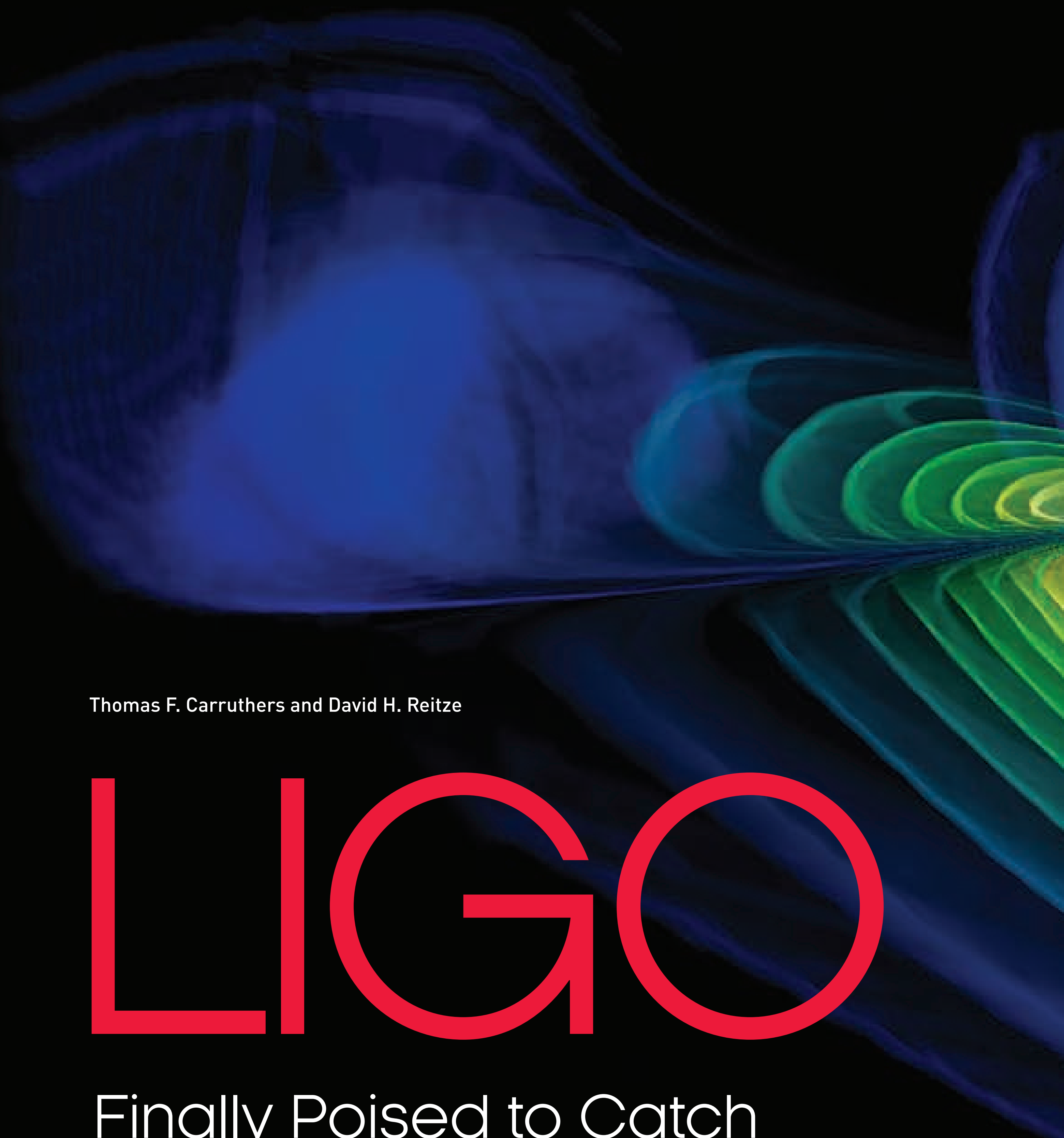
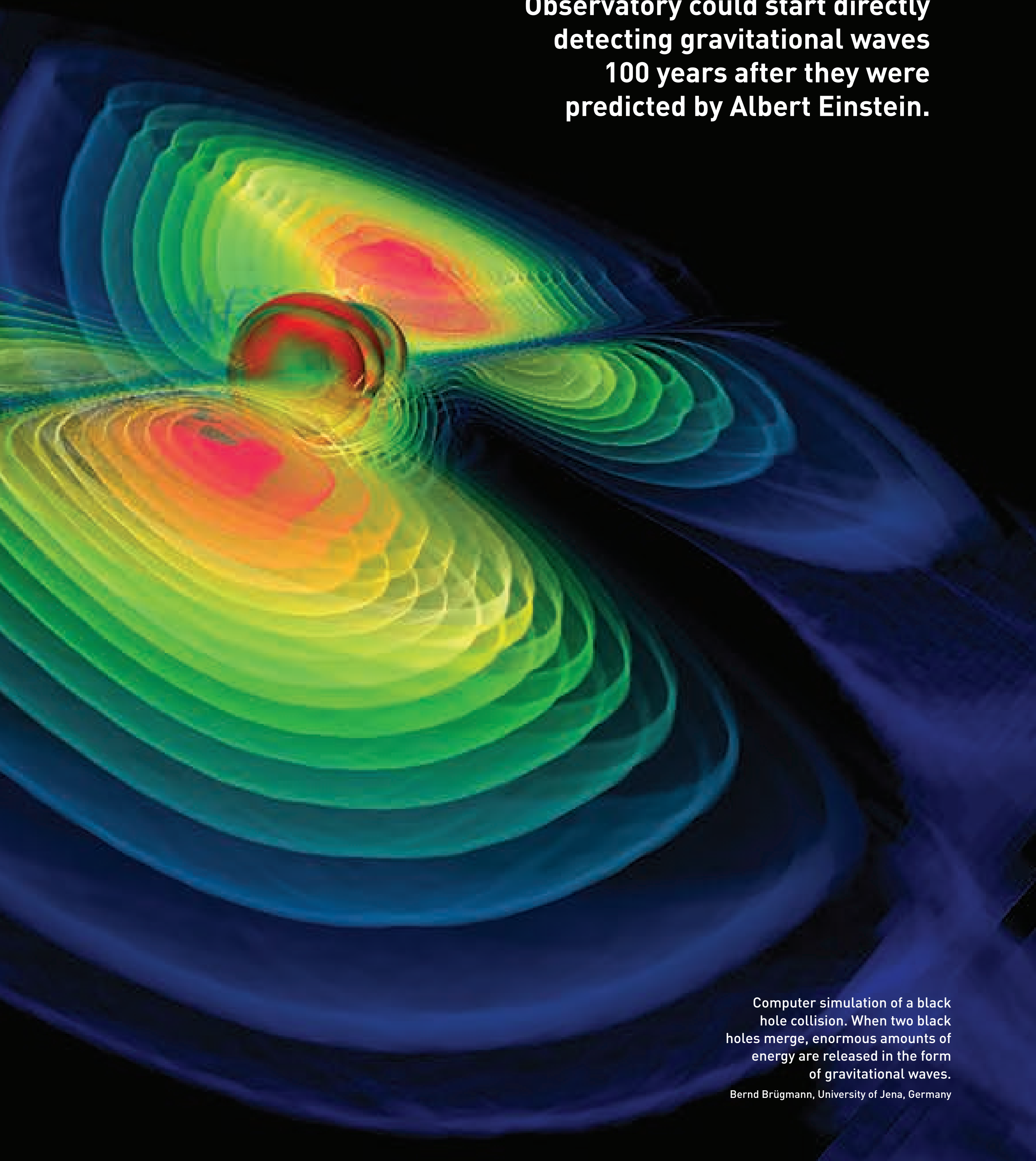


Thomas F. Carruthers and David H. Reitze

LIGO

Finally Poised to Catch Elusive Gravitational Waves?

After a seven-year upgrade project incorporating cutting-edge lasers and optics, the Advanced Laser Interferometer Gravitational-Wave Observatory could start directly detecting gravitational waves 100 years after they were predicted by Albert Einstein.



Computer simulation of a black hole collision. When two black holes merge, enormous amounts of energy are released in the form of gravitational waves.

Bernd Brügmann, University of Jena, Germany

The initial Laser Interferometer Gravitational-Wave Observatory (LIGO) instruments began collecting data from the cosmos in 2002 and concluded operations in 2010. After years of research and development, work began in 2008 on Advanced LIGO, a major upgrade that will increase LIGO's sensitivity; this project is scheduled for completion at the end of March 2015. Researchers hope that the Advanced LIGO project not only will make the first direct observations of gravitational waves in the coming years, adding weight to Albert Einstein's nearly 100-year-old theory of general relativity, but also will open a window to the universe that astrophysicists and astronomers will use for many decades.

From its inception, LIGO has been conceived as a multiphase project. The initial LIGO team used the best technology from the 1980s and 1990s to demonstrate the practicality of optical gravitational-wave detectors and to provide a reasonable chance of making the first direct detections of gravitational waves. (Even though LIGO surpassed its design sensitivity, no gravitational waves were ever detected.) The second phase, which is now underway, will incorporate 21st-century technology to increase LIGO's sensitivity by a factor of 10, eventually extending its range for detecting neutron-star mergers—a source of gravitational waves—from about 50 to 500 million light-years (Mly), expanding the volume of space that LIGO can search by a factor of 1,000.

Advanced LIGO will start collecting data later this year, and researchers are anxious to see if the latest improvements will pay off.

Advanced LIGO will start collecting data later this year, and researchers are anxious to see if the latest improvements will pay off. However, LIGO scientists aren't sitting at their desks waiting for the data to come in; they are already investigating ways to further increase detector sensitivity and are building relationships with other institutions to expand the project into a world-wide network of gravitational-wave observatories.

Ripples in space-time

Einstein's general theory of relativity tells us that massive objects curve space-time; the more massive the object, the more space-time bends. When such objects accelerate, the resulting curvature is dynamic, and gravitational waves—ripples in space-time—propagate away at the speed of light.

Gravitational waves are fundamentally different from the electromagnetic radiation that has given us most of our knowledge about the universe, and their unique properties provide a powerful new way of observing the universe. As a gravitational wave passes, it produces a strain h (change in length per unit length, $\Delta L/L$) that results in differential distortion in the two orthogonal dimensions of the space through which it passes. (Smoothly rotating cylindrically symmetric objects cannot emit gravitational radiation; only "lumpy" mass distributions possessing dynamic quadrupole mass moments can do so.)

Gravitational waves pass essentially unimpeded through matter, so that violent astrophysical events otherwise hidden by dust or even in the hearts of stars can be observed and recorded. Some events, such as the isolated merger of two black holes, are not believed to even generate an electromagnetic signal—they can only be studied through gravitational-wave emissions.

By detecting gravitational waves, researchers can test general relativity in the very strong gravity regime for the first time. Repeated observations of the dynamics of disturbed event horizons surrounding black holes could offer clues to the apparent conflict between general relativity and quantum mechanics.

Sources of gravitational waves

Detecting gravitational waves is a monumental challenge for two reasons. First, space-time is very stiff—if it were a material it would be about 10^{17} times stiffer than diamond—so that gravitational-wave strains from distant

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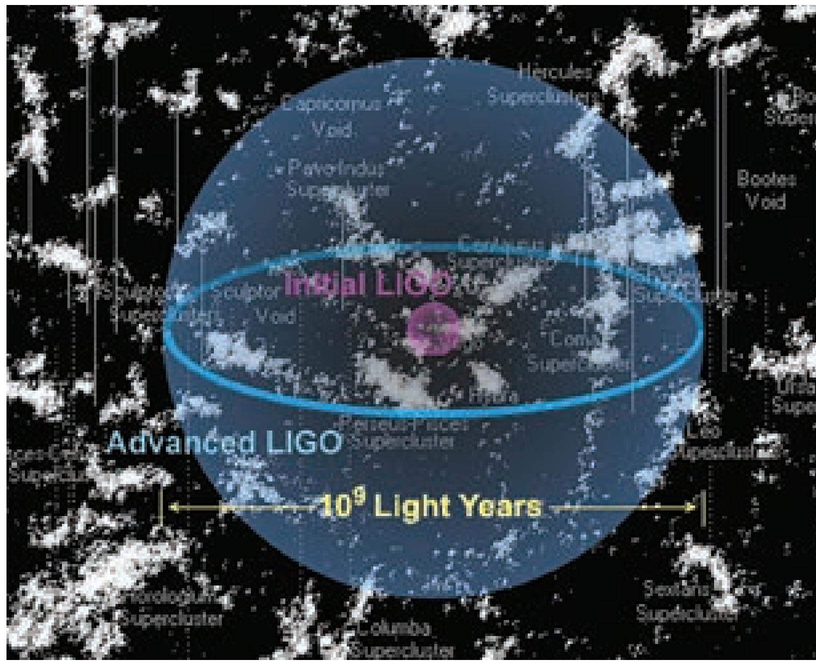
astrophysical events will be extremely small. And, second, the events that are capable of producing detectable signals happen very rarely, so that a detector must be sensitive enough to detect events that originate in a large number of galaxies at great distances.

The most likely sources of gravitational waves are thought to be co-orbiting binary compact stellar-mass objects, such as neutron stars or black holes. As these binary systems lose orbital energy to gravitational-wave radiation, their orbits decay and their orbital frequency increases until the two objects cataclysmically merge. The radiated power rises as the orbital frequency increases, and just before coalescence, the final burst of radiation is extremely energetic: a 10-solar-mass binary system can convert as much as the energy equivalent of one solar mass into gravitational waves during the merger phase.



The cosmic reach of initial LIGO and Advanced LIGO for binary neutron-star mergers.
Richard Powell and Beverly Berger

Merger rates for binary neutron-star systems are highly uncertain, but the middle of the range of estimates is for about 1 event per 5,000 years for binary neutron stars in a galaxy the size of the Milky Way; estimates are about 100 times lower for binary black hole and neutron star–black hole inspirals.

Given these very low event rates, any instrument built to reveal such events on a human time scale must be sufficiently sensitive to probe enough galaxies to ensure a reasonable chance of detection. For the first phase of LIGO, events would have to have been detectable over a distance of at least 50 Mly, reaching well into the Virgo cluster of galaxies (of which our Milky Way is a member) and encompassing some 300 galaxies.

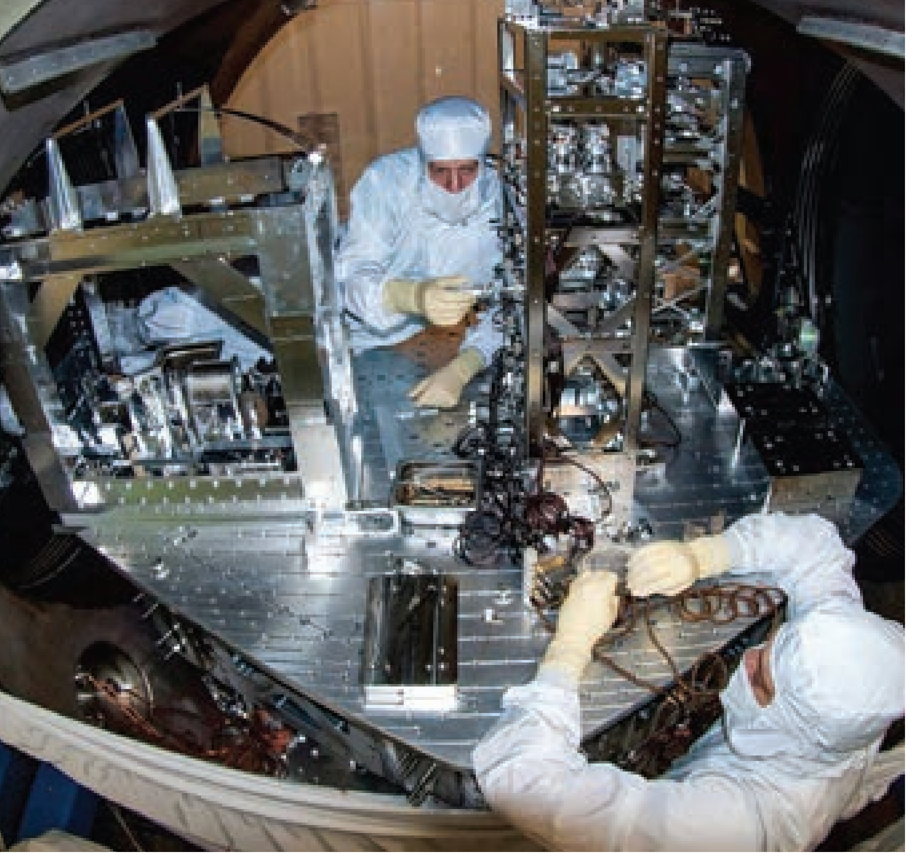
The magnitude of a signal generated in neutron star mergers at such distances can be analytically calculated, and initial LIGO was designed to detect strains of better than one part in 10^{21}, sufficient to detect gravitational waves at those distances. This corresponds to a change in length of less than one-half percent of the diameter of a proton over LIGO's 4-km length. Thus, truly heroic efforts are necessary to directly observe gravitational-wave radiation from distant astrophysical events. However, the anticipated inspiral detection rate for initial LIGO was roughly only one event per 50 years.

Other types of astrophysical events are predicted to generate detectable gravitational waves. Within our galaxy, asymmetric or "bumpy" neutron stars might generate nearly monochromatic continuous-wave gravitational waves, and asymmetries in supernovae explosions might generate millisecond-to-second–long bursts of gravitational waves. (A continuous rumble of otherwise subthreshold events or, conceivably, echoes from the Big Bang should generate a continuous stochastic signal, although the expected signal levels are likely too weak for LIGO to detect.)

Initial design: Increasing sensitivity and minimizing noise

In 1967, Rainer Weiss of the Massachusetts Institute of Technology (MIT, USA) proposed using a Michelson interferometer as a gravitational-wave detector: an impinging gravitational wave will shrink one arm of the Michelson interferometer while simultaneously stretching the other. Weiss built a model detector with arms 1.5 m long. Ronald Drever and James Hough of the University of Glasgow (U.K.) built a 10-meter prototype in 1973.

In 1982, Drever, who had by then moved to the California Institute of Technology (Caltech), proposed increasing instrument sensitivity by inserting a Fabry-Perot



Installation of components on a seismic isolation system in one of Advanced LIGO's high-vacuum chambers.
LIGO Laboratory

interferometer into each of the Michelson arms. This configuration—Fabry-Perot interferometers nested in each arm of a Michelson interferometer—is the basic design for initial LIGO and for other gravitational-wave detectors in Italy and Japan (though other interferometer configurations are being considered for next-generation detectors).

Scientists at Caltech and MIT, led by Drever, Weiss, Kip Thorne and Rochus Vogt, cofounded LIGO in 1989; the U.S. National Science Foundation (NSF) began funding the project in 1992. The facility consists of two identical instruments separated by 3,000 km—one located in Hanford, Washington, and the other in Livingston, Louisiana (USA).

All of the initial LIGO interferometer components—optics, seismic isolation systems and control systems—have been replaced.

To minimize spurious noise, the interferometer arms were adjusted so that very little light reaches the detector. Since nearly all the light incident from the laser onto the Michelson beamsplitter is coherently reflected back toward the laser, a partially transmitting "power recycling" mirror was precisely positioned between the laser and the beamsplitter. This mirror constructively reflected the light back into the main interferometer, further increasing the interior light intensity and improving the shot-noise limited sensitivity.

To achieve the remarkable strain sensitivities needed for catching a gravitational wave, the initial LIGO interferometers had arms 4 km long and were capable of measuring incredibly tiny displacements to the level of 10^{-18} m $Hz^{-1/2}$ in their most sensitive frequency band. Some 100 precise optomechanical control systems maintained mirror positions in an initial LIGO detector to less than 0.1 pm in the low-frequency control band (below 20 Hz), and on the attometer scale in the sensing band (above 100 Hz). Each interferometer was located in a voluminous 9,000 m^3 high-vacuum system. The lasers, optical components and the servo control systems making LIGO's unprecedented sensitivity possible represented groundbreaking research across a wide range of fields.

LIGO scientists expected that most signals would lie at the lower limit of interferometer sensitivity; therefore, the detectors had to distinguish gravitational-wave signals from spurious noise. The detectors avoided false positives by relying on coincidence measurements from two separate interferometers located far apart; environmental noise generated near the Hanford site or in the Hanford instrument was unlikely to appear in the Livingston instrument.

Not unexpectedly, given astrophysicists' understanding of compact binary merger rates, the initial LIGO project did not detect gravitational waves. Even so, data gathered from these runs have made significant contributions to the fields of precision measurement and astrophysics, including the LIGO Scientific Collaboration's publication of more than 90 observational papers since 2004. LIGO data have set upper limits for many types of proposed gravitational-wave-generating events and eliminated compact binary mergers as the source of a gamma-ray burst that might have originated in the nearby Andromeda galaxy.

Upgrades extend LIGO's reach

Once initial LIGO reached its design sensitivity and researchers completed their observations, NSF approved the long-planned upgrade. Construction on Advanced LIGO began in 2008, and the first scientific runs are planned for later this year.

A sketch of the Advanced LIGO layout reveals upgraded interferometers that use the original vacuum systems and improve on the layout of the original detectors. However, all of the initial LIGO interferometer components—optics, seismic isolation systems and control systems—have been replaced. The Albert Einstein Institute and Laser Zentrum in Hannover, Germany, designed and built the three-stage, 180-watt neodymium lasers. The lasers are exceptionally quiet, with an intensity noise of 1×10^{-9} Hz$^{-1/2}$ and are frequency stabilized to less than 1 Hz/Hz$^{1/2}$.

The 40-kg, 34-cm diameter ultrapure silica input and end "test mass" mirrors are polished to tolerances of almost 1Å and coated with ultralow absorption $SiO_2/Ta_2O_5{:}TiO_2$ multilayer coatings. The arm and power-recycling mirror reflectivities were chosen so that the standing-wave power in the arms approaches 1 MW over the 6-cm spot size. Due to mirror substrate and coating absorption, the test masses absorb as much as 1 W of laser light, sufficient to produce significant surface distortions and thermal lensing. Radiative ring heaters and CO_2 laser projectors are used *in situ* to correct these thermal distortions.

All Advanced LIGO mirrors are suspended and rest on optical tables that are actively stabilized to maintain their positions in the presence of low-frequency noise, ranging from tidal forces to seismic waves. The input and end mirrors are suspended from fine silica fibers in a quadruple pendulum system developed by researchers at the University of Glasgow. The mirrors are isolated from the external world by a factor of 10^{12} or more over the sensitive bandwidth of the detector. A signal-recycling mirror, similar in operation to the power-recycling mirror at the input, can reflect back and amplify a gravitational-wave signal in narrowband frequency ranges.

LIGO oversight and organization

The Hanford and Livingston LIGO observatories are operated by the LIGO Laboratory at the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) and are owned and overseen by the U.S. National Science Foundation.

The scientific program is carried out by the LIGO Scientific Collaboration (LSC), an international body comprising more than 900 scientists from over 85 institutions in 16 countries, including scientists from the LIGO Laboratory, Caltech and MIT. LSC researchers extract and analyze signals from the detector for four categories of expected gravitational-wave events: compact binary mergers, continuous-wave signals, bursts and stochastic background.

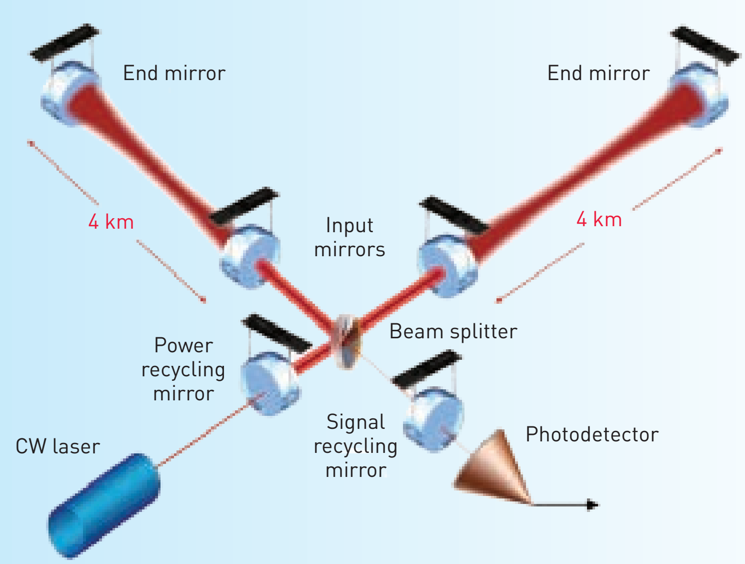
LIGO Hanford observatory, Wash., USA

LIGO Laboratory

LIGO Livingston observatory, La., USA

LIGO Laboratory

Advanced LIGO interferometer design



Once they reach full sensitivity, the new detectors might capture as many as tens to hundreds of gravitational-wave events per year.

LIGO noise sources

Advanced LIGO has five primary sources of noise; seismic, quantum, mirror coating, suspension and gradient.

Seismic noise rises rapidly at low frequencies and imposes a practical lower limit of about 10 Hz on the interferometer's sensitivity range.

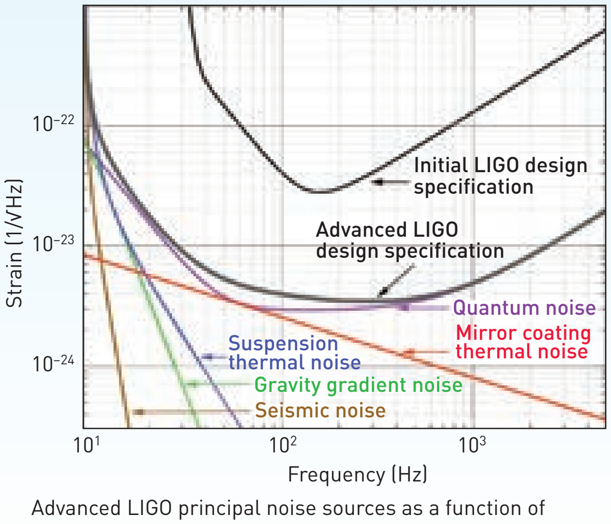
Quantum noise has two correlated components—the shot noise due to the statistical nature of detected photons; and, at low frequencies, radiation pressure noise arising from intrinsic photon momentum, which imparts a fluctuating force on the test masses (hence the need for massive mirrors).

Mirror coating thermal noise arises from the Brownian motion of the mirrors' surfaces and is a limiting source of noise at midrange frequencies.

Suspension thermal noise comes from thermal fluctuations in the silica fibers suspending the mirrors.

Gravity gradient noise is due to transient changes in the local gravitational field caused primarily by seismic pressure waves (and is distinct from seismic noise because the mirrors cannot be shielded from these fluctuations).

The noise floor of the Advanced LIGO detector is the sum of these five and all other sources.



Advanced LIGO principal noise sources as a function of frequency; the initial LIGO sensitivity specification is also displayed. LIGO Laboratory

As was the case with the initial LIGO interferometers, successful construction of the advanced interferometers required solving a large number of problems related to the handling of high optical powers, angstrom-level polishing of massive optical components, and precision control engineering in a high-vacuum environment. Information on many of these accomplishments can be found on the Advanced LIGO website, www.advancedligo.mit.edu.

Advanced LIGO is designed to have a strain sensitivity of better than 4×10^{-22} in a 100-Hz band surrounding its most sensitive frequency and an operational frequency range of approximately 10 Hz to 10 kHz. The extended low-frequency response, compared with initial LIGO, will allow for detection of binary neutron star inspirals earlier in their evolution and of higher-mass black hole mergers.

The initial LIGO detector required five years of tuning and reengineering before meeting its design specifications. After the Advanced LIGO interferometers come online, they will also require a period of tuning before they reach their full sensitivity. The first scientific run is planned for later in 2015, with a projected binary neutron star detection range of 130 to 200 Mly. Once they reach full sensitivity, the new detectors might capture as many as tens to hundreds of gravitational-wave events per year.

Future enhancements

Even though LIGO researchers expect to see evidence of gravitational waves in the next few years, they are already investigating enhancements that may lead to even more sensitive detectors.

For example, scientists have demonstrated reductions in shot-noise-limited sensing by injecting quantum-mechanically squeezed light into the GEO600 interferometer in Hannover, Germany, and the Hanford LIGO. They observed reductions in shot noise by as much as 30 percent at LIGO over most of its operating bandwidth, setting a new sensitivity record. Techniques to simultaneously reduce both radiation pressure noise at low frequencies and shot noise at high frequencies are also under development, with implementation planned for later this decade.

LIGO researchers are also investigating massive silicon mirrors with epitaxially grown crystalline multilayer coatings (operating at a wavelength of 1,550 nm) to further reduce mirror coating thermal noise. These mirrors are compatible with another approach to reducing thermal noise: operating the detectors at cryogenic temperatures. Increasing the optical beam diameter, possibly using a non-Gaussian profile, could further reduce the coating thermal noise and alleviate heating problems in the mirrors.

A global network of detectors

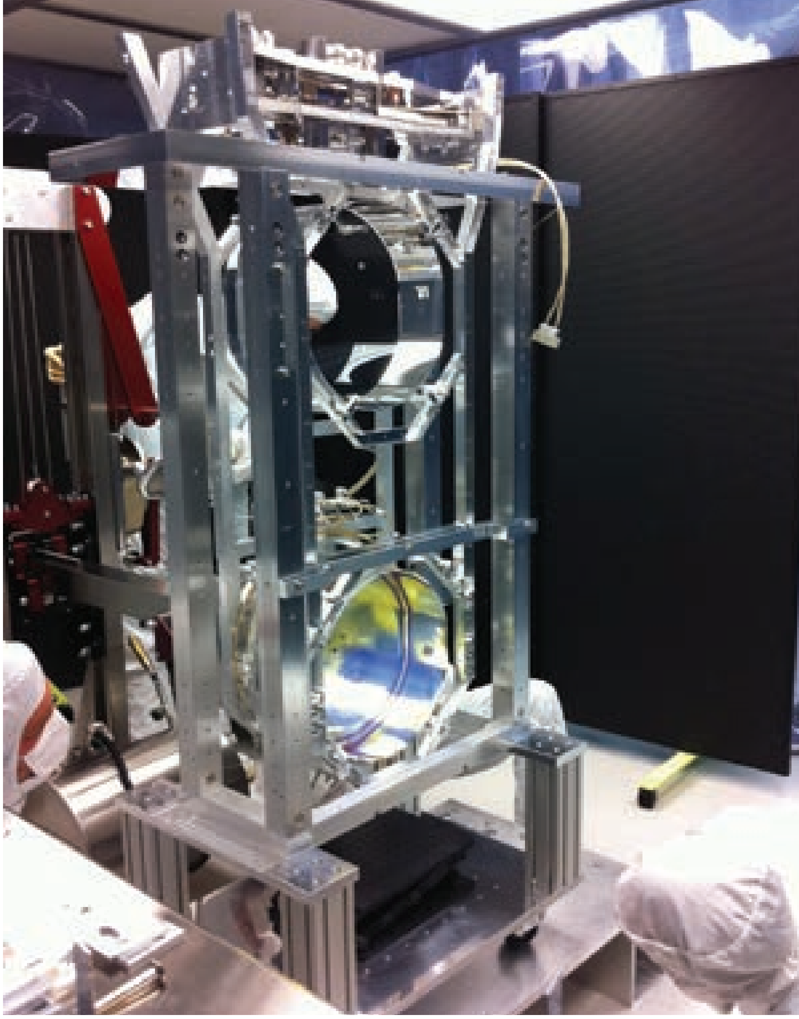
LIGO behaves more like an antenna than a telescope—it records a waveform from a gravitational-wave event but provides very little directional discrimination. However, a network of observatories spread over the globe can determine the direction of a gravitational wave through methods akin to triangulation. Directional information can be used to correlate the gravitational wave with an electromagnetic event, such as a gamma-ray burst, detected by rapid follow-up observations with traditional telescopes, or a neutrino-generating event detected by the Antares or IceCube observatory.

Such "multi-messenger" observations will greatly enhance the quality of information derived from gravitational-wave observations. It could give researchers the ability to measure the degree of asymmetry in a core-collapse supernova for the first time, and the progenitors of many other events, such as gamma-ray bursts, might be identified.

Enabling multi-messenger astrophysics requires close collaboration among all gravitational-wave observatories. LIGO conducts all science operations jointly with Virgo, a gravitational-wave interferometer located near Cascina, Italy, and with GEO600. The LIGO Laboratory is also working closely with the government of India to identify a location for a third Advanced LIGO interferometer, to be operated jointly by the LIGO Laboratory and laboratories in India. Underground gravitational-wave detectors such as KAGRA, which is currently under construction in the Kamioka mine in Japan, and the Einstein Telescope, an observatory planned for Europe, will bring even more capabilities to the global network. Together, these observatories will be able to paint a complete picture of the gravitational-wave sky.

Exploring the universe with new eyes

LIGO is poised make discoveries at the leading edge of science across a wide array of disciplines: general relativity in the extremely strong regime; the astrophysics of relativistic compact sources, including neutron stars, black holes, supernovae and pulsars; the science and engineering of the most precise measuring devices ever built; and in data analysis, the optimal extraction of the weakest possible signals out of noisy data.



LIGO staff with Advanced LIGO "test mass" mirrors in a quadruple pendulum suspension cage. LIGO Laboratory

Whenever new "eyes" have been turned to the sky, unforeseen phenomena have been discovered. LIGO is designed to probe the cosmos with radiation composed of disturbances in space itself. We can imagine only part of the insights that might be gleaned from its observations. OPN

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To learn more ...

- LIGO Scientific Collaboration: www.ligo.org
- Advanced LIGO: www.advancedligo.mit.edu
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