LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO) $45,000,000 -$4,430,000 / -9.0%

Laser Interferometer Gravitational-Wave Observatory Funding
(Dollars in Millions)

FY 2018 Actual[1]	FY 2019 (TBD)	FY 2020 Request	Change over FY 2018 Actual Amount	Percent
$49.43	-	$45.00	-$4.43	-9.0%

[1] FY 2018 Actual includes $10.0 million in additional FY 2018 funding above the requested amount.

Einstein's theory of general relativity predicts that cataclysmic processes involving extremely dense objects in the universe, such as the collision and merger of two black holes, will produce gravitational radiation. On September 14, 2015, NSF's LIGO directly observed gravitational radiation from a black-hole merger, verifying this 100-year-old prediction. This is an achievement of historic importance for fundamental physics, astrophysics, and astronomy, as it opens an entirely new observational window on the universe. This achievement was announced to the world in a series of international press conferences on February 11, 2016. LIGO announced detection of a second black-hole merger on June 15, 2016. In October 2017, LIGO announced the first detection of a neutron star-neutron star merger, observed on August 17, 2017. This event was also observed in the electromagnetic spectrum, from gamma rays to radio waves, by 70 telescopes around the world. These observations had the far-reaching consequence of confirming that most of the elements heavier than iron were produced by neutron star-neutron star mergers. The 2017 Nobel Prize in Physics was awarded to Barry Barish, Kip Thorne, and Rainer Weiss for their "decisive contributions to the LIGO detector and the observation of gravitational waves."

In two separate observational periods beginning with the September 14, 2015 detection, LIGO has now detected gravitational waves from 10 stellar-mass binary black hole mergers as well as the one binary neutron star inspiral. During the first observing period, or "run" (O1), from September 12, 2015 to January 19, 2016, gravitational waves from three binary black hole mergers were detected. The second observing run (O2), which lasted from November 30, 2016, to August 25, 2017, saw a binary neutron star merger and a total of seven binary black hole mergers. GW170729, the third event detected in O2 on July 29, 2017, is the most massive and distant gravitational wave source ever observed. In this coalescence, which happened approximately five billion years ago, an equivalent energy of almost five solar masses was converted into gravitational radiation.

The European Advanced Virgo interferometer joined NSF's two Advanced LIGO detectors on August 1, 2017, in O2. While the LIGO-Virgo three-detector network was operational for only three and a half weeks, five events were observed in this period. One of these, GW170814, was the first binary black hole merger measured by the three-detector network, enabling the first measurements of gravitational wave polarization and providing an additional confirmation of the theory of general relativity. The Virgo interferometer also contributed to the detection of the binary neutron star merger.

All these observations were made while LIGO is still in the process of fine-tuning its instrumentation to reach design sensitivity. Advanced LIGO is currently preparing for a third scientific run beginning in 2019, and a fourth beginning in 2021, incrementally increasing its sensitivity to reach the full capabilities of the current suite of instrumentation.

LIGO, the most sensitive gravitational-wave detector ever built, comprises two main facilities, one in Livingston Parish, LA and one in Hanford, WA. At each facility, an L-shaped vacuum chamber, with two

4-km long arms joined at right angles, houses an optical interferometer. The interferometers are used to measure minute relative changes in the distances between the vertex of the L and mirrors at the ends of the arms that are caused by a passing gravitational wave. A passing gravitational wave causes the distance along one arm to lengthen while the other arm shrinks during one half cycle of the wave, and then the first arm shrinks while the other arm lengthens during the second half cycle. The predicted distortion of space caused by a gravitational wave from a likely source is on the order of one part in 10^{21}, meaning that the expected amplitude of the length change over the four-km length is only about 1/1000th the diameter of a proton. LIGO's four-km length was chosen to make the expected signal as large as possible within terrestrial and financial constraints: longer arms would result in a bigger signal but would entail larger construction costs. Looking for coincident signals from both interferometers increases LIGO's ability to discriminate between a gravitational wave and local sources of noise.

In 2015, LIGO completed installation of the "Advanced LIGO" upgrade, funded through the MREFC account. The upgrade enabled the design, fabrication, and installation of an improved apparatus expected to increase LIGO's sensitivity 10-fold relative to the initial LIGO apparatus (which had operated through 2009). During O1, the Advanced LIGO interferometers operated at about four times the initial LIGO sensitivity, and at about six times the initial sensitivity during O2. LIGO's O3 goal is an eight-fold increase.

Components for a third interferometer, initially intended for installation at Hanford as a further tool to discriminate candidate signals from random noise, have been set aside in response to a proposed initiative from the Government of India to establish a gravitational wave observatory there. If realized, this third interferometer would greatly enhance LIGO's ability to locate gravitational wave sources on the sky, facilitating follow-up investigations using optical and radio telescopes. The scientific value of obtaining complementary gravitational wave and electromagnetic signals from the same source has already been demonstrated in the recent observation of a neutron star-neutron star merger. As the number of observations expands with enhanced sensitivity and localization, this will significantly increase our understanding of supernovae and neutron stars. Such scientific prospects help motivate the NSF Big Idea 'Windows on the Universe.'

Total Obligations for LIGO

(Dollars in Millions)

	FY 2018 Actual	FY 2019 (TBD)	FY 2020 Request	ESTIMATES[1] FY 2021	FY 2022	FY 2023	FY 2024	FY 2025
Operations & Maintenance	$39.43	-	$44.60	$45.00	$45.00	$45.00	$45.00	$45.00
Facility Upgrades[2]	10.00	-	0.40	-	-	-	-	-
TOTAL REQUIREMENTS	**$49.43**	**-**	**$45.00**	**$45.00**	**$45.00**	**$45.00**	**$45.00**	**$45.00**

[1] Outyear funding estimates are for planning purposes only. The current cooperative agreement ends in September 2023.

[2] FY 2018 Actual includes $10.0 million in additional FY 2018 funding above the requested amount.

Facility Upgrades: LIGO researchers are planning a series of instrumental upgrades to take place in the coming years. The first of these enhancements, known as Advanced LIGO Plus (or "A+"), will increase the volume of space surveyed by Advanced LIGO by a factor between four and seven, depending on the type of gravitational wave source. In FY 2018, NSF awarded $10.0 million to LIGO for the A+ enhancement, with an additional $10.47 million expected to be provided in FY 2019. This award is part of an international effort between NSF, the UK Research and Innovation (UKRI) and the Australian Research Council (ARC), who jointly support the U.S.-UK-Australian collaboration of researchers spearheading A+. The A+ upgrades are expected to start operating in 2024.

LIGO is pursuing an integrated program of periodic scientific operation of the LIGO observatories, interleaved with engineering studies and upgrades that continue to enhance operating performance. The operations budget also supports basic infrastructure maintenance, analysis, and dissemination of data obtained from the interferometers, and maintenance of computational resources for data storage and analysis. Operations funding also enables strategic research and development in instrument science that is expected to lead to longer-term enhancements to operational performance.

A small part of the operations budget supports education and public outreach (EPO) activities. The LIGO Science Education Center (LIGO SEC), located on the Livingston Observatory site, hosts 50 hands-on inquiry-based learning exhibits and reaches over 15,000 students, teachers and members of the public each year. Its activities benefit from a partnership with Southern University Baton Rouge (SUBR), the San Francisco Exploratorium, the Baton Rouge Area Foundation (BRAF), and other collaborating educational entities. Trained docents from SUBR assist participants and serve as collegiate-age role models for young visitors. LIGO SEC programs are supported both through LIGO's operations cooperative agreement and through grants to SUBR and BRAF. The LIGO Hanford Observatory also promotes a highly successful program of outreach to K-12 students and the general public in the Washington State Tri-Cities region, reaching approximately 10,000 people each year. In 2018, LIGO Laboratory secured funding from Washington State for the conceptual design of a LIGO Hanford STEM Exploration Center to carry out a high-impact, interactive EPO program similar in mission to the LIGO SEC. LIGO Laboratory/Caltech plans to submit a construction proposal to the Washington State House of Representatives in 2019. LIGO Laboratory members supported by the operations budget also contribute to many activities of the EPO working group of the LIGO Scientific Collaboration.

LIGO created a number of connections to industry in order to achieve the demanding technical performance requirements needed to detect gravitational waves. Innovations across a diverse range of technologies have led to new techniques with broad applications (for example, preparation of stainless steel for ultra-high vacuum application, adaptive laser beam shaping, and precision dielectric optical coatings). Other technological developments at LIGO have resulted in patents and commercial products (in-vacuum electrical connectors, high power electro-optic modulators).

The LIGO Scientific Collaboration (LSC), an open collaboration that organizes the major international groups doing research supportive of LIGO, has 108 collaborating institutions in 20 countries with nearly 1,300 participating scientists. The LSC plays a major role in many aspects of the LIGO effort. These include establishing priorities for scientific operation, data analysis and validation of scientific results, and contributing to instrumental improvements at the LIGO facilities and exploring future technologies, as well as fostering education and public outreach programs. NSF supports LSC activities in the United States at approximately $8 million per year, which is provided through regular disciplinary program funds.

Management and Oversight

LIGO activities are funded through a five-year cooperative agreement that began October 1, 2017. NSF continually assesses the appropriate level of financial support by monitoring actual expenditures contained in quarterly activity-based financial reports from LIGO, and through annual external reviews of operations that examine performance relative to objectives defined in LIGO's annual work plans. Infrastructure refurbishments recently accomplished, such as repairs and improvements to the vacuum system, as well as further work planned in 2020 will extend the facility life beyond 2030.

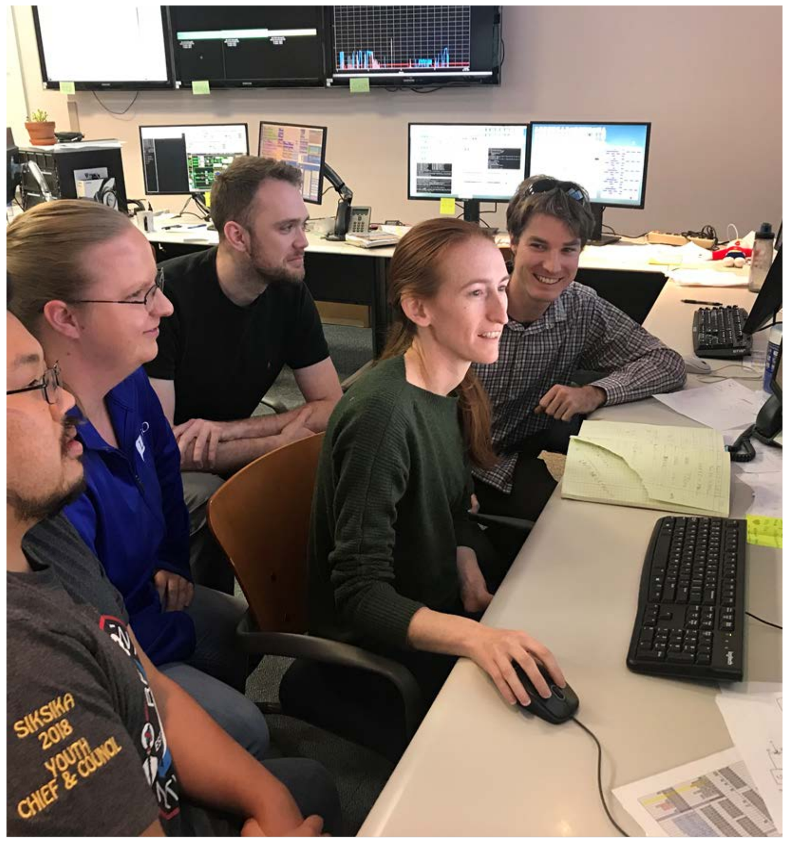
- NSF Structure: NSF oversight is coordinated internally by the LIGO program director in the MPS Division of Physics. The program director consults regularly with representatives from the Large Facilities Office and the NSF Division of Acquisition and Cooperative Support in BFA. The MPS Facilities team, together with the NSF Chief Officer for Research Facilities, also provide high-level guidance, support, and oversight.
- External Structure: LIGO is managed by the California Institute of Technology under a cooperative agreement. A subaward from California Institute of Technology to Massachusetts Institute of Technology supports a team of scientists and engineers that are fully integrated into all LIGO activities.

The management plan specifies significant involvement by the user community, represented by the LSC, and collaboration with the other major gravitational-wave detector activities in Asia, Europe, and Australia. External review committees organized by NSF help provide oversight through annual reviews.

- Recent Reviews: Reviews of observatory operation are held annually. Special purpose reviews using external expert panels have also been held as needed, examining topics such as long-term storage of the interferometer components set aside for possible deployment to India, LIGO computing plans, and LIGO ultra-high vacuum system needs. The most recent annual review was held in June 2018. The next annual review is planned for June 2019.

Renewal/Recompetition/Termination

In 2015 and 2016 MPS conducted a detailed consideration of whether to recompete the management of the LIGO Laboratory in conjunction with the current five-year award. As LIGO had just completed installation of the Advanced LIGO apparatus in early 2015, and its operational activities were focused on initial commissioning of the apparatus, NSF concluded recompetition was inappropriate. The NSB was apprised of this at their August 9-10, 2016 meeting, and the award was renewed for the period of October 1, 2018 to September 30, 2023. The 2015 study recommended that NSF, in partnership with the LIGO Scientific Collaboration and with input from the broader astrophysics community, again consider the circumstances and criteria for a possible recompetition midway through the current five-year period (i.e., 2020-21).



Scientists and graduate students in the LIGO Hanford Observatory control room conducting a series of experiments to improve the Hanford interferometer sensitivity. *Credit: Caltech/LIGO Laboratory.*