# COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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| PROGRAM ANNOUNCEMENT/SOLICITATION NO./DUE DATE<br>NSF 18-564 11/28/2018 | ☐ Special Exception to Deadline Date Policy | FOR NSF USE ONLY<br>NSF PROPOSAL NUMBER |
| FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)<br>PHY - LIGO RESEARCH SUPPORT | | |

| DATE RECEIVED | NUMBER OF COPIES | DIVISION ASSIGNED | FUND CODE | DUNS# (Data Universal Numbering System) | FILE LOCATION |
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| EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)<br>951-64-3307 | SHOW PREVIOUS AWARD NO. IF THIS IS<br>☐ A RENEWAL<br>☐ AN ACCOMPLISHMENT-BASED RENEWAL | IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S) |

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| NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE<br>California Institute of Technology | ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE<br>California Institute of Technology<br>1200 E California Blvd Mail Code 273-6<br>PASADENA,CA 911250600 US |
| AWARDEE ORGANIZATION CODE (IF KNOWN)<br>0011312000 | |
| NAME OF PRIMARY PLACE OF PERF<br>California Institute of Technology | ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE<br>California Institute of Technology<br>1200 E California Blvd, Mail Code 273-6<br>PASADENA,CA 911250600 US |

IS AWARDEE ORGANIZATION (Check All That Apply) ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT
Support for LIGO Scientific Collaboration core functions in the era of gravitational-wave observations

| REQUESTED AMOUNT | PROPOSED DURATION (1-60 MONTHS) | REQUESTED STARTING DATE | SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE |
|---|---|---|---|
| $ 798,152 | 48 months | 10/01/2019 | |

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES
- ☐ PROPRIETARY & PRIVILEGED INFORMATION
- ☐ HISTORIC PLACES
- ☐ VERTEBRATE ANIMALS IACUC App. Date
  PHS Animal Welfare Assurance Number
- ☒ TYPE OF PROPOSAL Research
- ☐ HUMAN SUBJECTS Human Subjects Assurance Number
  Exemption Subsection or IRB App. Date
- ☒ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED
  AS UK GM CA BR
- ☒ COLLABORATIVE STATUS
  Non-Collaborative

| | |
|---|---|
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| CO-PI/PD | | | | |
| CO-PI/PD | | | | |

# CERTIFICATION PAGE

### Certification for Authorized Organizational Representative (or Equivalent) or Individual Applicant

By electronically signing and submitting this proposal, the Authorized Organizational Representative (AOR) or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding conflict of interest (when applicable), drug-free workplace, debarment and suspension, lobbying activities (see below), nondiscrimination, flood hazard insurance (when applicable), responsible conduct of research, organizational support, Federal tax obligations, unpaid Federal tax liability, and criminal convictions as set forth in the NSF Proposal & Award Policies & Procedures Guide (PAPPG). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Section 1001).

### Certification Regarding Conflict of Interest

The AOR is required to complete certifications stating that the organization has implemented and is enforcing a written policy on conflicts of interest (COI), consistent with the provisions of PAPPG Chapter IX.A.; that, to the best of his/her knowledge, all financial disclosures required by the conflict of interest policy were made; and that conflicts of interest, if any, were, or prior to the organization's expenditure of any funds under the award, will be, satisfactorily managed, reduced or eliminated in accordance with the organization's conflict of interest policy. Conflicts that cannot be satisfactorily managed, reduced or eliminated and research that proceeds without the imposition of conditions or restrictions when a conflict of interest exists, must be disclosed to NSF via use of the Notifications and Requests Module in FastLane.

### Drug Free Work Place Certification

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent), is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Proposal & Award Policies & Procedures Guide.

### Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☐

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Proposal & Award Policies & Procedures Guide.

### Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

### Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:
(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.
(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.
(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

### Certification Regarding Nondiscrimination

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is providing the Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Proposal & Award Policies & Procedures Guide.

### Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:
(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:
(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

### Certification Regarding Responsible Conduct of Research (RCR)
### (This certification is not applicable to proposals for conferences, symposia, and workshops.)

By electronically signing the Certification Pages, the Authorized Organizational Representative is certifying that, in accordance with the NSF Proposal & Award Policies & Procedures Guide, Chapter IX.B. , the institution has a plan in place to provide appropriate training and oversight in the responsible and ethical conduct of research to undergraduates, graduate students and postdoctoral researchers who will be supported by NSF to conduct research.
The AOR shall require that the language of this certification be included in any award documents for all subawards at all tiers.

# CERTIFICATION PAGE - CONTINUED

## Certification Regarding Organizational Support

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is certifying that there is organizational support for the proposal as required by Section 526 of the America COMPETES Reauthorization Act of 2010. This support extends to the portion of the proposal developed to satisfy the Broader Impacts Review Criterion as well as the Intellectual Merit Review Criterion, and any additional review criteria specified in the solicitation. Organizational support will be made available, as described in the proposal, in order to address the broader impacts and intellectual merit activities to be undertaken.

## Certification Regarding Federal Tax Obligations

When the proposal exceeds $5,000,000, the Authorized Organizational Representative (or equivalent) is required to complete the following certification regarding Federal tax obligations.
By electronically signing the Certification pages, the Authorized Organizational Representative is certifying that, to the best of their knowledge and belief, the proposing organization:
(1) has filed all Federal tax returns required during the three years preceding this certification;
(2) has not been convicted of a criminal offense under the Internal Revenue Code of 1986; and
(3) has not, more than 90 days prior to this certification, been notified of any unpaid Federal tax assessment for which the liability remains unsatisfied, unless the assessment is the subject of an installment agreement or offer in compromise that has been approved by the Internal Revenue Service and is not in default, or the assessment is the subject of a non-frivolous administrative or judicial proceeding.

## Certification Regarding Unpaid Federal Tax Liability

When the proposing organization is a corporation, the Authorized Organizational Representative (or equivalent) is required to complete the following certification regarding Federal Tax Liability:

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is certifying that the corporation has no unpaid Federal tax liability that has been assessed, for which all judicial and administrative remedies have been exhausted or lapsed, and that is not being paid in a timely manner pursuant to an agreement with the authority responsible for collecting the tax liability.

## Certification Regarding Criminal Convictions

When the proposing organization is a corporation, the Authorized Organizational Representative (or equivalent) is required to complete the following certification regarding Criminal Convictions:

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is certifying that the corporation has not been convicted of a felony criminal violation under any Federal law within the 24 months preceding the date on which the certification is signed.

## Certification Dual Use Research of Concern

By electronically signing the certification pages, the Authorized Organizational Representative is certifying that the organization will be or is in compliance with all aspects of the United States Government Policy for Institutional Oversight of Life Sciences Dual Use Research of Concern.

| AUTHORIZED ORGANIZATIONAL REPRESENTATIVE | SIGNATURE | DATE |
| --- | --- | --- |
| NAME | | |

| TELEPHONE NUMBER | EMAIL ADDRESS | FAX NUMBER |
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| | | |

# Project Summary

## OVERVIEW

This proposal seeks funding for core functions of the LIGO Scientific Collaboration (LSC) in order to carry out its scientific mission of using gravitational-waves to explore the fundamental physics of gravity and as a new multi-messenger astronomical tool of discovery. This proposal requests funding for four years for the U.S. portion of the LSC Activities Fees, which amounts to about 52% (444 of 884 members) of all fees collected.

The LIGO Scientific Collaboration (LSC) was formed in 1997 to directly observe gravitational-waves (GW) in data collected by the two LIGO observatories. This goal was realized in September 2015 with the detection of GWs originating from the Binary Black Hole (BBH) merger, GW150914. In 2017 the LSC, together with the Virgo collaboration, inaugurated the era of multi-messenger GW astronomy with the detection of the Binary Neutron Star merger, GW170817. This is the dawn of a new and exciting era of astronomy, made possible by the organization and coherent vision of the LSC in managing fiscal, physical, and intellectual resources.

The LSC levies an Activities Fee on a per-member basis to fund key programs and functions deemed essential by the membership. These include the LSC Fellows Program, publication fees associated with collaboration papers, LSC service travel associated with organizational responsibilities, and LSC spokesperson's travel. About two thirds of the Activities Fee funds the LSC Fellows Program, which attracts a diverse and skilled set of (mostly) junior researchers to work at each LIGO site. The goals of the program are to provide opportunities for LSC members to learn about and contribute to LIGO's precision interferometery at the observatories, to have on-site LSC scientists monitoring the quality of data during observation runs, and to complement the activities of local engineers and scientists in improving the performance of the interferometers.

The Activities Fee assessment ensures that the publication fees for collaboration papers, including fees to make seminal detection papers open-access, and LSC Spokesperson and other members' travel associated with organizational responsibilities, are distributed evenly among collaboration members. The fee also funds reliable internet hosting and identity services, both of which are crucial for a large collaboration such as the LSC.

## INTELLECTUAL MERIT

Effective and efficient management of the LSC, and increased participation by LSC member institutions in on-site investigations that improve the sensitivity of the LIGO detectors and increase their duty cycle extends the scientific reach of the LIGO Observatories. Developing and maintaining a broad base of research scientists in the LSC that are trained in gravitational-wave science has enabled LIGO's observational success to date, and will be essential for future observations, facilitating the commissioning, calibration, and characterization of the detectors, and interpretation of the data. Engaging and training junior scientists is a core mission of the LSC, and it is crucial to ensuring successful evolution of this field. This is evidenced by the large number of current LSC members who entered the collaboration as graduate students.

## BROADER IMPACTS

Most LSC Fellows are junior scientists whose careers are significantly and positively impacted by the opportunity to engage directly with the instruments, the observatory staff, and other Fellows and visitors. Their on-site projects enhance their visibility in the field, often lead to short-author-list publications, and form significant components of their Ph.D. theses. Students and junior researchers from smaller institutions, many of whom are under-represented minorities, gain access to resources that would otherwise be out of reach. In the long-term, the field will benefit from training a larger and more diverse group of experimental scientists. The support for the organizational activities enables the LSC to communicate our science to the scientific community and the greater public.

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For font size and page formatting specifications, see PAPPG section II.B.2.



Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

# Support for LIGO Scientific Collaboration Core Functions in the Era of Gravitational-Wave Observations

November 27, 2018

## Contents

# Overview

This proposal requests funding of the Activities Fees for U.S. members of the LIGO Scientific Collaboration (LSC) for four years. These Activities Fees are currently collected from the collaboration members who qualify as authors on collaboration-wide publications based on the percentage of their available research time devoted to LIGO research. About 52% are from institutions in the United States. In FY2019, the LSC Activities fee was $400.00 per author. As detailed in this proposal, the fees are used to pay for critical collaboration services: the LSC Fellows program, Publication Fees, Spokesperson and Collaboration Service Travel, and Internet and LIGO Identity Services.

Currently, these fees are collected by invoicing each LSC institution based on its author count. Having a central source of funding, which does not appear to be a tax on groups, rather a feature of the Collaboration enabled by the NSF, will improve the science *and* the productivity of the Collaboration. This proposal asks for support of only the U.S. Fees; non-U.S. LSC groups will continue to pay their Activities Fees.

# The LIGO Scientific Collaboration

The LIGO Scientific Collaboration (LSC) was founded in 1997 as a self-governing collaboration using gravitational waves to explore the fundamental physics of gravity, and as a new multi-messenger astronomical tool of discovery [1]. The LSC works toward this goal through research on, and development of, techniques for gravitational-wave observation, and the development, commissioning, and exploitation of gravitational-wave detectors. Individual or group membership, and standing within the LSC are based on scientific merit, adherence to the LSC Code of Conduct, and willingness to participate in and contribute to the scientific mission of the LSC as described in the LSC Charter and the LSC Bylaws.

The LSC is the entity within LIGO that carries out LIGO's scientific research program. Memoranda of Understanding between member groups and the LIGO Laboratory establish individual group responsibilities that allow the LSC to perform the following functions:

* establish the overall data analysis strategy, goals, and timeline, and carry out the data analysis program
* identify priorities for research and development, and carry out the R&D program
* carry out an outreach program to communicate LIGO's activities and goals to the public, and provide educational opportunities for young people
* disseminate the results of the data analysis program and the R&D program
* participate in the scientific operations of the LIGO detectors
* perform internal evaluation of progress in data analysis and R&D, making adjustments as necessary

The LSC produces an annual Program and detailed White Papers that complement the LIGO Laboratory Annual Report and Work Plan [2–5].

The LSC and the LIGO Laboratory work in a mutually supportive fashion to accomplish LIGO's goals. Scientists and engineers at the LIGO Laboratory participate fully as members of the LSC in the entire LSC program. The LIGO Laboratory makes full use of the talents of LSC members at non-Lab institutions in carrying out the Lab's responsibilities for operating the existing instruments and developing new instruments.


Figure 1: Logos of the member institutions of the LIGO Scientific Collaboration. A complete list of current LSC institutional membership is available on the ligo.org website

The LIGO Directorate consists of the Director and the Deputy Director of the Laboratory, and the Spokesperson of the LSC. It is anticipated that the LSC will be reviewed annually by the NSF external panel as part of the LIGO Laboratory review.

The LSC currently has 1266 members in 120 groups across 17 countries. Logos of the member institutions are shown in Figure 1. Authorship is currently reserved for members committing 50% or more of their available research time. Of the total current membership, 848 members are authors, 52% (444 authors) of which are from institutions in the United States.

At its inception, the LSC structured itself to explore the basic measurement challenges of gravitational-wave detection, and to begin (in the context of the initial LIGO detectors undergoing installation and commissioning by the LIGO Lab) conceiving of the second generation of instruments that had been an intrinsic part of the LIGO Proposal to the NSF in 1989. The LSC recognized the need to focus on a limited range of practical avenues for that new detector, and in 1999, brought together the ideas in a White Paper for what would become Advanced LIGO.

Significant improvements in the sensitivity of the instruments came from LSC-coordinated instrument science working groups, including signal recycling, low-thermal-noise mirror suspensions and coatings, seismic isolation, and laser technology as examples. As the effort shifted from science to engineering, the LIGO Lab took the lead, resulting in a successful proposal to the NSF for

Advanced LIGO in 2003. Some member groups of the LSC chose to make capital contributions to Advanced LIGO.

The LSC instrument science effort has played a continuing role in refining the Advanced LIGO design, and a supporting role to the LIGO Lab in the ongoing commissioning of the Advanced LIGO detectors. In parallel, it has helped enable elements of the recently NSF-funded 'A+' instrument design. The instrument scientists are now looking further forward to creating feasible designs for third-generation detectors.

Since its start in 1997, the LSC has developed approaches to data analysis – both in signal recognition and in gleaning scientific results from the signals – essentially starting from a 'green field'. In the epoch of the initial LIGO detectors, the analysis pipelines and the means to characterize the data to work around its imperfections were established and honed. Significant networked computational facilities were proposed, realized, linked, and coordinated, and techniques to extract astrophysical parameters from the data were developed. As a consequence, the Collaboration was ready on 14 September, 2015, when during the engineering run preceding the first observing run, GW150914 swept past the LIGO detectors and signals were captured [6–24].

## The LSC Fellows Program

Since the LSC's inception, constituent members and groups have had the responsibility of working directly on site with the LIGO interferometers at the LIGO Hanford and LIGO Livingston Observatories. During initial LIGO's Science Runs, a rotation of scientists from all LSC groups visited the sites to act as science monitors (SciMons) of collected data. Visits were brief, on the order of a few days, and participants had vastly differing levels of expertise. It quickly became apparent across the LSC that this approach was sub-optimal and inappropriate for what we anticipated to be the Detection Era.

In response to this shortcoming, in 2015 the LSC created the LSC Fellows Program with the expressed goal of increasing the productivity of the searches for gravitational wave signals – the product of the volume of space searched and the time actually spent observing [25]. In other words, increasing the sensitivity of the instruments so that we search a greater fraction of the Universe, and increasing their robustness so that the instruments operate stably for longer stretches of time. The Fellows program confronts and solves the issue of limited SciMon expertise by requiring Fellows to commit to a minimum on-site stay of 3 months, with longer stays encouraged. The initial goal was to have, on average, four Fellows at each site at all times, including periods when the interferometers were in upgrade or commissioning phases.

The LSC Fellows Program has been a remarkable success. Several major projects (some examples are described below) have been completed by the Fellows, resulting in notable improvements in several aspects of LIGO detector operations.

We organize the LSC into "blocks", with a participation quota assigned to each block based on the author count within block-member institutions. This gives smaller institutions the opportunity to join together in order to take part in the LSC Fellows program. There are currently six blocks:

- **U.S.-Canada** consisting of institutions in the United States and Canada
- **LIGO Laboratory** consisting of LIGO Lab members from Caltech, MIT and the two LIGO observatories located near Richland, WA and Livingston, LA
- **Indigo** consisting of Indian institutions participating in LIGO Science and developing the community around the LIGO-India Observatory
- **GEO** consisting of mainly UK and German members of the GEO collaboration. This collaboration also operates a 600 meter interferometer near Hannover, Germany.

- **ACIGA** consisting of Australian collaborators
- **International** A collection of other institutions not already accounted for in the other blocks

The U.S.-Canada and LIGO Laboratory blocks are two of the largest, with an obligation to provide 12 and 10 quarters, respectively, of LSC Fellow visits per year across both sites. (There is currently one small Canadian group in the LSC, and it is not counted in the U.S. author assessment.) The program covers Fellows' travel costs from and to their home institutions, lodging in shared apartments, and shared use of rental cars for the duration of their stays. It does not provide per diem or health-care insurance, which are expected to come from continued support by the Fellows' home institutions.

Thus far, financial support for the Fellows program has come through the assessment of the per-author Activities Fee to LSC member institutions. When first proposed and realized in 2014, the Activities Fees were only to support the LSC Fellows program. In 2017, a re-assessment of the needs of the collaboration led to the addition of fees to cover other core LSC functions. Metrics for each group's contribution are established by the LSC Council, as is the scope of LSC Activities to be covered by the fee. The fee is paid by all groups worldwide, using the same metric and cost per paying member.

Logistical support in the form of administrative, accounting, and invoicing assistance has been provided by the LIGO Laboratory Business Office. Business Office personnel also coordinate travel, apartment rental, and car rental for visitors. They plan to continue providing this assistance for the duration of this grant as part of the LIGO Lab's contributions to the LSC. PI B. O'Reilly is the LSC Fellows liaison at the LIGO Livingston Observatory, Co-PI R. Savage is the Fellows liaison at the LIGO Hanford Observatory, and Co-PI David Shoemaker is the LSC Spokesperson, based at MIT.

The LSC Fellows program is now in its fourth year and has had much success in attracting a diverse and skilled set of (mainly) junior researchers to work at the sites. For any given year of the program, we aim to have 32 Fellow-Quarters (FQ) of participation, i.e., 4 Fellows per site per each 3-month period. During the first year of the program, 30 Fellows contributed 40 FQ. In the second year, 24 Fellows combined for 38 FQ. And in the third year, 33 Fellows contributed 51 FQ. The third year of the program was adjusted for budgeting purposes to cover 15 calendar months so as to align the Fellows' year with the Financial Year. Even so, third year numbers represent significant participation with many Fellows opting for return visits or longer stays. This is despite the fact that most of this period occurred after the second observing run, and prior to the start of the third observing run.

## Value of the Fellows Program to the LSC and the GW Community

The Fellows program has proven to be extremely valuable in three distinct ways. First, the observatory sites benefit by having additional scientists complementing full-time on-site staff. In turn, on-site scientists and engineers enthusiastically participate in the Fellows program as mentors and collaborators. The Fellows program provides them with opportunities to work with graduate students and postdocs, similar to what is available on the main Caltech and MIT campuses.

Second, the collaboration acquires a broader understanding of the performance of the LIGO instruments, gains better real-time insight into the quality of data collected, and in part due to Fellows' projects, benefits from more data collected at higher sensitivity and with better-understood noise and calibration. Fellows have enabled studies of the instrument performance to be both deeper and broader in scope.

And third, the Fellows themselves have found the program to be a unique and efficient way to gain training and experience that is useful for their work at their home institutions and their careers as research scientists. In many cases their Fellows projects have led to scientific publications and significant portions of their Ph.D. dissertations. The program has also given Fellows visibility within the collaboration and helped them choose career paths.

During observation runs LSC Fellows contribute in the following ways:

- Participation in the Rapid Response Team (RRT). The RRT reacts to Gravitational Wave (GW) candidates in real time. Starting in O3, a GW trigger will result in an Open Public Alert (OPA), which, within minutes of the detection, will be issued as a GCN (Gamma-ray Coordinates Network) notice. The RRT will vet these candidate events and either retract the OPA or issue a GCN circular describing the properties of the candidate. Fellows will play an integral role in this process.
- Liaising with the Detector Characterization (DetChar) team: The DetChar team monitors the interferometer strain data to identify issues that may arise, such as transient noise sources that compromise search algorithms, non-standard interferometer configurations, and problems with calibration etc. They interact closely with site engineers and scientists in order to understand day-to-day changes in the noise spectrum. LSC Fellows have been invaluable in liaising between the typically remote DetChar scientists and local site staff.
- Fellows work on projects that are designed to improve the quality of the data, improve instrument stability and duty cycle, better calibrate and characterize the data, and work on future software and hardware improvements to the interferometers.

## Core Functions Supported by the LSC Activities Fee

**LSC Fellows Program** As described above and in the Budget and Budget Justification, the Fellows Program is the largest component of the LSC Activities Fee. It funds essentially all of the costs of Fellows visiting the LIGO Observatory sites (airfare, lodging, transportation, start-up allowance, and some visa processing). On average, four Fellows are resident at each observatory throughout the year.

**LSC Publications** The Activities Fee supports publication costs for approximately nine papers per year that include the whole LSC author list. They include, when appropriate, fees to make papers accessible by the public. Now that the LIGO instruments have started to detect GW events more frequently, the need to communicate our science results and to fairly distribute publication fees for full-collaboration papers is much more acute.

**Spokesperson and Collaboration Service Travel** This core function includes both travel by the Spokespersons and service travel by other collaboration members. LSC-supported travel funds have enabled those in the LSC with organizational responsibilities to continue contributing without undue impact on their research program and its travel needs. The principal planned uses for this funding serve several functions: 1) It allows the chairs of the Data Analysis Groups to gather for an in-person meeting, where planning, priority setting, and coordination are addressed. In addition, this is an opportunity for “hard” discussions on leadership difficulties, leadership training, and the like. 2) There is a two-day annual review of all the memoranda of understanding between LIGO and the approximately 100 individual member groups. The participants in the review are the instrument and analysis working group chairs, and other senior members of the Collaboration. This two-day meeting is at the core of ensuring that the groups are all participating fully, and addressing issues of priority to the Collaboration. Limited other travel is supported for contributions to the functioning of the Collaboration. The Spokesperson’s travel was covered by the LIGO Laboratory until recently, when the prioritization of the use of available funding in the Laboratory caused the funding to be shifted to other needs; the LSC funding for this travel, which is associated with the Spokespersons' responsibilities, ensures this cost is fairly distributed to the Collaboration.

**Internet and LIGO Identity Services** The LSC depends heavily on the broad availability of LSC resources with managed access. Reliability is crucial to ensure that e.g., detections can be followed up by LSC members around the world. Having the key resources on "the cloud" and having access to the resources covered with high redundancy is necessary. The LSC (with Virgo) has determined that commercial resources are the best approach to guaranteeing this access. This proposal asks for support for Internet hosting and Identity services to ensure the high reliability and uptime required by the Collaboration to complement the 24/7 interest in, and activity within, the Collaboration. The Identity services allow us to have open collaboration-wide discussions of work in progress while also maintaining privacy until we are ready to share results publicly.

## Intellectual Merit

The LSC is a goal-driven, scientific collaboration that is at the leading edge of the field of gravitational-wave physics and astrophysics. It is closely coupled to academia with a key goal of educating the next generations of scientists and engineers in this emerging field. This proposal will enable the LSC to continue as an active and dynamic collaboration, leading the field of gravitational-wave research and discovery. The LSC has published extensively and will continue to do so.

The LIGO observatories offer unique opportunities for researchers to work on leading edge instrumentation, to develop tools for understanding and mitigating noise sources, and to participate in real-time in the detection of gravitational waves. The LSC Fellows experience will translate into chapters in theses, high impact papers with short author lists, and successful careers in the field built in part on visibility attained through work at the observatory sites. With funding from this proposal the LSC Fellows program will continue to make significant contributions to the LIGO instruments, gravitational-wave science and the careers of the future leaders in this field.

## Broader Impacts

This grant will help enable the LSC to continue to lead the way in the new field of gravitational-wave observation. To date, the LSC has been remarkably successful in bringing the LIGO instruments to operation, developing data analysis techniques, understanding and addressing data quality and calibration challenges, and drawing astrophysical conclusions from the LIGO (and Virgo) data. The LSC has also trained students, mentored postdocs, launched many faculty careers, and prepared a cadre of precision measurement scientists for our field and beyond. The LSC reaches out to a broad range of communities: K-12, underprivileged and underrepresented groups, as well as exciting the broader public with the new view of the cosmos given to us by gravitational-wave signals. All of these endeavors will be facilitated with the support that this grant will offer.

One of the strengths of the LSC Fellows program is that it provides a path for scientists from *both* inside and outside the LIGO Lab to work at the observatories. Of the U.S.-based Fellows during the first three years of the program, about 75% have been from institutions outside of the LIGO Laboratory. Funding the LSC Fellows program will facilitate continued broad access to the LIGO instruments by members of the LSC.

The Inter-University Centre for Astronomy and Astrophysics (IUCAA) is a founding member of the Indian Initiative in Gravitational-wave Observations (IndIGO) collaboration, tasked with nurturing the community that will build, commission and support the LIGO-India interferometer. N. Mukund's participation, described above, is an example of the reach of the LSC Fellows program, and its ability to contribute to training future engineers and scientists, and to expanding the field. We have had three LSC Fellows from IndIGO and expect to welcome more in the years ahead.

The University of Texas Rio Grande Valley (UTRGV) is an LSC institution with a student population that has a significant proportion of under-served minorities. The LSC Fellows program enables students and scientists at this and similar institutions to take advantage of opportunities at the LIGO Observatories which might otherwise be out of reach.

## People Responsible for the Project

**John E. (Brian) O'Reilly, Principal Investigator**
B. O'Reilly was one of the originators of the LSC Fellows program and has served as the local coordinator at LIGO Livingston since the program's inception. He is a Member of the Professional Staff at Caltech and has worked at the Livingston site since 2002. O'Reilly led the local effort to decommission the initial LIGO instrument and install the Advanced LIGO interferometer. He has worked on the the seismic isolation system, as member and then chair of the Calibration Committee, and as a run manager for several of the initial LIGO "Science Runs". In addition to his work on the LSC Fellows program, O'Reilly is the "Detection Coordinator" at Livingston. In this role he manages the Observation Runs, reacts to detections as they occur, liaises with the LSC analysis teams, and with his counterparts at the Hanford and Virgo sites. Dr. O'Reilly is a member of the LSC Council.

**Richard Savage, Co-Principal Investigator**
R. Savage is a Member of the Professional Staff at Caltech and a Senior Scientist at the LIGO Hanford Observatory where he is the LSC Fellows liaison. He has been with the LIGO project since 1992, and has long-term involvement with the Pre-stabilized Laser systems as well as the Calibration Committee. Savage has been a member of the LSC Council since its inception.

**David Shoemaker, Co-Principal Investigator**
D. Shoemaker is a Senior Research Scientist at MIT and current Spokesperson of the LIGO Scientific Collaboration. He has worked in the domain of gravitational wave detection via interferometry since 1979. Since helping to launch the LSC, he has served in a variety of roles, including leading the Advanced LIGO Project from its start as an R&D endeavor in the late '90s, to its completion in 2015.

## Results from Prior NSF Support

*NSF Cooperative Agreement (CA), PHY-0757058*, Title: *Operation and Maintenance of the Laser Interferometer Gravitational Wave Observatory (LIGO)*, Duration: October 1, 2013 to September 30, 2018, Amount: $205,451,141.

*NSF Cooperative Agreement (CA) PHY-1764464*, Title: *LIGO Management & Operations(M&O)*, Duration: October 1, 2018 to September 30, 2023, Projected Total Award Funding: (Subject to availability of funds) $225,000,000.

O'Reilly (PI), Savage (Co-PI) and Shoemaker (Co-PI) were supported, and continue to be supported by these grants. Additionally the LIGO Business office, which provides logistical support for the LSC Fellows program also derives its funding from the same cooperative agreement.

Most of the other U.S. LSC groups have also had substantial support from the NSF since the inception of the LSC, and the groups evince the substantial accomplishments rendered possible with that support when reporting to the NSF on their individual grants. More specific to this proposal, the LSC Council votes on and has approved the Activities Fees annually, and all LSC groups have voluntarily funded the Fellows program (and, for one year, the other core Activities as well). The examples of Fellows contributions described below are only a few selected vignettes of what the Fellows program has accomplished in just three years. Our one year of operating with the additional fees levied for publications was fortuitously coincident with the slew of Collaboration papers related to the binary neutron star coalescence (GW170817) [26–37]; having those funds be common rather than searching for one or another group to cover the costs was much more efficient and it helped to reduce friction within the Collaboration. The Service Travel enabled a broader spectrum of participants to attend some central Collaboration review and coordination activities; in the past some of the less-well-funded co-chairs or committee leaders could only participate remotely, which unfortunately is not yet comparable to in-person participation.

## Intellectual Merit

The LSC blazed the trail leading to the successful initiation of the field of gravitational-wave detection. The first direct observation of gravitational waves in 2015, from the binary black hole coalescence GW150914 [6–24], subsequent additional observations of binary black hole mergers [38–41], and the multi-messenger observation of the binary neutron star coalescence GW170817 in 2017 [26–37], have revolutionized the field. They have thrown open a new window onto the Universe and dramatically demonstrated the broad value of multi-messenger astrophysics.

The LSC has published extensively, returning the science to the greater community and furthering the careers of those involved in the LSC. The LSC database lists more than 3000 documents, with 247 papers citing LSC as the author scope. The LSC has also nurtured the field–more than 200 graduate theses in the LSC have been completed since 2003.

### Examples of Fellows' Contributions

A few select examples of the important contributions LSC Fellows are making to LIGO science are briefly described below.

#### – Pep Covas (UIB, Spain): Line and Comb Hunting

Covas, a graduate student from the University of the Balearic Islands, had almost no experimental physics experience before arriving at the LIGO Hanford Observatory in April 2017. Though his Ph.D. research was conducted exclusively on computers, he was eager to work on the detector. Within hours of meeting his mentors, Evan Goetz, a Hanford Research Scientist, and Robert Schofield, a professor from the University of Oregon, he was out in the experimental hall making measurements aimed at identifying and mitigating narrow spectral artifacts in the data streams that impact long-duration searches for continuous and stochastic GW signals. Figure 2 shows one of his magnetometers mounted in the back of a rack containing electronics that control interferometer optics in his efforts to identify sources of narrow-band lines and combs in the data.

The results of Covas' work while at LHO were published in Physical Review D [42], and they continue to make important contributions to searches for persistent GW signals. He will return to LHO in April 2019 for a second four-month stay as an LSC fellow.

#### – Jian Liu (UWA, Australia): Modeling and Fabrication of Optical Cavities

The University of Western Australia responded to a call for an additional LSC Fellow at LHO during the O2 observing run by sending their senior graduate student, Jian Liu in June, 2017. Already experienced with optical resonators, Liu worked with R. Savage, an LHO staff scientist, on the construction, testing, and optimization of the fabrication of the optical resonators that serve as pre-modecleaners (PMC) in the interferometer pre-stabilized laser systems. They eventually constructed eight of these optical filters [43].

Figure 3 shows Liu in the Optics Laboratory at LHO testing one of the pre-modecleaners he fabricated.

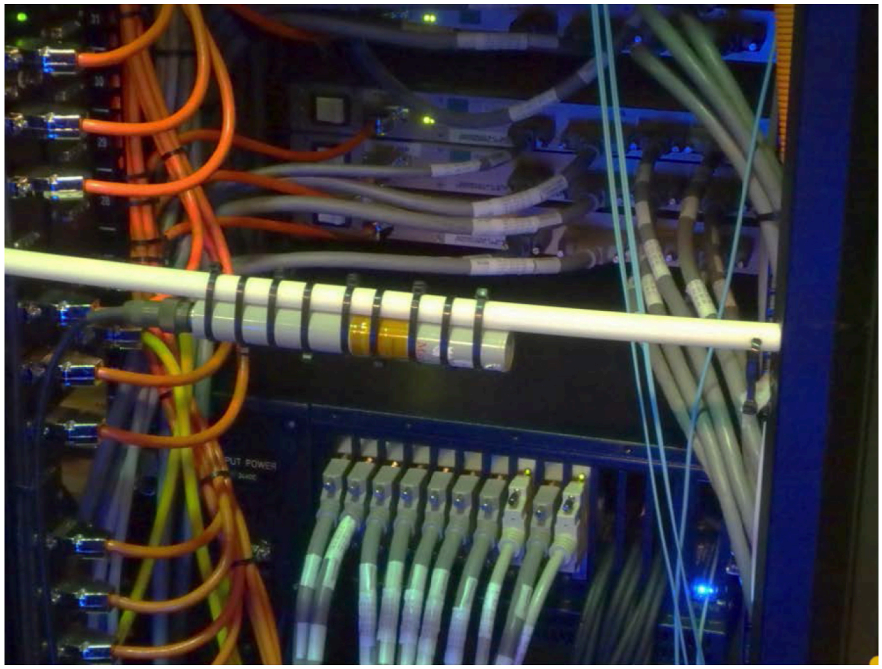

Figure 2: Magnetometer mounted near an electronics rack to investigate sources of spurious narrow spectral features in the interferometer data streams

One new PMC is currently installed in LHO's interferometer, and another is operating in KAGRA, the Japanese GW detector currently under construction. Liu also worked on the conceptual design of a "Jitter Attenuation Cavity" for an upgrade of the LIGO interferometers [44]. These cavities, which will be constructed using the methods developed for the pre-modecleaners, will operate inside the LIGO vacuum envelopes to reduce laser beam pointing variations that impact interferometer performance. Liu's work on the pre-modecleaner and JAC efforts comprise a significant portion of his Ph.D. dissertation. A second LSC Fellow from the group at UWA will visit LHO in April, 2019 to continue Liu's work on the Jitter Attenuation Cavity.

**– Kentaro Mogushi (UMiss, USA): LIGO Optics Investigations**
Kentaro Mogushi, from the University of Mississippi, visited the LIGO Hanford Observatory for a six-month-long stay in July, 2017. When he arrived, he was in the process of writing a paper on rates of signals LIGO might detect from binary neutron star coalescences as part of his Ph.D. research. He soon experienced the eventful month of August, 2017, that included the first multi-messenger observation of a binary neutron star merger. Knowing that it would soon be announced to the scientific community stimulated him to make a very significant effort, and, his paper has now been circulated within the Collaboration and submitted for publication. Being at the observatory at this exciting time was particularly meaningful for him and his research [45].

During his six months at LHO, K. Mogushi undertook several challenging problems, though he arrived with little directly relevant experience, just his inquisitiveness and his tenacity. He eventually succeeded in solving all of them, including a long-standing issue related to distortions in images used to assess scattering on the interferometer optics. Figure 4 shows him working on an improvised setup in one of LHO's laboratory spaces that enabled distant views of detailed objects, as require to view particulates on the surfaces of the input test masses.

He eventually devised and tested a method of reducing the optical distortions such that the camera systems installed were finally able to capture images of sufficient resolution to be useful for

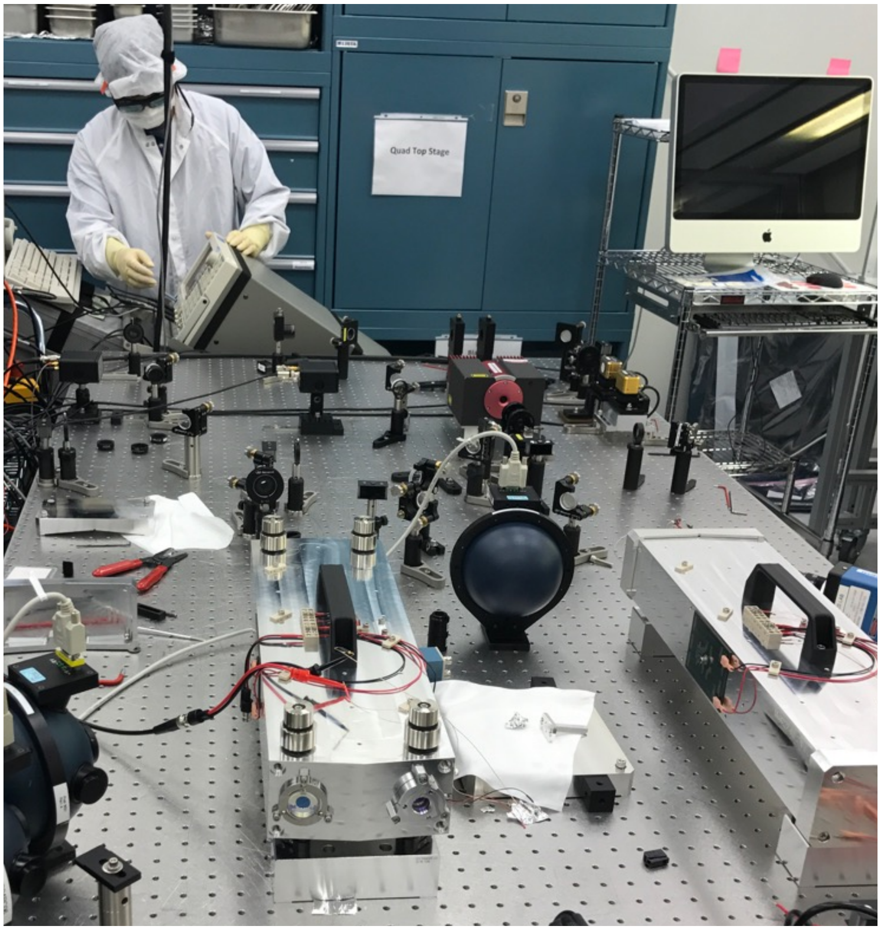


Figure 3: J. Liu testing a pre-modecleaner cavity he fabricated in the optical laboratory at LHO

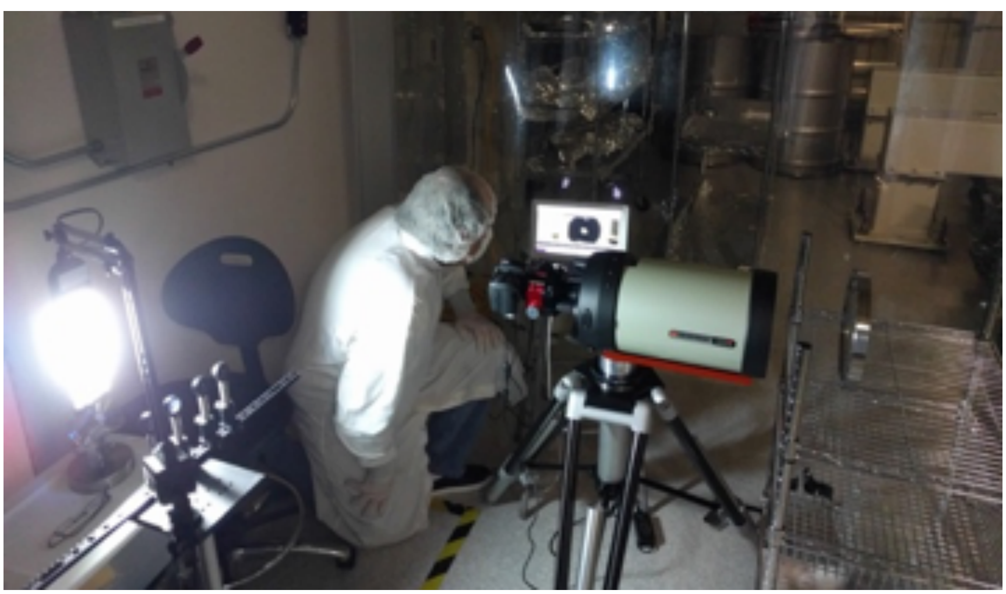

Figure 4: K. Mogushi investigating distortions in optical systems used to image particulates on the surfaces of the test masses.

assessing contamination of the critical optical surfaces [46].

**– Nikhil Mukund (IUCAA, India): Seismic Studies and Lock Loss**

Nikhil Mukund visited LIGO Livingston from April 2016 to December 2016, and worked with a team developing a seismic monitoring system, SEISMON [47], that predicts the expected amplitude of ground motion at the site due to distant seismic events. This tool allows us to transition the detectors to a more robust state in advance of the arrival at the observatory. Once a disturbance has passed we can quickly transition back to the lowest noise configuration and avoid many lost hours of duty cycle [48].

Several hundred control loops act in concert to achieve the highest sensitivity "locked" state of the interferometer. When an external disturbance or instability in one of the control loops takes us out of this state, we refer to losing lock or LockLoss. Mukund developed a LockLoss monitoring tool, which can be configured by the user to allow a rapid search of hundreds of channels of instrument data to determine the reason for specific losses of lock. The software also incorporate a "best guess" feature, which uses machine learning to identify the probable culprit. This tool continues to be a valuable resource for the commissioning teams, and was used to great effect in improving the stability of Livingston's interferometer during the second observing run.

Mukund has continued to study the effects of earthquakes on the LIGO instruments. Two papers, which are about to be published, owe their genesis to his work at Livingston. The first is a method to predict surface wave velocities at the sites using archival seismic data [49]. The second is a study of the effect of induced seismicity on the operation of the LIGO instruments [50]. Induced seismicity due to hydraulic fracking for oil and gas exploration has led to a huge increase in seismic activity in parts of the United States. The Livingston interferometer lies close to the Tuscaloosa shale formation and stands to be impacted if exploitation of its resources becomes commercially viable. This study, which Mukund and O'Reilly started together, is the first of its kind and demonstrates the first known lockloss ascribed to a human-induced seismic event.

**– Maggie Tse (MIT, USA): Squeezing**

Maggie Tse arrived at the LIGO Livingston site in August 2017 and stayed until November 2018. Her project was to install and commission the squeezed-light source at LIGO Livingston [51]. Squeezing is important because it provides an alternative to increasing the input laser power as a means of increasing the sensitivity of our detectors. Higher-power operation of the interferometers is complicated by thermal heating of the test-mass optics, which changes their radii of curvature and can lead to lower sensitivity and increased instability. Squeezing has been operational at the GEO interferometer for many years [52] and was demonstrated on a LIGO interferometer in 2011 [53]. Tse and the rest of the squeezing team recently successfully demonstrated squeezing on Livingston's interferometer, the first time it has been shown to work on an advanced LIGO detector, see Figure 5.

Work continues on automating the squeezer operation and improving its performance in advance of the third observation run. A similar effort to implement squeezing on the Hanford interferometer has been ongoing for the past 14 months, led by three LSC fellows, two from the University of Western Australia and one from MIT.

**– Guillermo Valdes (UTRGV, USA): Scattered-Light Investigations**

Guillermo Valdes was an LSC Fellow at LIGO Livingston from September 2015 to June 2016. His project focused on identifying sources of scattered-light noise in the Livingston instrument. Valdes developed a novel method, based on the Hilbert-Huang transform, to identify sources of noise caused by scattered light and allow their mitigation. His Fellows project formed the core of his thesis and resulted in a publication [54]. Figure 6 shows an example of the identification

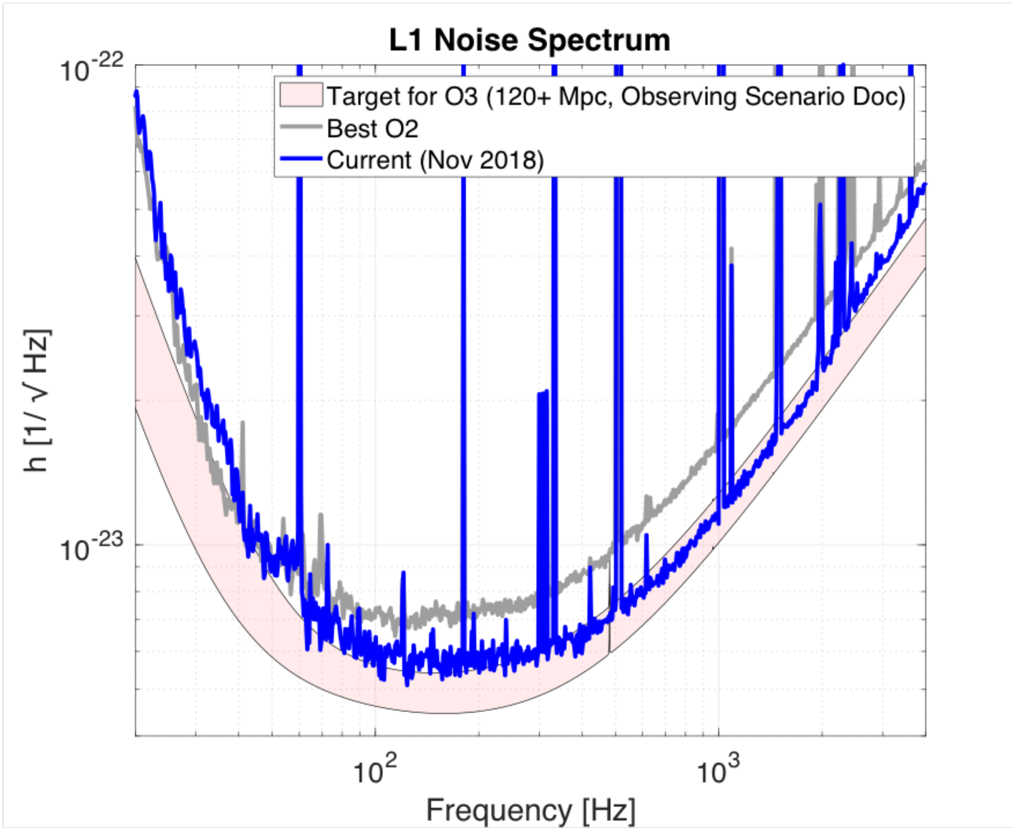


Figure 5: Sensitivity improvement of the Livingston detector. Most of the improvement from the gray curve to the blue one is due to lower shot noise resulting from quantum mechanical squeezing. There is also a small contribution from increased input power and increased recycling gain.

tool's output. In this case the scattered light "arches" in the time-frequency spectrogram match the motion of an optic in the signal recycling cavity. Scattered-light noise continues to be a focus of noise investigations, and as a postdoctoral researcher at Louisiana State University (an LSC member institution), Valdes has continued to develop the software and apply it to aid in solving this problem.

## Broader Impacts

Prior support from the NSF has enabled the LSC to fully exploit the onset of the era of gravitational-wave detections. The collaboration has published extensively and provides open access to data around each detection [55]. Data from the entirety of the first observation run (O1) is publicly accessible and data from the second observation run (O2) will be publicly accessible beginning in February 2019. The collaboration continues to foster the growth of a worldwide network of detectors as part of a collaborative global community of gravitational-wave research.

The LSC Fellows program has significantly impacted the science done at the observatories and the careers of junior members of the collaboration. Previous LSC Fellows from IndIGO are now engaged in the construction of the LIGO-India detector. We expect that many of the scientists and engineers who build and operate the LIGO-India facility will receive training at the LIGO Observatories under the auspices of the LSC Fellows program.

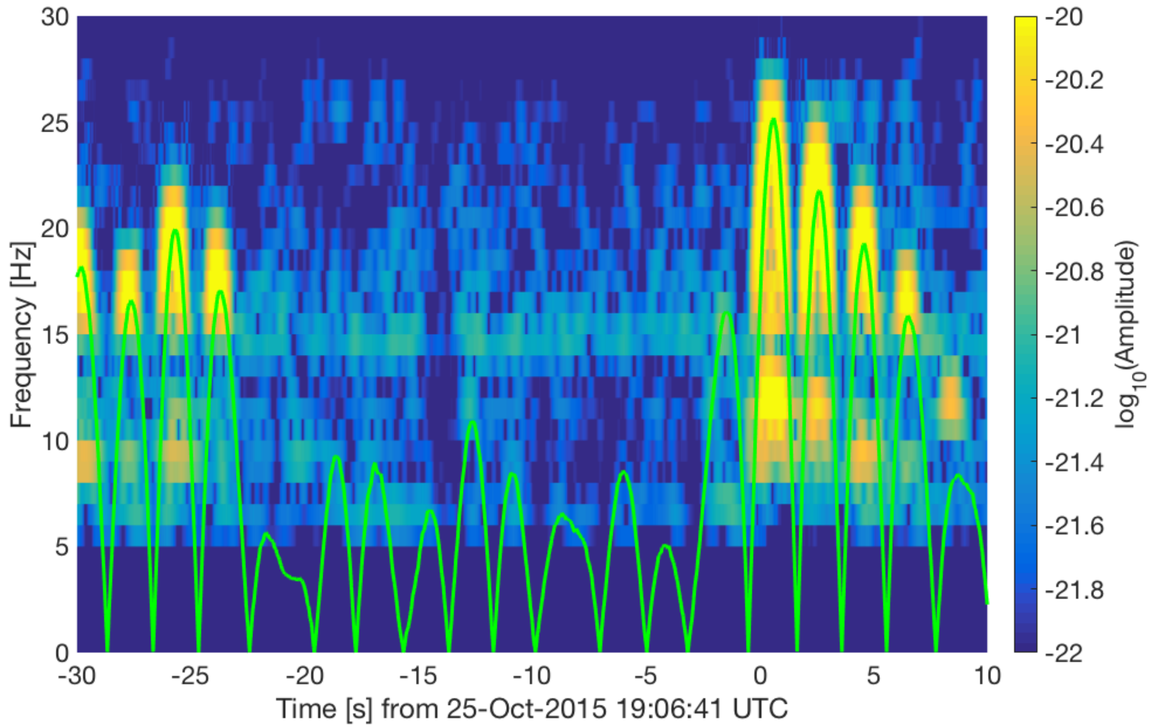


Figure 6: Fourier spectrogram of the differential arm signal from the Livingston interferometer (i.e. the gravitational wave channel). The "arch-like" features match the prediction of the scattering tool based on the velocity of motion of an optic in the signal recycling cavity.

Members of the LSC from small institutions, including institutions where under-served minorities form a significant part of the student population, have used the opportunities provided by the LSC Fellows program to access resources that would otherwise be beyond their reach.

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F. Matichard, N. Mavalvala, D. E. McClelland, S. McCormick, L. McCuller, G. McIntyre, T. McRae, E. L. Merilh, J. Miller, R. Mittleman, G. Mo, K. Mogushi, D. Moraru, G. Moreno, G. Mueller, N. Mukund, A. Mullavey, J. Munch, T. J. N. Nelson, P. Nguyen, L. K. Nuttall, J. Oberling, O. Oktavia, P. Oppermann, Richard J. Oram, B. O'Reilly, D. J. Ottaway, H. Overmier, J. R. Palamos, W. Parker, A. Pele, S. Penn, C. J. Perez, M. Phelps, V. Pierro, I. Pinto, M. Principe, L. G. Prokhorov, O. Puncken, V. Quetschke, E. A. Quintero, H. Radkins, P. Raffai, K. E. Ramirez, S. Reid, D. H. Reitze, N. A. Robertson, J. G. Rollins, C. L. Romel, J. H. Romie, M. P. Ross, S. Rowan, K. Ryan, T. Sadecki, E. J. Sanchez, L. E. Sanchez, V. Sandberg, R. L. Savage, D. Sellers, D. A. Shaddock, T. J. Shaffer, B. Shapiro, D. H. Shoemaker, B. J. J. Slagmolen, B. Smith, J. R. Smith, B. Sorazu, A. P. Spencer, A. Staley, K. A. Strain, L. Sun, D. B. Tanner, J. D. Tasson, R. Taylor, M. Thomas, P. Thomas, K. Toland, C. I. Torrie, G. Traylor, M. Tse, D. Tuyenbayev, G. Vajente, G. Valdes, A. A. van Veggel, A. Vecchio, P. J. Veitch, K. Venkateswara, T. Vo, C. Vorvick, M. Wade, M. Walker, R. L. Ward, J. Warner, B. Weaver, R. Weiss, P. Weßels, B. Willke, C. C. Wipf, J. Wofford, J. Worden, H. Yamamoto, C. C. Yancey, Hang Yu, Haocun Yu, L. Zhang, S. Zhu, M. E. Zucker, and J. Zweizig. *Identification and mitigation of narrow spectral artifacts that degrade searches for persistent gravitational waves in the first two observing runs of advanced ligo.* Phys. Rev. D, **97**:082002, 2018. doi: 10.1103/PhysRevD.97.082002.

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**PROFESSIONAL PREPARATION**

| | | | |
|---|---|---|---|
| Dublin City University | Dublin, Ireland | Applied Physics | B.Sc. 1987 |
| Northwestern University | Evanston, IL | Physics | Ph.D. 1995 |
| University of Colorado | Boulder, CO | Particle Physics | 1996-2002 |

**APPOINTMENTS**

2016 – Present Lead Scientist, California Institute of Technology
2007 – 2016 Member of the Professional Staff, California Institute of Technology
2002 – 2007 Staff Scientist, California Institute of Technology

**PUBLICATIONS**

1. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Observation of Gravitational Waves from a Binary Black Hole Merger", Phys. Rev. Lett. **116**, 061102 (2016). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102
2. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral", Phys. Rev. Lett. **119**, 161101 (2017). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.161101
3. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries", Phys. Rev. Lett. **116**, 131103 (2016). https://doi.org/10.1103/PhysRevLett.116.131103
4. B.P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Multi-messenger Observations of a Binary Neutron Star Merger", The Astrophysical Journal Letters **848**, Number 2.
5. (LIGO Scientific Collaboration, Virgo Collaboration), "Observations of Compact Binary Mergers by Advanced LIGO and Advanced Virgo during the First and Second Observation Runs", *in preparation*
6. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "A gravitational-wave standard siren measurement of the Hubble constant", Nature **551**, 85-88 (02 November 2017).
7. Guillermo Adrian Valdes, Brian O'Reilly and Mario Diaz, "A Hilbert-Huang transform method for scattering identification in LIGO", Classical and Quantum Gravity **34**, 23 (2017).
8. H. Wang, C. Blair, M. Dovale Alvarez, A. Brooks, M.F. Kasprzack, J. Ramette, P.M. Meyers, S. Kaufer, B. O'Reilly, C.M. Mow-Lowry, "Thermal modelling of Advanced LIGO test masses", Classical and Quantum Gravity **34**, 115001 (2017).

9. B. Abbott, et al. (LIGO Science Collaboration), “Observation of a kilogram-scale oscillator near its quantum ground state”, New J. Phys. **11**, 073032 (2009).
10. N. Mukund, B.O’Reilly, S. Somala, S. Mitra, “Effect of Induced Seismicity on Advanced Gravitational Wave Interferometers (submitted for publication)”, LIGO Document P1800289 (2018).

**SYNERGISTIC ACTIVITIES**

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**PROFESSIONAL PREPARATION**

| | | | |
|---|---|---|---|
| UCLA | Los Angeles, CA | Physics | B.S. 1978 |
| UCLA | Los Angeles, CA | Electrical Engineering | M.S. 1988 |
| UCLA | Los Angeles, CA | Electrical Engineering | Ph.D. 1992 |

**APPOINTMENTS**

Adjunct Professor, Physics, The University of Texas, Rio Grande Valley, 2015 to Present
Adjunct Professor, Physics, The University of Texas, Brownsville, 2011 to 2015
Member of the Professional Staff, California Institute of Technology, 1995 to Present
Senior Scientist, California Institute of Technology, 1993 to1995
Scientist, California Institute of Technology, 1992 to 1993
Graduate Student Researcher, University of California, Los Angeles, 1986 to1992
Owner, F.I.R. Enterprises, Santa Monica, CA, 1984 to 1986
Consultant, University of California, Los Angeles, 1979 to 1984
Senior Development Engineer, University of California, Los Angeles, 1976 to 1979

**PUBLICATIONS**

1. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Observation of Gravitational Waves from a Binary Black Hole Merger", Phys. Rev. Lett. **116**, 061102 (2016). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102
2. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral", Phys. Rev. Lett. **119**, 161101 (2017). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.161101
3. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries", Phys. Rev. Lett. **116**, 131103 (2016). https://doi.org/10.1103/PhysRevLett.116.131103
4. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Multi-messenger Observations of a Binary Neutron Star Merger", The Astrophysical Journal Letters **848**, Number 2.
5. J. Aasi, et al., (The LIGO Scientific Collaboration), "Advanced LIGO", Class. Quantum Grav. **32** 074001 (2015). http://iopscience.iop.org/article/10.1088/0264-9381/32/7/074001/meta
6. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "A gravitational-wave standard siren measurement of the Hubble constant", Nature **551**, 85-88 (2017).

7. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Tests of General Relativity with GW150914", Phys. Rev. Lett. **116**, 221101 (2016).
8. S. Karki, D. Tuyenbayev, S. Kandhasamy, et al., "The Advanced LIGO Photon Calibrators," Rev. Sci. Instrum. **87**(11), 114503 (2016).
9. D. Tuyenbayev, S. Karki, J. Betzwieser, et al, "Improving LIGO calibration accuracy by tracking and compensating for slow temporal variations," Class. Quantum Grav. **34**, 015002 (2017).
10. M. Rakhmanov, R.L. Savage, Jr., D.H. Reitze, and D.B. Tanner, "Dynamic Resonance of Light in Fabry-Perot Cavities,", Phys. Lett. A, **305**, 239 (2002).

**SYNERGISTIC ACTIVITIES**

Member of LIGO Scientific Collaboration (LSC) and LSC Council since its inception in 1997.
Partnership between the LIGO Hanford Observatory and the Center for Gravitational Wave Astronomy at UTRGB, funded by NSF CREST grant supplements, to provide UTB undergraduate and graduate students opportunities to participate in LIGO-related research at the LIGO Hanford Observatory.
Collaboration with the Albert Einstein Institute and the Laser Zentrum in Hannover, Germany on the development of high-power lasers for gravitational wave detectors.
Member of the LSC Laser and Optics Working group since its inception.

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**PROFESSIONAL PREPARATION**

Diplôme de Doctorat, Université de Paris-Sud, 1987
Master of Science, Massachusetts Institute of Technology, 1980

**APPOINTMENTS**

1975-77 Laboratory Instructor, MIT Physics Department
1980-84 Staff member, MIT Gravitation and Cosmology research group
1984-86 Gast Wissenschaftler, Max-Planck-Institut für Quantenoptik (Munich, West Germany)
1986-87 Poste Rouge, Centre Nationale de la Recherche Scientique (Orsay, France)
1987-89 Ingenieur, Centre Nationale de la Recherche Scientique
1989 July-August Visiting Scientist, Institute of Space and Astronautical Science (ISAS), Tokyo, Japan
1989-91 Research Scientist, MIT Center for Space Research
1991-97 Principal Research Scientist, MIT Center for Space Research
1995-99 Deputy Group Leader for Detector, LIGO Project
1997- Senior Research Scientist, MIT Center for Space Research
2001-2016 Director, MIT LIGO Laboratory
2003-2006 Leader, Advanced LIGO R&D
2006- Leader, Advanced LIGO Project
2006- Visiting Associate Faculty, California Institute of Technology

**PUBLICATIONS**

1. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Observation of Gravitational Waves from a Binary Black Hole Merger", Phys. Rev. Lett. **116**, 061102 (2016). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102
2. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence", Phys. Rev. Lett. **116**, 241103 (2016). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.241103
3. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2", Phys. Rev. Lett. **118**, 221101 (2017). https://doi.org/10.1103/PhysRevLett.118.221101
4. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", Phys. Rev. X **6**, 041015 (2016). https://doi.org/10.1103/PhysRevX.6.041015

5. J. Aasi, et al., (The LIGO Scientific Collaboration), "Advanced LIGO", Class. Quantum Grav. 32 074001 (2015). http://iopscience.iop.org/article/10.1088/0264-9381/32/7/074001/meta
6. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Astrophysical Implications of the Binary Black-Hole Merger GW150914", Astrophys. J. Lett. **818**, L22 (2016). http://iopscience.iop.org/article/10.3847/20418205/818/2/L22?pageTitle=IOPscience
7. B. P. Abbott, et al., (LIGO Scientific Collaboration, Virgo Collaboration), "Tests of General Relativity with GW150914", Phys. Rev. Lett. **116**, 221101 (2016). http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.221101
8. B. Abbott, et al. (LIGO Science Collaboration), "Observation of a kilogram-scale oscillator near its quantum ground state", New J. Phys. **11**, 073032 (2009). http://iopscience.iop.org/1367-2630/11/7/073032
9. J. Abadie, et al. (LIGO Science Collaboration), "First search for gravitational waves from the youngest known neutron star", Astrophys. J. **722**, 1504-1513 (2011). http://iopscience.iop.org/0004-637X/722/2/1504

**SYNERGISTIC ACTIVITIES**

1. Advisory Committees: Chair of the European Gravitational Observatory Technical Advisory Committee
2. Program Committees: Executive Committee of the LISA Space Gravitational Detector Consortium

Data Not Available

# SUMMARY PROPOSAL BUDGET

YEAR 1

| ORGANIZATION | FOR NSF USE ONLY | | |
|---|---|---|---|
| California Institute of Technology | PROPOSAL NO. | DURATION (months) | |
| | | Proposed | Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR | AWARD NO. | | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. | | | | | |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |
| 5. | | | | | |
| 6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.0 | | | 0 | |
| 7. ( ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.0 | | | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.0 | | | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.0 | | | 0 | |
| 3. ( 0 ) GRADUATE STUDENTS | | | | 0 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 0 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 0 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS) | | | | 16,078 | |
| 2. INTERNATIONAL | | | | 14,292 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 0<br>2. TRAVEL 141,849<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 32 ) TOTAL PARTICIPANT COSTS | | | | 141,849 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 5,990 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 9,425 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 0 | |
| TOTAL OTHER DIRECT COSTS | | | | 15,415 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 187,634 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>MTDC (Rate: 26.0, Base:45785) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 11,904 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 199,538 | |
| K. SMALL BUSINESS FEE | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | 199,538 | |

| M. COST SHARING PROPOSED LEVEL $ | AGREED LEVEL IF DIFFERENT $ | | |
|---|---|---|---|
| PI/PD NAME | FOR NSF USE ONLY | | |
| | INDIRECT COST RATE VERIFICATION | | |
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

# SUMMARY PROPOSAL BUDGET

YEAR 2

| ORGANIZATION | FOR NSF USE ONLY | | |
|---|---|---|---|
| California Institute of Technology | PROPOSAL NO. | DURATION (months) Proposed | Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR | AWARD NO. | | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. | | | | | |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |
| 5. | | | | | |
| 6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.0 | | | 0 | |
| 7. ( ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.0 | | | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.0 | | | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.0 | | | 0 | |
| 3. ( 0 ) GRADUATE STUDENTS | | | | 0 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 0 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 0 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS) | | | | 16,078 | |
| 2. INTERNATIONAL | | | | 14,292 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 0<br>2. TRAVEL 141,849<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 32 ) TOTAL PARTICIPANT COSTS | | | | 141,849 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 5,990 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 9,425 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 0 | |
| TOTAL OTHER DIRECT COSTS | | | | 15,415 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 187,634 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>MTDC (Rate: 26.0, Base:45785) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 11,904 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 199,538 | |
| K. SMALL BUSINESS FEE | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | 199,538 | |

| M. COST SHARING PROPOSED LEVEL $ | AGREED LEVEL IF DIFFERENT $ | | |
|---|---|---|---|
| PI/PD NAME | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION | | |
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

2 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

# SUMMARY PROPOSAL BUDGET

YEAR 3

| | | | | | |
|---|---|---|---|---|---|
| ORGANIZATION<br>California Institute of Technology | | | FOR NSF USE ONLY<br>PROPOSAL NO. | DURATION (months)<br>Proposed | Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR | | | AWARD NO. | | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. | | | | | |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |
| 5. | | | | | |
| 6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.0 | | | 0 | |
| 7. ( ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.0 | | | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.0 | | | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.0 | | | 0 | |
| 3. ( 0 ) GRADUATE STUDENTS | | | | 0 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 0 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 0 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS) | | | | 16,078 | |
| 2. INTERNATIONAL | | | | 14,292 | |
| F. PARTICIPANT SUPPORT COSTS | | | | | |
| 1. STIPENDS $ 0 | | | | | |
| 2. TRAVEL 141,849 | | | | | |
| 3. SUBSISTENCE 0 | | | | | |
| 4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 32 ) TOTAL PARTICIPANT COSTS | | | | 141,849 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 5,990 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 9,425 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 0 | |
| TOTAL OTHER DIRECT COSTS | | | | 15,415 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 187,634 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>MTDC (Rate: 26.0, Base:45785) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 11,904 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 199,538 | |
| K. SMALL BUSINESS FEE | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | 199,538 | |
| M. COST SHARING PROPOSED LEVEL $ | AGREED LEVEL IF DIFFERENT $ | | | | |

| | | | |
|---|---|---|---|
| PI/PD NAME | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION | | |
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

3 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

# SUMMARY PROPOSAL BUDGET

YEAR 4

| FOR NSF USE ONLY | | |
|---|---|---|
| PROPOSAL NO. | DURATION (months) Proposed | Granted |
| AWARD NO. | | |

ORGANIZATION
California Institute of Technology

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. | | | | | |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |
| 5. | | | | | |
| 6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.0 | | | 0 | |
| 7. ( ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.0 | | | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.0 | | | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.0 | | | 0 | |
| 3. ( 0 ) GRADUATE STUDENTS | | | | 0 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 0 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 0 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS) | | | | 16,078 | |
| 2. INTERNATIONAL | | | | 14,292 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 0<br>2. TRAVEL 141,849<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 32 ) TOTAL PARTICIPANT COSTS | | | | 141,849 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 5,990 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 9,425 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 0 | |
| TOTAL OTHER DIRECT COSTS | | | | 15,415 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 187,634 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>MTDC (Rate: 26.0, Base:45785) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 11,904 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 199,538 | |
| K. SMALL BUSINESS FEE | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | 199,538 | |

M. COST SHARING PROPOSED LEVEL $ AGREED LEVEL IF DIFFERENT $

PI/PD NAME

ORG. REP. NAME*

| FOR NSF USE ONLY | | |
|---|---|---|
| INDIRECT COST RATE VERIFICATION | | |
| Date Checked | Date Of Rate Sheet | Initials - ORG |

4 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

# SUMMARY PROPOSAL BUDGET

Cummulative

| | | | | | |
|---|---|---|---|---|---|
| ORGANIZATION<br>California Institute of Technology | | | FOR NSF USE ONLY<br>PROPOSAL NO. | DURATION (months)<br>Proposed | Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR | | | AWARD NO. | | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. | 0.0 | | | 0 | |
| 2. | 0.0 | | | 0 | |
| 3. | 0.0 | | | 0 | |
| 4. | 0.0 | | | 0 | |
| 5. | 0.0 | | | 0 | |
| 6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.0 | | | 0 | |
| 7. ( ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.0 | | | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.0 | | | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.0 | | | 0 | |
| 3. ( 0 ) GRADUATE STUDENTS | | | | 0 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 0 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 0 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS) | | | | 64,312 | |
| 2. INTERNATIONAL | | | | 57,168 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 0<br>2. TRAVEL 567,396<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 128 ) 0 TOTAL PARTICIPANT COSTS | | | | 567,396 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 23,960 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 37,700 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 0 | |
| TOTAL OTHER DIRECT COSTS | | | | 61,660 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 750,536 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 47,616 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 798,152 | |
| K. SMALL BUSINESS FEE | | | | | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | 798,152 | |
| M. COST SHARING PROPOSED LEVEL $ | AGREED LEVEL IF DIFFERENT $ | | | | |

| | | | |
|---|---|---|---|
| PI/PD NAME | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION | | |
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

**Support for LIGO Scientific Collaboration Core Functions in the Era of Gravitational-Wave Observations (FY 2020 through FY 2023) Proposal Budget Justification**

## Summary

The total funding request related to the proposal for Support for LIGO Scientific Collaboration (LSC) Core Functions in the Era of Gravitational-Wave Observations is $798,147. The proposed period of performance is October 1, 2019 through September 30, 2023. This proposal requests NSF Research and Related Activities (R&RA) funding to support the LIGO Scientific Collaboration core functions through FY2023.

## Line A - Senior Personnel

All salaries for the Principal and Co-Principal investigators are covered under NSF Award 1764464, “LIGO Laboratory Operations and Maintenance 2019-2023”.

## Line B – Personnel and Salaries

n/a

## Line C - Fringe Benefits

n/a

## Line D – Equipment

n/a

## Line E – Travel

Domestic and Foreign travel was estimated for the LSC Spokesperson and Deputy Spokesperson, as well as, LSC members. This estimate covers travel costs to various meetings, such as the Memoranda Of Understanding (MoU) Reviews, Data Analysis Council (DAC) meetings, LSC semi-annual meetings and NSF annual reviews. The LIGO Financial Analyst developed an average trip cost using all travel costs incurred in FY2016 and FY2017 for domestic and foreign trips. This average trip cost was applied to the number of trips indicated by functional group leaders to arrive at a cost estimate. The average trip cost for a domestic trip was calculated at $1,706 and a foreign trip was calculated at $3,412.

| Item Description | Category | Expenditure Type | Direct Unit Cost | Qty/Year | FY2020 Direct Cost | FY2021 Direct Cost | FY2022 Direct Cost | FY2023 Direct Cost |
|---|---|---|---|---|---|---|---|---|
| Service Travel-Domestic | LSC Activity Costs | Travel - Domestic Allocable | $1,706 | 10 | $17,060 | $17,060 | $17,060 | $17,060 |
| Service Travel-Foreign | LSC Activity Costs | Travel - Foreign | $3,412 | 5 | $17,060 | $17,060 | $17,060 | $17,060 |
| LSC Spokespersons Domestic Travel | LSC Activity Costs | Travel - Domestic Allocable | $1,706 | 8 | $13,648 | $13,648 | $13,648 | $13,648 |
| LSC Spokespersons Foreign Travel | LSC Activity Costs | Travel - Foreign | $3,412 | 3 | $10,236 | $10,236 | $10,236 | $10,236 |

*Table 1: Travel costs by category and Fiscal Year*

## Line F - Participant Costs

The LSC Fellows Program offers opportunities for members of the LSC to become resident fellows at the Observatory sites. Fellows are expected “to increase the product of searched volume and time” i.e. to undertake projects aimed at both increasing the sensitivity of the interferometers and increasing the reliability or duty cycle of the detectors. Each site typically hosts four fellows on average throughout the year. LSC Fellows commit to a minimum 3-month stay. The budget includes participant costs to cover a portion of travel expenses, shared lodging and shared car rental.

| Item Description | Category | Expenditure Type | Direct Unit Cost | Qty/Year | FY2020 Direct Cost | FY2021 Direct Cost | FY2022 Direct Cost | FY2023 Direct Cost | Notes |
|---|---|---|---|---|---|---|---|---|---|
| Rental Cars LHO (includes gas) | LSC Fellows Costs | Participant Support - Travel | $1,000 | 24 | $24,000 | $24,000 | $24,000 | $24,000 | Two cars per month |
| Rental Cars LLO (includes gas) | LSC Fellows Costs | Participant Support - Travel | $1,100 | 24 | $26,400 | $26,400 | $26,400 | $26,400 | Two cars per month |
| LLO Housing (2 Bedroom Apt) | LSC Fellows Costs | Participant Support - Travel | $3,375 | 24 | $81,000 | $81,000 | $81,000 | $81,000 | Two apartments per month |
| LHO Housing (3 Bedroom Apt) | LSC Fellows Costs | Participant Support - Travel | $2,800 | 24 | $67,200 | $67,200 | $67,200 | $67,200 | Two apartments per month |
| Foreign Travel Ticket | LSC Fellows Costs | Participant Support - Travel | $1,900 | 16 | $30,400 | $30,400 | $30,400 | $30,400 | Four foreign fellows per quarter (16 per year) |
| Domestic Travel Ticket | LSC Fellows Costs | Participant Support - Travel | $500 | 16 | $8,000 | $8,000 | $8,000 | $8,000 | Four domestiic fellows per quarter (16 per year) |
| Startup  Allowance | LSC Fellows Costs | Participant Support - Travel | $400 | 32 | $12,800 | $12,800 | $12,800 | $12,800 | 32 fellows per year |
| VISA Allowance | LSC Fellows Costs | Participant Support - Travel | $250 | 16 | $4,000 | $4,000 | $4,000 | $4,000 | 16 foreign fellows per year |
| Inter-site travel (1-week trip) | LSC Fellows Costs | Participant Support - Travel | $1,500 | 8 | $12,000 | $12,000 | $12,000 | $12,000 | 2 trips per quarter (8 per year) |
| Fellows coord. LVC mtg. Domestic Travel | LSC Fellows Costs | Participant Support - Travel | $1,706 | 1 | $1,706 | $1,706 | $1,706 | $1,706 | 1 foreign, 1 domestic LVC meeting |
| Fellows coord. LVC mtg. Foreign | LSC Fellows Costs | Participant Support - Travel | $3,412 | 1 | $3,412 | $3,412 | $3,412 | $3,412 | 1 foreign, 1 domestic LVC meeting |

*Table 2: Participant Support by Cost Description and Fiscal Year*

**Line G1 – Materials and Supplies**
Amazon Web Services is contracted to host the LSC public web site (http://www.ligo.org) on AWS.  The LSC public web site host fee for a highly available cloud solution is $120/month.

LIGO identity services will be outsourced to a professional organization that will host them in a commercial cloud platform for improved reliability and reduced operational costs. In particular, CILogon 2.0 services are being contracted through the University of Illinois Urbana Champaign (UIUC) for $30k/y to host and maintain central identity management services in a highly available configuration on Amazon Web Services (AWS). The plan is to split this fee 3-ways between: this proposal for the LSC, the LIGO Laboratory, and the Virgo Collaboration.  A partial list of services being contracted include a highly available (HA) SAML IdP/SP proxy for centrally managed policy enforcement and access control and for supporting a HA LIGO identity provider (IdP) infrastructure, a HA Grouper service as the LIGO group registry, and a HA LDAP directory as the primary authorization backplane used by LIGO IdM infrastructure and other services.

**Line G2 – Publication/Documentation/Dissemination**
Projected expenses for publications are based on historical costs. It is assumed that 9 papers will be published annually at an average fee of $2k. When appropriate, this includes costs to make papers accessible to the public.

**Line G3 – Consultant Services**
n/a

**Line G5 – Subawards**
n/a

**Line G6 - Other Direct Costs**
n/a

**Line I. Indirect Costs**
Indirect Cost and Benefits calculations are based on the following rates:

- The Facilities and Administrative Rates ("F&A") for FY 2019 has been negotiated with the Office of Naval Research. These rates have been used to price the cost estimates for FY 2020 – FY 2023.
- Off-Campus Overhead Rate is calculated at 26.0 percent MTDC.

Cumulative Amounts:
Base MTDC: $183,137
Indirect $47,616

The Indirect Cost basis excludes Equipment, Participant Costs, Subaward amounts in excess of $25,000, and Tuition Remission.

The Caltech indirect rate is applied based on the following criteria:

- Where the expenses are being incurred (on- or off-campus have different rates)
- Whether the work being performed is part of an equipment fabrication (no indirect, regardless of where the expense is being incurred)
- What type of expense it is; expenses exempt from indirect include:
    - Equipment & Rentals of Equipment
    - Tuition Remission
    - Participant Support costs
    - Subcontracts after the first $25k
    - Subawards