Gravitational waves detected 100 years after Einstein's prediction

February 11 2016

An aerial view of the Laser Interferometer Gravitational-wave Observatory (LIGO) detector in Livingston, Louisiana. LIGO has two detectors: one in Livingston and the other in Hanaford, Washington. LIGO is funded by NSF; Caltech and MIT conceived, built and operate the laboratories. Credit: LIGO Laboratory

For the first time, scientists have observed ripples in the fabric of spacetime called gravitational waves, arriving at Earth from a cataclysmic event in the distant universe. This confirms a major prediction of Albert Einstein's 1915 general theory of relativity and opens an unprecedented new window to the cosmos.

Gravitational waves carry information about their dramatic origins and about the nature of gravity that cannot be obtained from elsewhere. Physicists have concluded that the detected gravitational waves were produced during the final fraction of a second of the merger of two black holes to produce a single, more massive spinning black hole. This collision of two black holes had been predicted but never observed.

The gravitational waves were detected on Sept. 14, 2015 at 5:51 a.m. EDT (09:51 UTC) by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington. The LIGO observatories are funded by the National Science Foundation (NSF), and were conceived, built and are operated by the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). The discovery, accepted for publication in the journal *Physical Review Letters* , was made by the LIGO Scientific Collaboration (which includes the GEO Collaboration and the Australian Consortium for Interferometric Gravitational Astronomy) and the Virgo Collaboration using data from the two LIGO detectors.

Based on the observed signals, LIGO scientists estimate that the black holes for this event were about 29 and 36 times the mass of the sun, and the event took place 1.3 billion years ago. About three times the mass of the sun was converted into gravitational waves in a fraction of a second—with a peak power output about 50 times that of the whole visible universe. By looking at the time of arrival of the signals—the detector in Livingston recorded the event 7 milliseconds before the detector in Hanford—scientists can say that the source was located in the Southern Hemisphere.

Live stream of NSF press conference: You Tube www.youtube.com/user/VideosatNSF/live *and Onstream* www.webcaster4.com/Webcast/Page/219/13131

According to general relativity, a pair of black holes orbiting around each other lose energy through the emission of gravitational waves, causing them to gradually approach each other over billions of years, and then much more quickly in the final minutes. During the final fraction of a second, the two black holes collide at nearly half the speed of light and form a single more massive black hole, converting a portion of the combined black holes' mass to energy, according to Einstein's formula $E=mc^2$. This energy is emitted as a final strong burst of gravitational waves. These are the gravitational waves that LIGO observed.

The existence of gravitational waves was first demonstrated in the 1970s and 1980s by Joseph Taylor, Jr., and colleagues. In 1974, Taylor and Russell Hulse discovered a binary system composed of a pulsar in orbit around a neutron star. Taylor and Joel M. Weisberg in 1982 found that the orbit of the pulsar was slowly shrinking over time because of the release of energy in the form of gravitational waves. For discovering the pulsar and showing that it would make possible this particular gravitational wave measurement, Hulse and Taylor were awarded the 1993 Nobel Prize in Physics.

The new LIGO discovery is the first observation of gravitational waves themselves, made by measuring the tiny disturbances the waves make to space and time as they pass through the earth.

"Our observation of gravitational waves accomplishes an ambitious goal set out over five decades ago to directly detect this elusive phenomenon and better understand the universe, and, fittingly, fulfills Einstein's legacy on the 100th anniversary of his general theory of relativity," says Caltech's David H. Reitze, executive director of the LIGO Laboratory.

The discovery was made possible by the enhanced capabilities of Advanced LIGO, a major upgrade that increases the sensitivity of the instruments compared to the first generation LIGO detectors, enabling a large increase in the volume of the universe probed—and the discovery of gravitational waves during its first observation run. NSF is the lead financial supporter of Advanced LIGO. Funding organizations in Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council, STFC) and Australia (Australian Research Council) also have made significant commitments to the project.

Several of the key technologies that made Advanced LIGO so much more sensitive were developed and tested by the German UK GEO collaboration. Significant computer resources were contributed by the AEI Hannover Atlas Cluster, the LIGO Laboratory, Syracuse University and the University of Wisconsin-Milwaukee. Several universities designed, built and tested key components for Advanced LIGO: The Australian National University, the University of Adelaide, the University of Florida, Stanford University, Columbia University of the City of New York and Louisiana State University.

"In 1992, when LIGO's initial funding was approved, it represented the biggest investment NSF had ever made," says France Córdova, NSF director. "It was a big risk. But NSF is the agency that takes these kinds of risks. We support fundamental science and engineering at a point in the road to discovery where that path is anything but clear. We fund trailblazers. It's why the U.S. continues to be a global leader in advancing knowledge."

LIGO research is carried out by the LIGO Scientific Collaboration (LSC), a group of more than 1,000 scientists from universities around the United States and in 14 other countries. More than 90 universities and research institutes in the LSC develop detector technology and analyze data; approximately 250 students are strong contributing members of the collaboration. The LSC detector network includes the LIGO interferometers and the GEO600 detector. The GEO team includes scientists at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI), Leibniz Universität Hannover, along with partners at the University of Glasgow, Cardiff University, the University of Birmingham, other universities in the United Kingdom and the University of the Balearic Islands in Spain.

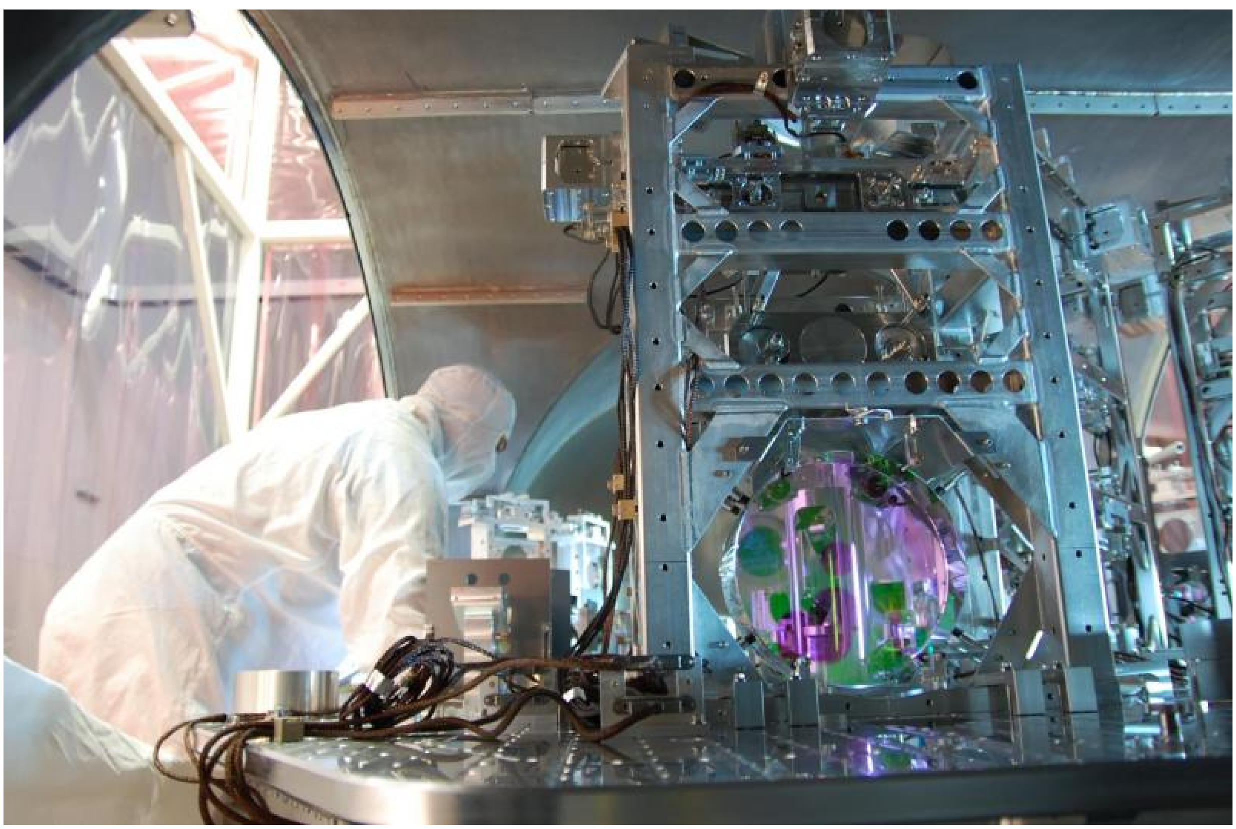
"This detection is the beginning of a new era: The field of gravitational wave astronomy is now a reality," says Gabriela González, LSC spokesperson and professor of physics and astronomy at Louisiana State University.

LIGO was originally proposed as a means of detecting gravitational waves in the 1980s by Rainer Weiss, professor of physics, emeritus, from MIT; Kip Thorne, Caltech's Richard P. Feynman Professor of Theoretical Physics, emeritus; and Ronald Drever, professor of physics, emeritus, also from Caltech.

"The description of this observation is beautifully described in the Einstein theory of general relativity formulated 100 years ago and comprises the first test of the theory in strong gravitation. It would have been wonderful to watch Einstein's face had we been able to tell him," says Weiss.

"With this discovery, we humans are embarking on a marvelous new quest: the quest to explore the warped side of the universe—objects and phenomena that are made from warped spacetime. Colliding black holes and gravitational waves are our first beautiful examples," says Thorne.

Virgo research is carried out by the Virgo Collaboration, consisting of more than 250 physicists and engineers belonging to 19 different European research groups: six from Centre National de la Recherche Scientifique (CNRS) in France; eight from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; two in the Netherlands with Nikhef; the Wigner RCP in Hungary; the POLGRAW group in Poland; and the European Gravitational Observatory (EGO), the laboratory hosting the Virgo detector near Pisa in Italy.



A technician works on one of LIGO's optics. At each observatory, the 2 1/2-mile long L-shaped LIGO interferometer uses laser light split into two beams that travel back and forth down the arms. The beams are used to monitor the distance between mirrors precisely positioned at the ends of the arms. According to Einstein's theory, the distance between the mirrors will change when a gravitational wave passed by the detector. Credit: LIGO Laboratory

Fulvio Ricci, Virgo spokesperson, notes that: "This is a significant milestone for physics, but more importantly merely the start of many new and exciting astrophysical discoveries to come with LIGO and Virgo."

Bruce Allen, managing director of the Max Planck Institute for Gravitational Physics adds: "Einstein thought gravitational waves were too weak to detect, and didn't believe in black holes. But I don't think he'd have minded being wrong!"

"The Advanced LIGO detectors are a tour de force of science and technology, made possible by a truly exceptional international team of technicians, engineers, and scientists," says David Shoemaker of MIT, the project leader for Advanced LIGO. "We are very proud that we finished this NSF-funded project on time and on budget."

At each observatory, the 2 1/2-mile (4-km) long, L-shaped LIGO interferometer uses laser light split into two beams that travel back and forth down the arms (four-foot diameter tubes kept under a near-perfect vacuum). The beams are used to monitor the distance between mirrors precisely positioned at the ends of the arms. According to Einstein's theory, the distance between the mirrors will change by an infinitesimal amount when a gravitational wave passes by the detector. A change in the lengths of the arms smaller than one-ten-thousandth the diameter of a proton (10^{-19} meter) can be detected.

"To make this fantastic milestone possible took a global collaboration of scientists—laser and suspension technology developed for our GEO600 detector was used to help make Advanced LIGO the most sophisticated gravitational wave detector ever created," says Sheila Rowan, professor of physics and astronomy at the University of Glasgow.

Independent and widely separated observatories are necessary to determine the direction of the event causing the gravitational waves, and also to verify that the signals come from space and are not from some other local phenomenon.

Toward this end, the LIGO Laboratory is working closely with scientists in India at the Inter-University Centre for Astronomy and Astrophysics, the Raja Ramanna Centre for Advanced Technology, and the Institute for Plasma to establish a third Advanced LIGO detector on the Indian subcontinent. Awaiting approval by the government of India, it could be operational early in the next decade. The additional detector will greatly improve the ability of the global detector network to localize gravitational-wave sources.

"Hopefully this first observation will accelerate the construction of a global network of detectors to enable accurate source location in the era of multi-messenger astronomy," says David McClelland, professor of physics and director of the Centre for Gravitational Physics at the Australian National University.

LIGO Livingston FAQ

What do we know about this first-ever detected

gravitational wave?

LIGO has made the first-ever observations of gravitational waves arriving on Earth from space, and the first detection of two black holes colliding.

The gravitational wave signal was detected in Livingston and seven milliseconds later, the instrument at the LIGO observatory in Hanford, Washington detected the same gravitational wave. It confirms that black holes exist in binary systems with solar masses. It confirms aspects of Einstein's Theory of General Relativity.]

From this, we will be able to learn more about gravity near a black hole, where space-time is warped, that would not be possible to learn in other ways.

How do the LIGO instruments work?

The LIGO detectors are interferometers that shine a laser through a vacuum down two arms in the shape of an L that are each 4 kilometers in length. The light from the laser bounces back and forth between mirrors on each end of the L. Scientists measure the length of both arms using the light.

If there's a disturbance in space-time, such as a gravitational wave, the time the light takes to travel 4 kilometers will be slightly different in each arm making one arm look longer than the other. LIGO scientists measure the interference in the two beams of light when they come back to meet, which reveals information on the space-time disturbance.

The discovery was made possible by the enhanced capabilities of Advanced LIGO, a major upgrade that increases the sensitivity of the instruments compared to the first-generation LIGO detectors, enabling a large increase in the volume of the universe probed – and the discovery of gravitational waves during its first observational run.

How do we know it's a black hole?

The scientists compared the observation with Einstein's prediction to identify that black holes produced this gravitational wave, how far they were, what the masses were and how large the final black hole was because of the energy emitted.

What is the LIGO Scientific Collaboration?

LIGO research is carried out by the LIGO Scientific Collaboration, or LSC, a group of more than1,000 scientists from universities around the United States and in 14 other countries. More than 90 universities and research institutes in the LSC develop detector technology and analyze data; approximately 250 students are strong contributing members of the collaboration.

The LSC detector network includes the LIGO interferometers and the GEO600 detector. It includes matching LIGO facilities in Livingston, LA and Hanford, WA. The location of the two observatories with another one in Europe creates a triangle that can verify astronomical observations.

LSU Physics & Astronomy Professor Gabriela Gonzalez is the elected spokesperson for the LIGO Scientific Collaboration, a post she has held for five years. LSU Physics & AstronoProfessor Joe Giaime is the Observatory Head of LIGO Livingston.

What is LIGO Livingston?

LIGO Livingston is one of two laser interferometer observatories built to detect gravitational waves. About 40 people work at LIGO Livingston, which is about 36 miles north-east of Baton Rouge, Louisiana, where LSU is located. LIGO Livingston employs engineers, scientists and staff who support facilities, outreach and information technology to run the observatory. It is funded completely by the National Science Foundation, or NSF, and managed by the California Institute of Technology, or Caltech, and the Massachusetts Institute of Technology, or MIT. LSU owns the land, which is 180 acres, leased to the NSF until 2044.

LIGO Livingston began collecting data in 2005. In 2015, it received a major upgrade. The Advanced LIGO configurations increased the sensitivity of the instrumentation ten-fold. LIGO Livingston's annual budget is $6-9 million per year.

About 17,000 people from the general public visit LIGO Livingston's Science Education Center each year. Free hands-on educational activities are available for school groups as well as professional development training for educators.

What's next?

This is only the beginning of the field of gravitational wave astronomy. LIGO Scientific Collaboration scientists continue to conduct research on the existing data and expect to detect more astronomical events as the LIGO detectors and technology become more sensitive, and the French-Italian gravitational wave detector, VIRGO, located in Cascina, Italy begins to collect data this year.

Scientists anticipate detecting other events including neutron stars in our galaxy, other black holes and supernova explosions.

More information: *PRL*: journals.aps.org/prl/abstract/ … .116.061102#fulltext

www.nsf.gov/news/special_reports/ligoevent/

LIGO website: ligo.caltech.edu/LA

Provided by National Science Foundation