSC analysis software;
(ii) Waveform model improvements and computational optimizations targeted for application in LSC analyses, provided these activities lead to a fully implemented model within two years;
(iii) Review of model implementations and tests of the LSC's analysis sensitivity and performance under model changes;
(iv) Production of numerical waveform data that are readily usable by the LSC's analysis software within two years;
(v) Maintenance of waveform-related LSC infrastructure;
(vi) General interactions and knowledge transfer between modeling experts and analysts, in support of the LSC's observational results.

To obtain the best scientific interpretations of gravitational wave observations outlined above, it will be important to continue to improve the accuracy of the analytical waveform models, so that systematics from modeling do not dominate the statistical and calibration errors. Furthermore, it is relevant to enlarge the set of numerical-relativity waveforms used to calibrate and validate the waveform models. To take full advantage of the discovery potential, it is crucial to include all physical effects in the waveform models, such as spin-precession and higher modes, eccentricity, higher-order tidal and spin effects.

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