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LIGO SCIENTIFIC COLLABORATION

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LIGO Scientific Collaboration Program 2020–2021

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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 multi-messenger 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 GEO600 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 GEO600) in perpendicular arms in each detector, above ground and in vacuum [2, 3].

The LSC is engaged to bring its advanced detectors to their design sensitivity, undertake observing runs, and collect calibrated gravitational wave data. The Collaboration develops, maintains, and updates/optimizes complex software to identify times of good data quality and perform searches for gravitational wave signals in the LIGO data, using 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 multi-messenger observations of gravitational wave events. The LSC extracts the details of the gravitational wave signals from the data and, using the measured properties of the signal, presents in publications the astrophysical implications of the observations.

The LSC works closely with the Virgo Collaboration and KAGRA Scientific Collaboration operating gravitational wave detectors to ensure the coordinated operation of the global network of ground-based detectors.

Following a proprietary period, the LIGO data 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, manipulating the quantum nature of the light in the interferometers to reduce the quantum noise in the measurement, and attenuating further the effect of seismic noise. The LSC will assist the LIGO-India project team to construct a LIGO detector in India and bring it to a comparable sensitivity to the other LIGO detectors to expand the global network. The LSC will participate in the planning of a future generation of gravitational wave detectors.

The LSC has more than 1,300 members from about 100 institutions in 20 countries, so there is significant infrastructure 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 2020–2021, and 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].

1.2 LSC Science Goals: Gravitational Wave Targets

The Advanced LIGO and Virgo detectors took data during the third observation run between April 1, 2019 and March 27, 2020. The observatories were operating with binary neutron star inspiral ranges of 100–120 Mpc (LIGO Hanford), 118–142 Mpc (LIGO Livingston), and 43–59 Mpc (Virgo). A total of 56 (non-retracted) public alerts were issued, corresponding to approximately one event candidate every six days. Sky localization information was provided for all public alerts. Most events were classified as binary black holes. One, GW190425, had a total mass of 3.4 solar masses, and a good chance of having one or two neutron stars as components [8]. Unlike GW170817, no optical counterpart was identified, but this was not unexpected due to the larger distance and poorer localization.

During the one year period of this program the detectors will undergo a number of upgrades and are not expected to be observing. In the meantime there are a number of planned publications based on O3 data, including catalog papers and a few high impact results from extraordinary events. This schedule might however see modifications due to the current COVID-19 pandemic. We describe below the gravitational wave targets for which we will publish results using the O3 LIGO and Virgo data.

(A) **Gravitational waves emitted during the coalescence of compact binaries**. We will search for mergers of compact binaries that produce gravitational waves in the sensitive frequency range of the LIGO detectors, including binary systems with neutron stars and stellar-mass black holes. These searches have been developed over the history of the Collaboration and are now mature. They are run in low latency to provide alerts to electromagnetic observers, and offline to produce the final catalog of observed binary mergers. Despite their maturity, these searches and parameter estimation codes will benefit from improvements, e.g., using more accurate waveforms, or incorporating additional physical effects into the search waveforms, such as the presence of matter in mergers of neutron stars, or eccentricity, precession, and higher harmonics in black hole mergers. This software must also deal, at times, with poor data quality, especially for brief transients, such as from high mass black hole mergers. Upgrading the software to handle these complications can improve search sensitivity.

(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 gamma-ray bursts, fast radio bursts, supernovae, and magnetar flares. 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) **Gravitational waves emitted by previously unknown non-axisymmetric neutron stars.** We will search for continuous gravitational wave emission from fast-spinning galactic neutron stars, both isolated and in binary systems. 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 mergers, cosmic string cusps and kinks, and of cosmological origin. We will also search for an anisotropic background, where the anisotropy could arise if the background is of astrophysical origin and may be correlated with structure in the local Universe.

1.3 LSC Science Goals: Gravitational Wave Astronomy

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 O3 data.

(A) **Public alerts.** During an observation run we will issue prompt and public alerts of significant gravitational wave events in newly recorded data to allow for follow-up observations with electromagnetic and neutrino observatories. While currently no observations are planned for the upcoming year, the current COVID-19 pandemic might force a change.

(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 merger, 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 best-fit maps of sky position and distance.

(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 mergers of binary neutron stars and/or black holes.

(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 mergers or through continuous gravitational wave emission, we will probe the underlying structure of the 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 merger 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. 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 mergers) or statistically derived from overlaying a galaxy catalog on the source localization. Similarly, we will also study gravitational lensing effects on gravitational waves.

2 LIGO Scientific Operations and Scientific Results

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, O3 started April 1, 2019 and ended March 27, 2020. 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. The LSC also makes sure the acquired gravitational wave data are 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 LIGO/Virgo/KAGRA 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.

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 that have been or will be taken and the use or operation of analysis tools to obtain scientific results from the data. It also includes the remaining development or upgrades of existing tools to successfully complete the analysis, and begin 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.

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

COVID-19: At the time of writing this program the world was in the middle of the COVID-19 pandemic, affecting almost every aspect of life. Naturally the pandemic will have an effect on the operation of the LSC and LIGO Laboratory, slowing down progress towards the LSC's goals. Indeed the O3 observation run was already cut short one month; the LIGO Hanford and Livingston Observatories are effectively shut down. While we cannot foresee the total impact of the pandemic at this time, we will try to highlight possible effects on the LSC throughout this document.

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. During the 2020–2021 period, the LIGO Laboratory will be planning and carrying out the detector improvements that have been identified as targets for sensitivity improvement in preparation for the O4 observing run. Concurrently, the A+ construction project will be making preparations for a first phase of instrumentation installation during the O3–O4 break. The focus of the A+ team will be making the necessary procurements and instrumentation designs to be prepared to begin installing those elements of A+ that can be introduced without affecting preparations for O4. In addition site facilities will undergo modifications at both observatories to accommodate the filter cavities for A+. The pace of this work in 2020 and 2021 will depend on how quickly restrictions put in place to suppress the spread of COVID-19 are relaxed in the regions and localities where the LIGO Laboratory and LSC institutions are located.

The LIGO Laboratory will plan all activities related to the detectors and vacuum refurbishment efforts. Typical activities that will be undertaken over the next year will include the following: replacing some of the core optics that have point absorbers; continuing test mass point absorber R&D; completing the installation of baffling systems to reduce scattered light noise; improving particulate contamination control;

increasing the laser power for eventual power increase once the point absorber issues are surmounted; improving automation of detector operation; and vacuum system recovery. Again, the relaxation of COVID-19 restrictions will determine how much of this work can be accomplished in the coming year.

The LIGO Laboratory personnel will also maintain and update the Control and Data Systems (CDS) suite of software [9] 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 O3–O4 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 FY2021. The AWP is currently in draft form and will be finalized in July 2020. A detailed list of detector improvements can be found in the LIGO Detector Improvements Work Packages document.

The GEO Collaboration is responsible for the operation and maintenance of the GEO600 Observatory, taking data in AstroWatch mode while the LIGO detectors are being commissioned, and testing new technology developments later to be implemented 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 Commissioning Leader 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 and making tests that could produce incremental sensitivity improvements. Longer breaks for commissioning or implementing detector improvements are possible with the approval of the LIGO Operations Management Team.

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, Chief Engineer, 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 most contributions are from LIGO Laboratory personnel, other LSC institutions make important contributions as well: a recent example being some components of the Squeezed Light Injection system.

During the 2020–2021 period, commissioning activities will be interleaved with the detector improvement and A+ upgrade program (described in Section 2.1) as detector improvements are carried out. At present, a brief (2–4 week) commissioning period is planned sometime in the July or August 2020 time frame once the Hanford and Livingston detectors have been brought back to an operational state. Longer commissioning periods are scheduled for later in 2020 — a 3.5 month commissioning break for LHO and two 2 month commissioning breaks for LLO beginning in the Fall of 2020 or early 2021. These schedules are likely to change as the impacts of COVID-19 become more clear. The restrictions on travel due the COVID-19 situation may increase the opportunity for more remote participation in commissioning that could benefit the Collaboration going forward. This could include increased offsite detector systems analysis and modeling specific to commissioning. It could be facilitated by establishing a list of open commissioning questions that would benefit from additional remote effort.

2.3 LSC Fellows Program

LSC Fellows are scientists and engineers who are resident at the LIGO observatories for extended periods of time [10]. LSC Fellows work with on-site mentors or liaisons depending on their initial level of expertise and the nature of their project.

The LSC Fellows program is entering its sixth year and 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 LSC Fellows carry out 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 the learning opportunity to gain hands-on experience at either of the two LIGO observatories. Their time spent at the observatories contributes to their development as scientists at the beginning of their careers, whether they pursue experimental or data analysis foci.

At the time of this writing the coronavirus pandemic has led to the shutdown of operations at both LHO and LLO: the LSC Fellows Program was one of the first casualties of the pandemic as all fellows were advised to do what they felt was in their best interest. Several could return to their home institutions. Others remained in their accommodations working remotely, as did the rest of the Laboratory staff. This suspension will last at least until the end of 2020. The Laboratory is evaluating options for returning to different levels of operation, based on guidance provided by state and local authorities, as well as Caltech as the institutional operator of the observatories for the NSF. The full extent and impact of the current shutdown will become evident as the Laboratory evaluates the situation.

According to the original plan, during the year 2020–2021 the observatories will be undergoing upgrades for O4 and in further support of A+. When LSC Fellows are allowed to return to the observatories, they will have the opportunity to take part in hardware installation, and then participate in investigations with the commissioning and detector characterization groups.

2.4 Detector Calibration and Data Timing

Timely, accurate calibration of each detector's differential arm length channels into equivalent gravitational wave strain 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 on-line gravitational wave searches and the off-line analysis of gravitational wave signals or 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 calibration) to track calibration at certain frequencies, and a model for the detector's frequency-dependent sensitivity to produce time-dependent calibration and estimated uncertainties. The model is vetted with measurements before, during and after each observing run [11].

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 online calibration (called C00) allows low latency analysis and regular assessment of systematic errors in the data. The final offline calibration (called C01) is used in final analyses of the data and for public bulk data release. The goal for C00 is that it will be sufficient for writing most exceptional-discovery papers (see sections 2.8 and 2.9), except where tracking of systematic errors indicates otherwise. The final C01 calibration will be used for production of final catalog papers, and in cases where systematics in C00 are significant enough to prevent its use for exceptional-discovery papers.

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 for example cosmological measurements), needs to be quantified. Hence all follow-up analyses and searches to be run on O4 data need to document the calibration error impact on the analysis results and communicate this information to the calibration group to establish the acceptable level of accuracy both for C00 and C01 calibrations before the run.

Furthermore, independently on whether the C00 calibration will be used for the final results of the papers, it is highly recommended that parameter-estimation analyses and their interpretation start as soon as possible using the C00 calibration, so that the results can be used to write the papers, guaranteeing their swift completion.

The calibration accuracy of C00 should be assessed within 1 month of taking data to enable exceptional-discovery publication decisions. Calibrated data (C01) and associated uncertainty estimates should be produced with sufficient quality for publication of final results within 2 months of the end of each 3-month data segment. Since improved calibration can improve the gravitational wave science, some development projects are now underway, including Newtonian calibrators and improved, NIST-traceable power monitoring for the photon-calibrator subsystem.

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 sub-systems of the detector. The timing distribution system's status is monitored, and periodically tested in-depth via timing diagnostics studies.

2.5 Operating computing systems and services for modeling, analysis, and interpretation

The timely production of LSC results requires significant computing resources, and dedicated, expert computing personnel. Below is a list of essential services. Turnover in computing support personnel working on those services is of particular concern. Continued support is essential for the LSC to operate.

(A) **Provision of computational hardware for analyses.** 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. Usage of the clusters has to be tracked accurately to ensure efficient use of computing resources and guide code-optimization efforts.
(B) **Transition to grid-based computing environment.** The LSC, in coordination with Virgo and KAGRA, will transition to a joint computing environment based on the Open Science Grid Platform, with shared responsibility for provisioning computing resources and computing FTEs. 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.

(C) **Data 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.

(D) **Engineering and operations of computing environments.** 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. Engineering and operations includes: system provisioning and maintenance; operating and maintaining automated build and test tools and systems; packaging software for easy installation by users; 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.

(E) **Collaboration operations support.** 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. 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.

(F) **Curation and preservation of the LIGO data.** As described in the LIGO Data Management Plan [12] LIGO maintains a copy of all LIGO gravitational wave interferometer data taken during observational runs up to and including O3 data in the central data archive at Caltech with remote backups at the observatories.

2.6 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 in 2020–2021, work that will require expertise in both the astrophysical searches and instrumentation.

2.7 The operations 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 following activities are critical for the effective and timely analysis of the gravitational wave data:

(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 public alerts for significant events, and rapidly update or retract the alerts based on 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 false alarm rate, 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) **Running the gravitational wave searches on archived data.** Preparation and execution of searches for all gravitational wave targets on archived O3 data, with final calibration and data quality. 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 resources. Therefore, we would generally expect to run no more than two analyses for a given source or a region of the parameter space, and that pipelines run in production be justified, following the LSC–Virgo multiple pipeline policy.
(E) **Maintenance of production search software.** Although the search algorithms, analysis algorithms and waveforms should be reviewed and tested before use in production, there are often maintenance activities needed to address bugs, security and unforeseen problems.
(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.

(G) **Multi-messenger searches.** Conduct multi-messenger 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. Current examples include low threshold gravitational wave triggers shared with the Fermi GBM Collaboration, and joint searches with the neutrino detectors.

(H) **Review of results.** Prompt and thorough review of the analysis results and of the LSC publications enabling publication of high impact results as soon as possible and before data become public.

2.8 Deliver data analysis tools to search and interpret the gravitational wave data

The LSC has carried out gravitational wave searches on the O1–O3 data to identify the targets listed in section 1.2, and to extract the gravitational wave science detailed in section 1.3. The existing tools generally performed well in the O3 run. However further delivery, automation and review of analysis tools are required to ensure timely and effective searches of the O4 data, and to characterize 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 Data Analysis white paper [5]. Examples of those required for completion of the O4 analysis include:

(A) **Automation of 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 to keep up with the observations. Additionally, where possible, review tasks should be automated to enable high numbers of analyses to be checked efficiently.

(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. The infrastructure for public alerts was developed, tested and reviewed before the beginning of the O3 run. However O3 operations show the need for further development and updates. Required are improved methods for handling alerts from multiple search algorithms and correctly prioritize the right information to provide in the alerts.

(C) **Implementing and testing operation plans for the O4 observing run.** This is critical to enable sustainable use of both human and computational resources in delivering gravitational wave science from the data. The work includes the ongoing efforts to optimize gravitational wave search and parameter extraction analyses for computational efficiency and run-time. It also requires documenting the calibration error impact on the analysis results before the run, and communicate this information to the calibration group (see section 2.4).

(D) **Prepare existing analyses for exceptional discoveries.** The O4 run is 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 or enable significant improvements in the measurement of physical or astrophysical quantities. The Observational Science groups should identify potential events and discoveries and ensure that analyses are in place, tested (with mock data challenges) and reviewed prior to the start of the next observing run to enable rapid identification and publication of significant new discoveries.

(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. In addition, refined methods for applying information on data quality and accounting for detector non-stationarity should be improved 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.

(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 and to update rate and population information are required. Mock data challenges are suggested to avoid bias from un-blinded post-event analysis (such as cosmological measurements or neutron star equation of state measurements).

(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 (higher 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. Additionally, waveform generation can be the computationally dominant part of parameter estimation routines, requiring optimization work to speed up the analyses.

2.9 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 observation run we will provide prompt and open public alerts for significant transient event candidates. These alerts will include the significance of the event, the estimated probability of the event being a BBH, NSBH or BNS candidate, as well as a source localization. Alerts will be updated as further information becomes available from follow-up studies.

(B) **Publication of Scientific Papers:** We will produce high-impact publications using O3 data for results on all of our gravitational wave targets in a timely manner. We divide the O3 run, which started on April 1, 2019, into two sets, O3a and O3b, about six months each. The publication plan is produced and updated, jointly with Virgo and, if appropriate, KAGRA, with detailed plans for teams and dates for collaboration papers, following the plan described in this section. The current COVID-19 pandemic has impacted progress on many of our papers, typically with a one month delay due to the disruption, but all papers are moving forward.

   (i) **2nd quarter 2020** (i.e. as this program is written)**:** Several publications related to O3a exceptional discoveries have been submitted during the last three months (GW190412, GW190521, GW190814).

   (ii) **3rd quarter 2020:** We will produce a set of high-impact papers with the analysis of O3a, including a catalog of detections from coalescing binary systems (black hole binaries of diverse masses, binary neutron star and neutron star-black hole systems), characterization of their properties and astrophysical distribution, tests of general relativity, searches for gravitational waves associated with gamma-ray bursts, and constraints on the ellipticity of millisecond pulsars. Also, we plan to release papers on searches of continuous signals from unknown pulsars in the Galaxy and from supernova remnants.

   (iii) **4th quarter 2020:** We plan to produce a set of publications related to the analysis of O3b data, including a catalog of detections from coalescing binary systems and the characterization of their properties; studies of the astrophysical distribution and the measurement of the Hubble constant; tests of general relativity; results for coincident detections with gamma-ray bursts and high-energy neutrinos; results from searches of continuous signals from known pulsars in the Galaxy; and results for a gravitational wave stochastic background (isotropic, anisotropic and focused on promising directions). Furthermore, using O3a data, we also plan to release results of searches for continuous waves from neutron stars in binary systems. Finally, using all O3 data we plan to release results of searches for unmodeled transients.

(iv) **1st quarter 2021:** KAGRA collected observational data from April 7-21, 2020, along with GEO600 (after LIGO and Virgo suspended O3 operations), in a run period named O3GK. Plans are being made to write a paper covering the detector status, joint data taking, and searches for any type of signals which occurred during that time. We also plan to publish a paper searching for cosmic strings.

(v) **2nd quarter 2021:** We plan to publish results from searches for continuous gravitational wave signals from as-yet-undiscovered isolated neutron stars; sources in the direction of the galactic centre; low mass X-ray binaries, including Scorpius X-1; dark matter sources, such as boson clouds around black holes; emission from pulsar r-modes. We also plan to publish results of searches for sub-solar mass compact binaries and a stochastic background from binary black hole coalescences.

Within six months or less from an exceptional discovery: Looking towards O4, prior to the publication of catalog papers, we will submit to journals papers describing exceptional new discoveries. Certain discoveries, such as events with optical counterparts, might require a much shorter time-to-publication, while unexpected discoveries that do not fall into an anticipated category might require extra time. Within one month from the discovery, the appointed science team will present details of the publication timeline and paper scope. Examples of exceptional discoveries are: a new class of binary systems; a binary with parameters definitely outside the previously observed region (a significant neutron star–black hole, a binary with high spin magnitudes, spin precession, large mass ratio, large/small component masses, etc); observations leading to new insights about the neutron star equation of state; observable post-merger signal; deviations from general relativity; or an exceptional unmodeled gravitational wave transient (with or without associated multi-messenger transient).

(C) **Release of Data at times of Gravitational Wave Transients:** 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 [12], the LSC will make public the calibrated strain data taken in observation runs. The current plan calls for the data from O3a to be made public on April 1, 2021 and O3b data to be released on October 1, 2021. Where possible, we advocate releasing the same data, data quality and segment information as used for LSC analyses, including the final parameter estimation, localization and population inference information described above. This will lead to the release of non-observing mode data. 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 LIGO Auxiliary Data:** The publication of a selection of auxiliary channels around some selected events will go forward. The LSC will assess the usefulness of this auxiliary data to outside researchers in order to decide whether to continue, expand or stop releasing auxiliary data in the future.

2.10 Outreach to the public and the scientific community

Activities that are important for the LSC to broadcast its mission and results are related to several aspects listed below. More details can be found in the LSC Education and Public Outreach (EPO) and Data Analysis white papers [6, 5].

(A) **Observatory EPO**: We will expand the LLO Science Education Center (SEC) 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. The 2020 teacher summer teacher workshops will be held virtually. We will continue work to develop the LIGO Exploration Center (LExC) at LHO, for which $7.7M was approved by Washington State for design and construction planned for 2021. The annual International Physics and Astronomy Educator Program at LHO will be held remotely in 2020. Both LLO and LHO will consult with their local communities to determine how they can continue their EPO focus during the pandemic.

(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 EPO**: We will maintain, update and renovate the ligo.org website for informal users. We will continue worldwide outreach and communication through social media (Twitter, Facebook, Instagram, Reddit) and other informal educational materials that showcase our observational and instrument science and the importance of multi-messenger astronomy. In particular, we will provide educational materials and social media support for exceptional event announcements. We will continue answering question@ligo.org 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. We will support the Humans of LIGO blog, Gravity Spy and other relevant citizen science initiatives. We will support our LSC members communicating our science through public talks, writing popular articles, and communications on social media such as Twitter, Reddit 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. We will support the provision of information and materials for professional astronomers, including 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 [7]. 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) O3 exceptional event papers and webinars. We will also develop a framework (appropriate both for O3b and 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 teffective 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.

2.11 A+ Upgrade Project

The A+ detector project is a major upgrade to the existing Advanced LIGO detectors. The project began in 2019 and is expected to continue through the end of 2023. The key goals of A+ are frequency dependent squeezing with a 300m 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 300m filter cavity, are scheduled for the O3–O4 break, and thus fall in the validity period of this program. The current COVID-19 pandemic however may cause significant changes in scope and schedule for this installation break.

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].

2.12 LIGO-India

LIGO-India is a project of the Government of India with primary responsibilities to build facilities and assemble, install, commission and operate an Advanced LIGO detector provided by LIGO and the US National Science Foundation. In principle approval by the Cabinet of the Government of India for LIGO-India was granted on February 17, 2016.

Successful acquisition of land for the observatory site concluded in August 2019. Review of the Vacuum Systems Requirement Document will also concluded in early 2020. Approval of the Detailed Project Report by the Government of India is awaited.

Several important activities are expected to be completed in 2020–2021: Initiation of site construction activities, vacuum infrastructure prototyping, beam-tube prototyping and testing, year-round seismic survey of the acquired site-land and analysis of that data. The LSC is engaged in developing and training the LIGO-India scientific workforce and planning the integration of LIGO-India data into the full detector network. The off-site detector facility, at RRCAT, Indore (India), will be completed in 2020-02021 and be used to train commissioners and operators. LIGO-India scientists will contribute to commissioning work at the LIGO sites. Some of these activities, e.g. observatory construction, are paced by the formal approval of the LIGO-India Project by the Government of India, yet to be announced. The current COVID-19 pandemic may in addition cause some changes in schedule of the activities mentioned above.

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.

2.13 Post-A+ planning

The A+ upgrade project is scheduled to complete by the end of 2023, resulting in the crowning O5 observation run (scheduled to end in 2026). 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. Developing concrete plans for this period is essential for the operational health of the Collaboration. Detector improvements that can increase sensitivity, improve stable operation, and reduce the technology risk for third-generation detectors are of particular interest. Potential updates and upgrades span from replacing individual optics or suspensions, through improving coatings and squeezing, to the full LIGO Voyager cryogenic upgrade. The relative merits of different upgrade options should be assessed in the context of desired science goals and impact on potential future gravitational wave observatory networks. The instrument science group is tasked with developing a post-A+ plan. A variety of upgrade paths exist. One possible upgrade path is focusing on developing a dedicated kilohertz detector such as described in the recent OzGrav Nuclear Extreme Matter Observatory (NEMO) paper [13]. Another path would be to upgrade low frequency performance with larger optics and improved control systems like those described in [14]. By focusing on particular frequency bands, we can use the existing facilities to explore new astrophysics. Many 3G technologies can be prototyped in such a detector development.

2.14 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, co-chairing or serving as secretary of LSC governance bodies, 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 [16] 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.

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 [17]. 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 LIGO 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 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 [18] 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 fixed 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 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. maintaining low thermal noise levels.

(A) **Suspensions of lower thermal noise:** The final stages of the suspended optics require suspension elements of appropriate design to give improved levels of thermal noise, influencing requirements for specific geometry and intrinsic dissipation levels of such elements. Such R&D has a constructive interaction with characterization and monitoring of the in situ performance of suspensions currently installed in Advanced LIGO. 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 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 the 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 cancellation and/or 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 could include for example materials modeling, design, development, deposition and characterization of properties of coatings (optical and thermo-mechanical). The LSC is working intensely to obtain prompt results for oxide materials for use at 1064 nm and room temperature to be implemented in A+ (see Section 2.11). Further improvement for coatings are desired for Cosmic Explorer, and additional effort is needed to explore operation at longer wavelengths and lower temperatures for the second phase of Cosmic Explorer.

(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:** Promising alternative coating production techniques involving small-scale production of crystalline coatings materials have been demonstrated, however R&D is required to develop techniques that can produce such coatings on large-scale optics and to demonstrate their performance.

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. The Caltech 40 m will be upgraded to Mariner, a cryogenic silicon Voyager prototype. A design report for the Einstein Telescope Pathfinder cryogenic prototype in Maastricht was written. Work is ongoing to learn from and leverage the experience with cryogenics in KAGRA. And several smaller labs are building experience with cryogenic technology.

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 O3 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. The current record is held by the GEO600 detector with 6dB of noise reduction 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 (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 LSC white papers [5], 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 citizen science.** Research and development of machine learning, citizen 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 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 LSC–Virgo 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.

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 interpret the results of our gravitational wave searches to make statements about the source population, using both the properties of single events and the ensemble of a population of detections. 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 tiny 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 gamma-ray bursts, 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 Hubble constant H_0 can be determined from gravitational wave distance measurements of individual binary neutron star or neutron star-black hole signals combined with counterpart redshifts measured electromagnetically, or it can be inferred with some precision from a statistical ensemble of compact binary mergers, including from binary black hole events, by using galaxy catalogs and sky localization of the mergers. The LSC will work to improve measurements of counterpart standard siren cosmology. This will require developing tools to improve measurements including potential sources of systematic error, and collaborating with electromagnetic observers and modelers to incorporate improved galaxy catalogs and available follow-up observations that inform inclination determination.

(E) **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 exotic processes in the early Universe, direct dark matter detection (clumped or background field, primordial black holes), or superradiance induced by a condensate of new, ultra-light bosons, such as axions created by extracting energy from a fast-spinning black hole. The LSC will 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 incremental model improvements into the appropriate LSC analysis software;
(ii) Waveform model improvements 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.

4.6 Development of computational resources for future runs and improved detectors

In addition to developing new data-analysis software, it is also important to develop plans to deliver computing for future observing runs. This includes, for example:

(A) **Future computing requirements.** Accurate accounting of the evolution of computational requirements as detector sensitivity, network size and rate of observed signals increases;
(B) **Optimization of analyses.** Identification and assessment of potential new software and hardware that could be used to further optimize gravitational wave searches, including the use of machine learning and AI techniques.
(C) **Code portability.** Evaluation of the utility of grid and cloud resources for LSC analyses, and software packaging, virtual machines and containers for increased portability of LSC software packages.
(D) **Identity and Access management.** Development of new identity and access management tools to facilitate the smooth running of collaboration services.
(E) **Distributed computing.** Development of Open Science Grid (OSG) and distributed computing capabilities for gravitational wave analysis.

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