LIGO Discovery Press Kit

February 11, 2016

Massachusetts Institute of Technology

Gravitational waves detected 100 years after Einstein's prediction

LIGO opens new window on the universe with observation of gravitational waves from colliding black holes

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.

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.

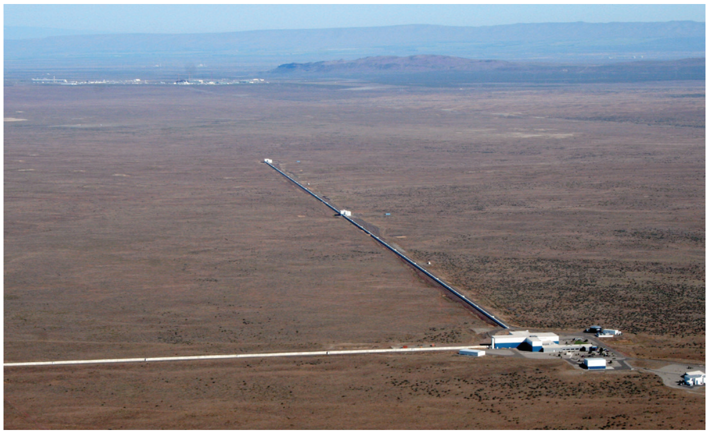
"Our observation of gravitational waves accomplishes an ambitious goal set out over five decades ago to directly detect this elusive phenomenon and better understand the universe, and, fittingly, fulfills Einstein's legacy on the 100th anniversary of his general theory of relativity," says Caltech's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



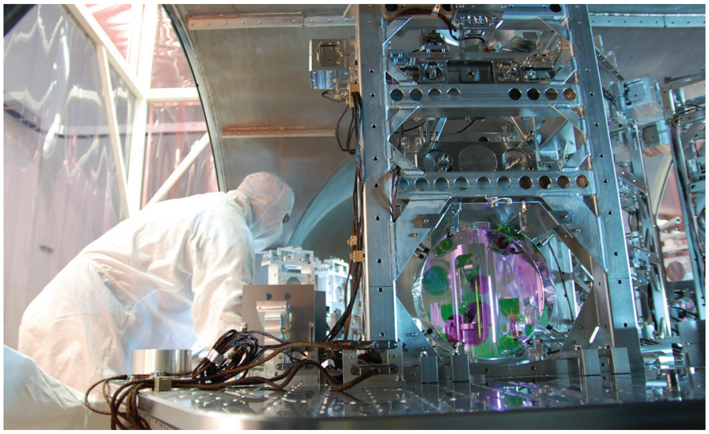
“This detection is the beginning of a new era: The field of gravitational wave astronomy is now a reality,” says Gabriela González, LSC spokesperson and professor of physics and astronomy at Louisiana State University.

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.



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.

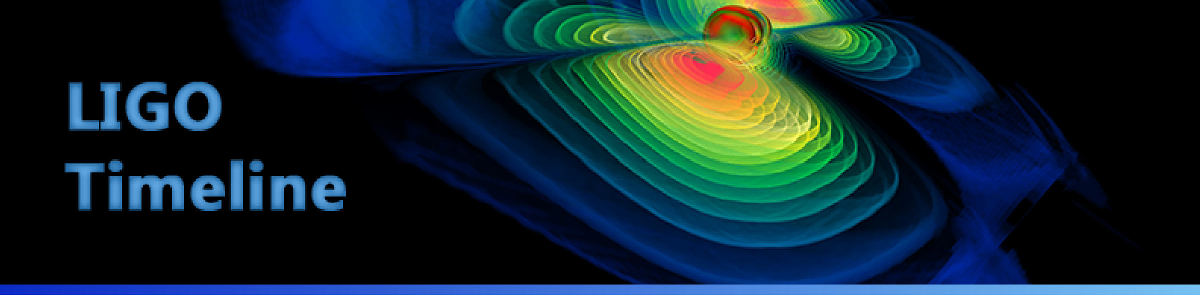
“To make this fantastic milestone possible took a global collaboration of scientists -- laser and suspension technology developed for our GEO600 detector was used to help make Advanced LIGO the most sophisticated gravitational wave detector ever created,” says Sheila Rowan, professor of physics and astronomy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



1970s

Early work on gravitational-wave detection by laser interferometers, including a 1972 MIT study describing a kilometer-scale interferometer and estimates of its noise sources.

1979

The National Science Foundation (NSF) funds a new group at Caltech for laser interferometer research and a prototype interferometer. It funds MIT to complete its prototype and design and lead industry study of technology, costs and sites for a kilometer-scale interferometer.

1983

MIT and Caltech jointly present results of the kilometer-scale interferometer study to NSF. Receive NSF committee endorsement on new large programs in physics.

1984

LIGO founded as a Caltech/MIT project. National Science Board approves LIGO development plan.

1986

Physics Decadal Survey and special NSF Panel on Gravitational Wave Interferometers endorse LIGO.

1990

The National Science Board (NSB) approves LIGO construction proposal, which envisions initial interferometers followed by advanced interferometers.

1992

NSF selects LIGO sites in Hanford, Washington, and Livingston, Louisiana. NSF and Caltech sign LIGO Cooperative Agreement.

1994-95

Site construction begins at Hanford and Livingston locations.

1997

The LIGO Scientific Collaboration (LSC) is established and expands LIGO beyond Caltech and MIT, including the British/German GEO collaboration, which operates the GEO600 interferometer in Hannover, Germany.

2002

First coincident operation of initial LIGO interferometers with GEO600 interferometer.

2004

NSB approves Advanced LIGO.

2006

Initial LIGO design sensitivity achieved. First gravitational wave search at design sensitivity.

2007

Joint data analysis agreement ratified between LIGO and the Virgo Collaboration, which operates the Virgo interferometer in Cascina, Italy. Joint observations with enhanced initial LIGO interferometer and Virgo.

2008

Start of Advanced LIGO construction.

2010

Initial LIGO operations conclude; Advanced LIGO installation begins.

2011-14

Advanced LIGO installation and testing.

2014

Advanced LIGO installation complete.

2014-15

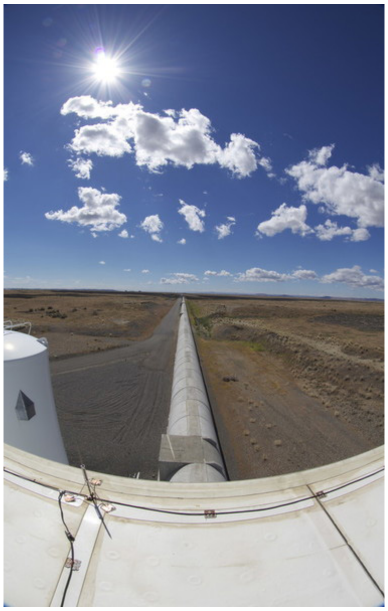
Advanced LIGO sensitivity surpasses initial LIGO.

9/2015

During an engineering test a few days before the first official search begins, Advanced LIGO detects strong gravitational waves from collision of two black holes.

Image credit: Werner Benger/ Max Planck Institute for Gravitational Physics

NSF and the Laser Interferometer Gravitational-Wave Observatory



In 1916, Albert Einstein published the paper that predicted gravitational waves – ripples in the fabric of space-time resulting from the most violent phenomena in our distant universe, such as supernovae explosions or colliding black holes. For 100 years, this prediction has stimulated scientists around the world, who have been seeking to directly detect gravitational waves.

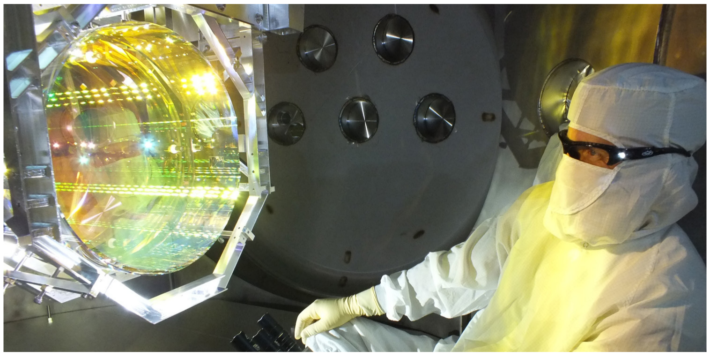
Approximately 40 years ago, the National Science Foundation (NSF) joined this quest and began funding the science and technological innovation that would ultimately lead to direct detection of gravitational waves. More importantly, it would also lead to a scientific capability to observe and study our universe in new ways, much like the advent of radio astronomy or even when Galileo first used a telescope to view the night skies.

NSF's funding of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the science behind its operation and research began in the 1970s. On February 11, 2016, NSF organized a press conference for scientists from LIGO to announce they had directly observed gravitational waves arriving on earth that resulted from merging black holes approximately 1.3 billion light-years away.

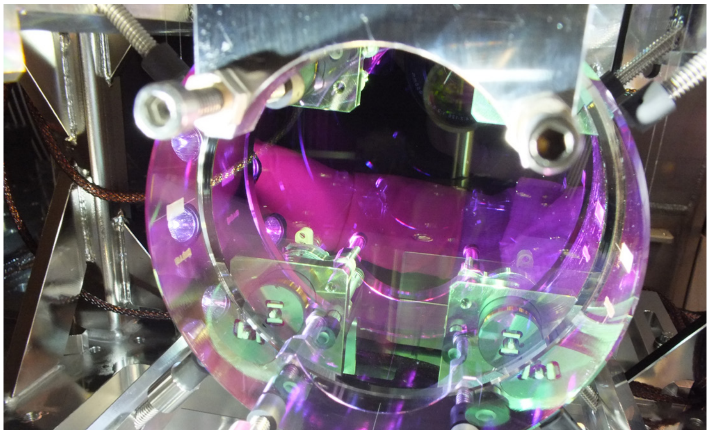
What is LIGO?
LIGO consists of two widely separated interferometers within the United States – one in Hanford, Washington, and the other in Livingston, Louisiana – each a laser interferometer inside an L-shaped ultra-high vacuum tunnel and operated in unison to detect gravitational waves. Caltech and MIT led the design, construction and operation of the NSF-funded facilities.

What are gravitational waves?
Gravitational waves are emitted when any object that possesses mass accelerates. This can be compared in some ways to how accelerating charges create electromagnetic fields (e.g. light and radio waves) that antennae detect. To generate gravitational waves that can be detected by LIGO, the objects must be highly compact and very massive, such as neutron stars and black holes. Gravitational-wave detectors act as a "receiver." Gravitational waves travel to Earth much like ripples travel outward across a pond. However, these ripples in the space-time fabric carry information about their violent origins and about the nature of gravity – information that cannot be obtained from other astronomical signals.

How does LIGO work?
Einstein himself questioned whether we could create an instrument sensitive enough to capture this phenomenon. Inside the vertex of the L-shaped LIGO vacuum systems, a beam splitter divides a single entering laser beam into two beams, each travelling along a 4-km-long arm of the L. The beams reflect back and forth between precisely positioned and exquisitely configured mirrors that are suspended, like a child on a swing, near each end and near the vertex on either side of the beam splitter.



As a gravitational wave passes by, the lengths of the paths that the divided laser beams take along each arm will actually stretch the laser beam ever-so slightly – by only 1/10,000th of the diameter of a proton. It's this signal change – occurring at both interferometers within 10 milliseconds of one another – that indicates a gravitational wave. And from that minute change, scientists are further able to identify the wave's source and very broadly where in the universe it originated.



Worldwide commitment to world-class research

The LIGO Scientific Collaboration (LSC), which carries out this work, is a group of some 1,000 scientists at universities around the United States and in 14 countries. The LSC network includes the LIGO interferometers and the GEO600 interferometer, a project located near Hannover, Germany, designed and operated by scientists from the Max Planck Institute for Gravitational Physics, along with partners in the United Kingdom funded by the Science and Technology Facilities Council (STFC). Additionally, a new node of the LIGO network in India may be operational around 2022.

The LSC works jointly with the Virgo Collaboration — which designed and constructed the Virgo interferometer, with 3-km-long arms and located in Cascina, Italy. Virgo is currently undergoing an enhancement to the original facility – Advanced Virgo – and is expected to be operational later in 2016.

International partners have contributed equipment, labor and expertise to LIGO, including Britain's STFC supplying the suspension assembly and some mirror optics; the Max Planck Society of Germany providing the high-power, high-stability laser; and an Australian consortium of universities supported by the Australian Research Council offering systems for initially positioning and measuring in place the mirror curvatures to better than nanometer precision.

NSF investment

LIGO is one of the largest experiments the agency has ever funded. It was the biggest NSF investment ever when the National Science Board gave the go-ahead to fund initial construction in 1990. Since LIGO's inception, NSF has invested approximately $1.1 billion in construction and upgrades, in operational costs, and in research awards to individual scientists, who study LIGO data to learn more about our universe.

Maximizing what we learn from LIGO

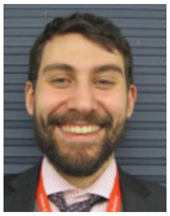
NSF supports basic research that drives innovation and innovators that transform our future. Basic research offers no promises and is often risky but is also potentially revolutionary. LIGO is a perfect example. The direct detection of gravitational waves is not only an historic moment in science, it also has already spawned other scientific innovations. For example, a laser developed by LIGO Scientific Collaboration scientists has many applications. The same technique used to stabilize LIGO's sensitive laser frequencies also helps to build the semiconductors in our computers and cell phones. Other spin-offs are being realized in areas such as measurement science, seismic isolation, vacuum technology, mirror coatings and optics.

As is often the case with research in fundamental science, few would have invested in LIGO from the beginning. However, this discovery significantly changes what we can learn about the universe. With plans to further increase LIGO's sensitivity between now and 2018 and the potential addition of other countries' interferometers to the network, LIGO provides an opportunity to detect more gravitational waves and also hone in more precisely on the whereabouts of the universe's most violent phenomena.

Image credits: (front top) Caltech/MIT/LIGO Lab; (front bottom) Matt Heintze/Caltech/MIT/LIGO Lab; (back) LIGO Laboratory

Q&A with Scientists of the LIGO and Virgo Collaboration (LVC)

Dr. Madeline C. Wade
Assistant Professor of Physics at Kenyon College
Co-chair of the LVC calibration working group
Member of the LVC data analysis software working group (DASWG)
Member of the LVC compact binary coalescence (CBC) working group



Dr. Grant David Meadors
Junior Scientist/Postdoc at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute)
Member of the LVC continuous waves working group

Dr. Samaya Nissanke
Assistant Professor of Physics at Radboud University
Member of the LVC electromagnetic counterparts working group
Member of the LVC compact binary coalescence (CBC) working group
Member of the LVC diversity committee

Ms. Marissa B. Walker
PhD Candidate in Physics at Louisiana State University
graduate representative in the LIGO Academic Affairs Council (LAAC)
member of the LVC burst analysis working group
member of the LVC detector characterization working group

Mr. Corey Gray
Lead Operator, LIGO Hanford Observatory

What are the most challenging and rewarding aspects of working in the LVC?

MCW: The most challenging aspect of working in the LVC is probably coordination. However, the most rewarding aspect is related to this: It's amazing to be part of a 1000+ person science engine that can achieve such a high quality level of cutting edge research. Additionally, being a member of the LVC awards me the opportunity to work closely with many amazing, bright people on a regular basis. I know my personal research abilities have grown exponentially due to the support from the LVC community.

GM: Uncertainty! We have faced uncertainty in many forms. Some of my best advisers cautioned me about going into gravitational waves. I read intently about the detector and got familiar until I could justify that my trust was based on good science. Then we had to wait for a signal! Yet lack of certainty is a window for possibility. Our international collaboration abounds in opportunities to work with dedicated scientists, whose experiences and curiosities are more diverse than I imagined. The LIGO-Virgo Collaboration is a sort of family; some branches are growing better detectors, others reaching for sensitive analyses, but its roots remain anchored in general relativity, in the fabric of space-time. I have learned how much more exists, even in gravitational-wave astrophysics, than any one person could comprehend. While I may not always know the destination, the journey is an adventure. The universe is full of surprises — that is why I joined the LVC.

SN: I love working with and being part of a truly international and diverse team of scientists and engineers — the collaboration's expertise spans experimental, observational and theoretical aspects of gravitational waves physics, with members coming from all backgrounds and with their own unique ways of approaching science. Personally, I find supervising undergraduate and graduate students particularly rewarding — their enthusiasm and endless curiosity reminds me daily of how amazing the instruments and the scientific goals are of the LIGO and Virgo detectors. Perhaps the most challenging aspect is the sheer number of emails per day that I receive but this in itself is an illustration of how gravitational wave physics is a worldwide effort 24/7!

MBW: It is quite a challenge to be part of a large collaboration working on such a complex endeavor. But I'm so grateful to be a member of this amazing community. The LVC has given me opportunities to travel, get to know wonderful people from around the world, and contribute to some spectacular science!

CG: Currently my most challenging and rewarding work is helping to ensure we have the best Operator Team running the LIGO Hanford interferometer. This is a complex machine: helping to lead my excellent staff of operators to run this machine was a daunting task. A truly rewarding experience was being on shift in the Control Room, and being humbled by the big picture: from starting with the project almost two decades ago and turning my first bolt to collecting data in the middle of the night in search of events that are truly mind-blowing is unequivocally rewarding.

How did you come to join the LVC team?

MCW: I joined as a graduate student, but I really made the decision to join as an undergraduate. I specifically targeted graduate schools that were strong in LIGO research. I saw a seminar given by Larry Price my senior year of undergrad, and I got more excited about physics research during that talk than I had been any time in my physics career thus far.

GM: In my freshman year at Reed College, I noticed posters on the physics department wall for Research Experiences for Undergraduates (REU) internships funded by the National Science Foundation. LIGO was seeking undergrads for an REU. I had heard of it in the news a few years earlier, when LIGO started its first science run, so I decided to apply. A few months into 2005, Dick Gustafson, at LIGO Hanford Observatory, invited me out to the high desert of Eastern Washington. After ten weeks of hands-on time with the electronics and optics of a gravitational-wave observatory — and another ten weeks on data analysis at Caltech in 2007 — I applied to grad school. In 2008, Keith Riles at Michigan hired me to study the detectors and search for neutron stars. I have been an LVC member ever since.

SN: I joined the LVC team first at Caltech and then at Radboud University in the Netherlands. It is incredibly exciting to be building a new group in gravitational-wave astronomy at Radboud, with so many enthusiastic and passionate young scientists in this frontier field of observational astronomy!

MBW: For my undergraduate general relativity class, I chose to do a presentation about LIGO because I have family living in Washington near Hanford. As I did research for that assignment, I was fascinated by the LIGO project. I was currently working on my teaching certification and was not planning to go to graduate school, but I decided to spend that summer doing LIGO research at Louisiana State University. I enjoyed the summer so much that I returned to LSU the following year to pursue my PhD.

CG: I first joined Caltech in 1997 when I accepted a position as an Operations Specialist at the LIGO Hanford Observatory. I helped install the initial LIGO Seismic Isolation System, then operated the iLIGO detectors, then helped build/install the aLIGO Seismic Isolation System, and then became the Lead Operator for LHO.

How did your background prepare you for work in the LVC?

MCW: I've always been good at working with other people, which is certainly required in the LVC. I've also served in leadership roles throughout my life (from captain of a sports team to vice president of student council), and I believe this experience in leadership roles has helped me co-chair the calibration team in LIGO.

GM: An observatory in the Pacific Northwest is no common sight. I was delighted to discover LIGO Hanford is just a drive down along the Columbia River Gorge from where I grew up, though the tumbleweed-strewn landscape was a world apart. Computers connect those two worlds. Tinkering with machines feels familiar, and the concomitant patience and experimental zeal helps with every aspect of the LVC. I was lucky to have a mechanical family in youth and to have a fantastic lab science program, and even reactor experience, in undergrad. While I rarely derive equations in my work, every so often math offers a profound insight into a knotty problem. I am grateful to all my professors who insisted on rigorous solutions. My parents encouraged me to explore both nature and culture: that above all nurtured the excitement I have now for this world-spanning research.

SN: I discovered gravitational wave physics as a second year undergrad working on a summer project in Princeton — and have literally been hooked ever since! Over the past 15 years, I have been fortunate to have worked in many aspects of gravitational wave astronomy from source modeling and analytical relativity to Bayesian source characterization to transient astronomy.

MBW: My physics and math courses were important for me to be able to understand the research in the LVC, but I'm also glad to have had some teaching experience, which helped me develop communication and collaborative skills.

CG: My B.S. degrees in physics and applied math were big tools for getting my foot in the door with my work. I always keep in my role as a role model especially to Native American youth. In my academic career there were not many role models like myself. I hope my work and my example can inspire other underrepresented groups to consider pursuing studies and work in physics.

What does this discovery mean to you?

MCW: This discovery means not only the validation of the field that I've dedicated my career to, but it also establishes a supremely exciting future for the field of gravitational-wave physics. We have now entered the era that I've always been longing for — the days when gravitational-wave observations can become a routine contributor to our understanding of the universe and the remaining mysteries it holds.

GM: Even though it may be a cliché, I am eager for "a new window on the universe" to "hear" the cosmos. Someday we will sort out our metaphors. Right now, I am more interested in knowing what comes next. Until recently, few would have guessed we would see a binary black hole this soon. This discovery already promises to tell us much about how the biggest stars in the universe formed. When will we see binary neutron stars? Will our partners see a gamma-ray burst simultaneously? Or a supernova, and neutrinos? At the moment I am looking for neutron stars that continuously emit gravitational waves, a serene and steady tone, in contrast to the sudden chirp of an inspiral. Eventually, I hope we see the Big Bang's gravitational waves — directly. As we go through these firsts, something is bound to appear that we did not expect, and that will be even more wonderful. Whether out among the stars or amidst our equations, such strange novelties are welcome. I am only sad that, besides particles, there is not another fundamental force such as electromagnetism and gravity that can radiate waves across the universe. Perhaps, though, we will learn about those forces from seeing gravitational waves: what lies beyond Einstein? This discovery may be just the beginning.

SN: The discovery and seeing the actual gravitational wave strain in the detection paper is awe-inspiring, beautiful and mind-blowing. It is difficult to find the words to express the intense emotions that I have felt since last September — the scientific method relies on testing one's theories with measurements and observations, and for the first time in a hundred years and after enormous challenges and perseverance from so many folk, we have now reached this point of studying the universe in a truly unique way… and it is simply amazing!

MBW: Part of what drew me to LIGO was the fact that the goal seemed nearly impossible to me, but through the tenacious efforts of hundreds of scientists over several decades, the first detection of gravitational waves actually appeared to be just over the horizon. This discovery shows how much people can accomplish by working together, and it is only just the beginning, the dawn of a truly exciting era of astronomy.

CG: It's life-changing! I remember waking up the morning after the discovery (I had been on shift until midnight) and still feeling like I might be dreaming. After so many years of focusing microscopically on only pieces of LIGO (i.e. hardware and running the machine), everything changed in one fell swoop. Honestly, up until the discovery, my work was just a job; I really didn't think a lot about the potential of a discovery. But after the discovery, it really puts so many things in perspective. I can appreciate the broad strokes of humanity which led to this point starting a century ago with Einstein's general theory of relativity, to Rai Weiss' visions of a detector, to my turning of a bolt years ago, and to the mad rush of phone calls early in the morning on September 14, 2015. Everything changes, and this is only the beginning!

Some Thoughts and Impressions about the Arrival of GW150914

Nutsinee Kijbunchoo
Operations Specialist, LIGO Hanford Observatory


Courtesy N. Kijbunchoo

The post-midnight hours on September 14 were quiet in the LHO control room, just like every other graveyard shift. The H1 detector was locked and running smoothly. I was so focused on some work I was doing that at one point during the shift I ignored a teleconference conversation that was playing over the speaker; it was LIGO Livingston personnel. I stayed for the 8:30am LIGO Hanford weekly meeting and nothing was mentioned about an event. I went home with no idea that something big had happened. When I woke up on the evening of September 14 a friend sent me a text from LIGO Livingston and jokingly asked if I had walked around with a slide whistle during my shift. That's when I knew.

This event (that I TOTALLY MISSED) could be a life-changer for me. I decided to become an operator before going to graduate school in order to participate in observing runs. This discovery will shape the nature of my graduate studies when I return to school for my Ph.D.

Peter Saulson
Martin A. Pomerantz '37 Professor of Physics, Syracuse University


Courtesy Syracuse University

I spent Monday September 14 in prayer at my synagogue, in observance of Rosh Hashanah, the Jewish New Year. (And no, I wasn't praying for a beautiful gravitational wave signal to arrive . . .) My computer remained completely shut down until the end of the day. I ought to also have observed the second day of the holiday on Tuesday, but I didn't feel that I could do that, so after sunset on Monday evening I decided to catch up on my email. I couldn't believe my eyes when I saw all of the email traffic about the event!

We're all optimists in this business, otherwise we wouldn't be here. Here's proof that I'm an optimist. In 1983, while I was a postdoctoral scholar with Rai Weiss, I asked him how long it was likely to take before we discovered a gravitational wave signal. Rai worked it out for me: one year to convince the NSF to fund LIGO, two years for construction, one year for commissioning to design sensitivity, and one more year to observe until we found signals.

Thus, we should expect to discover gravitational waves before the end of the 1980s. And I believed him. It is thrilling to see that optimism finally justified!

Daniel Holz
Associate Professor, Physics Department, Enrico Fermi Institute, and Kavli Institute for Cosmological Physics, University of Chicago


Courtesy D. Holz

It was a Monday morning, the beginning of a beautiful fall day in Chicago. I scanned my cell phone before getting out of bed and saw an email about a "very interesting event" in LIGO. I assumed it was a false alarm or injection, especially since the other search pipelines hadn't noticed it. I didn't take it very seriously, and went to the office in no particular hurry. By the time I got there it had already become apparent that this was a high mass event, which meant LIGO's other online searches weren't looking for it. At that point I allowed myself a little excitement. This continued to build as it became apparent that the interferometers were operating well, that the data was clean, and that the signal was strong. But the first time I genuinely thought this might be *real* was when I saw the time-frequency plots. The event looked just like the signal we had dreamed about for all those years; it sent shivers down my spine. (It *still* sends shivers down my spine!) Now the excitement was approaching a fever pitch, but it was still tempered by the possibility that this was a blind injection. Then I heard that there were no blind injections during the engineering run and the excitement changed to complete delirium. And here I am, months later, and this feeling hasn't subsided. Every day I have to pinch myself that this is really happening, and we have truly heard the echoes of two black holes swallowing each other at hundreds of millions of light years away. This has been an insanely intense and marvelous experience, and I feel so lucky to be a part of it.

Keith Riles

Professor of Physics, University of Michigan

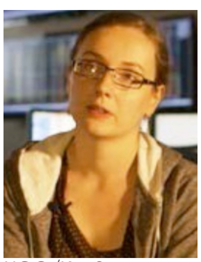
Courtesy K. Riles

My first news of GW150914 came from checking my smartphone on the morning of September 14. Sergey Klimenko had just sent an email inquiring about a loud event in the data several hours before. The tone of Sergey's message got my attention; it was clear he thought the data quality looked fine and that this event was very significant. My immediate conclusion was that a hardware injection had been made but had not been flagged. I thought that Eric Thrane might have inserted the injection, but he reported a short time later that he did not. I concluded that the blind injection team must have done a test without telling the rest of us. This surprised me, given that they provided no advance warning, but it seemed within their prerogative to do such a thing.

Shortly into the weekly detector characterization call at noon, Andy Lundgren announced that the blind injection team had stated definitively they had done no injections. I sat upright at that point and listened (in a bit of a daze) as Alan Weinstein asked -- very slowly -- for confirmation: "Do you mean to say that this was not a blind injection?" When Andy confirmed that yes, there had been no injection, I realized that we had just entered uncharted territory.

Anamaria Effler

Caltech Postdoctoral Scholar stationed at LIGO Livingston Observatory



LIGO/Kai Staats

Robert Schofield and I were testing the L1 detector's sensitivity to environmental noise at LIGO Livingston on the night of September 13. Our tests were part of LIGO's preparations for the O1 run. We were still working at 2am on Monday, September 14. Pausing until about 4am to evaluate our data, we debated whether or not to do "car injections" in which one of us would drive a large car near the main detector building and apply the brakes violently every five seconds to see if the seismic noise from the car would appear in the interferometer data. But the GPS wristwatch that we needed for the test had become disconnected from the satellite signal. This was the last straw. We said, "Fine, we can live without this test." I distinctly remember (because I was asked many times during the next few days) looking at my car clock as I was driving away from the site and seeing that the time was 4:35am. I knew that my clock was three minutes in error, which annoyed me.

The next day or the following, I saw some email traffic on GW150914 and my heart stopped because of the possibility that it occurred during our tests (although this couldn't have happened because we keep the detector out of observation mode while we're testing). Nevertheless I experienced a second or two of "oh no . . . " (the polite version of what I thought). Then I breathed a giant sigh of relief knowing that we were off-site by the time of the event and that we didn't do the last few tests. But knowing how close we were . . .

I didn't expect a detection during this run and I didn't believe that GW150914 was real for quite a while. Not until it was established that no injections had occurred and that the signal didn't appear in other data channels; even then I didn't dare believe. The realization slowly seeped in over time. The event was too big and I can't imagine how people feel who have been in the field for a long time.

Interviews courtesy of LIGO Magazine, www.ligo.org/magazine.php

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BIOS

France Córdova is 14th director of the National Science Foundation. Córdova leads the only government agency charged with advancing all fields of scientific discovery, technological innovation, and STEM education. Córdova has a distinguished resume, including: chair of the Smithsonian Institution's Board of Regents; president emerita of Purdue University; chancellor of the University of California, Riverside; vice chancellor for research at the University of California, Santa Barbara; NASA's chief scientist; head of the astronomy and astrophysics department at Penn State; and deputy group leader at Los Alamos National Laboratory. She received her B.A. from Stanford University and her Ph.D. in physics from the California Institute of Technology.

Gabriela González is spokesperson for the LIGO Scientific Collaboration. She completed her PhD at Syracuse University in 1995, then worked as a staff scientist in the LIGO group at MIT until 1997, when she joined the faculty at Penn State. In 2001, she joined the faculty at Louisiana State University, where she is a professor of physics and astronomy. The González group's current research focuses on characterization of the LIGO detector noise, detector calibration, and searching for gravitational waves in the data. In 2007, she was elected a fellow of the American Physical Society for her experimental contributions to the field of gravitational wave detection, her leadership in the analysis of LIGO data for gravitational wave signals, and for her skill in communicating the excitement of physics to students and the public.

David Reitze is executive director of the LIGO Laboratory at Caltech. In 1990, he completed his PhD at the University of Texas, Austin, where his research focused on ultrafast laser-matter interactions. He held research positions at Bell Communications Research and Lawrence Livermore National Laboratory before joining the physics faculty at the University of Florida in 1993. He began working on LIGO in 1996 as the initial LIGO Input Optics subsystem leader, a role he reprised for Advanced LIGO. In 2006, he was elected a fellow of the American Physical Society for leadership in the applications of lasers in diverse areas from the detection of gravitational waves to the ultrafast response of matter. Reitze served as the spokesperson for the LIGO Scientific Collaboration from 2007 to 2011 and took an extended leave of absence from the University of Florida in 2011 to serve as LIGO's executive director. In 2015, he was elected a fellow of the Optical Society.

Kip Thorne is Caltech's Richard P. Feynman Professor of Theoretical Physics, Emeritus. He obtained his PhD in physics from Princeton University in 1965 and joined Caltech's physics faculty in 1966. He cofounded the LIGO Project in 1984 with Rainer Weiss and Ronald Drever; in 2004 he cofounded, with Cornell's Saul Teukolsky, the SXS Numerical Relativity Project, which simulates LIGO's gravitational wave sources on supercomputers. Thorne was elected to the American Academy of Arts and Sciences in 1972, the National Academy of Sciences in 1973, and the Russian Academy of Sciences in 1999. His research has focused on general relativity and astrophysics with emphasis on relativistic stars, black holes, and gravitational waves. Thorne, along with film producer Lynda Obst he coauthored the treatment that gave rise to Christopher Nolan's 2014 movie Interstellar. Thorne was the movie's executive producer and science adviser.

Rainer Weiss is an emeritus professor of physics at MIT. In 1962, he completed his PhD at the MIT, where his research focused on atomic beams. He worked as a research associate at Princeton University until 1964, when he joined the physics faculty at MIT. Weiss worked on measurements of the cosmic background radiation and was chair of the science working group for NASA's Cosmic Background Explorer mission. He cofounded the LIGO project in 1984 with Kip Thorne and Ronald Drever. In 1996, Weiss was elected a fellow of the American Physical Society for his pioneering work in the development of laser-interferometric detectors for gravitational radiation and his contributions to the study of the spectrum and anisotropy of the cosmic microwave background. He is a fellow of both the American Association for the Advancement of Science and the American Academy of Arts and Sciences, and is a member of the National Academy of Sciences. Weiss and Ronald Drever received the Einstein Prize of the American Physical Society in 2007.

Other Searches for Gravitational Waves

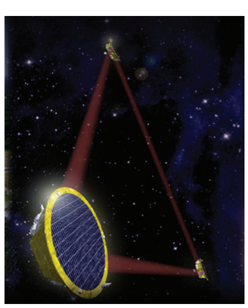
Astronomers study the universe with light, radio waves, X-rays, and other radiations. These are all made from oscillating electric and magnetic fields — “electromagnetic waves” they are called. They differ only in the waves’ oscillation frequencies. In light the waves oscillate about a thousand trillion (10^{15}) times per second; in X-rays, roughly a million trillion (10^{18}) times per second; in radio waves, roughly a hundred million (10^{8}) times per second. When astronomers use each of these kinds of electromagnetic waves, we refer to them as “looking through the optical window” onto the universe, or the “X-ray window” or the “radio window.”

Gravitational waves are radically different from electromagnetic waves. Instead of being made from oscillating electric and magnetic fields, they are made from oscillations in the shape (the “fabric”) of space and time. And as with electromagnetic waves, astronomers will study gravitational waves through several different “windows,” each differing in the frequency at which the gravitational waves oscillate — though in the gravitational case, it is more convenient to state the waves’ oscillation period (one divided by their frequency). In the coming one or two decades, physicists and astronomers will open up four different gravitational windows onto the universe:

High Frequency Window — Periods: 0.1 to 100 Milliseconds

This is LIGO’s window, and it was opened on September 15, 2015, when LIGO discovered the gravitational waves from a collision of two black holes.

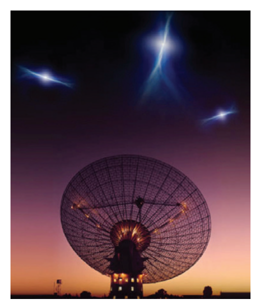
Low Frequency Window — Periods: Minutes to Hours



This window will likely be opened by LISA, the Laser Interferometer Space Antenna, a huge laser interferometer in space millions of kilometers long. LISA will comprise three spacecraft at the corners of a triangle, trailing the earth in its orbit around the sun, and tracking each other with laser beams. LISA will observe, throughout the universe, merging pairs of supermassive black holes, millions of times heavier than the sun (by contrast with LIGO’s black holes, which are only ten to 100 times heavier than the sun), and will also observe small black holes or stars being swallowed by supermassive black holes. It will enable us to trace the evolution of galaxies all the way to the beginning, and it might allow us to watch amazing processes in the first fraction of a second of the universe’s life, such as the births of the electromagnetic force and the weak nuclear force.

LISA’s precursor mission, LISA Pathfinder, was launched last December by the European Space Agency (ESA). It will test all of LISA’s important technologies. The satellite has now arrived at the Lagrange point L1, that is the place between earth and the sun where their gravitational attractions almost cancel, and its technology tests will commence on March 1, 2016. LISA Pathfinder is expected to give us confidence that the technologies needed for LISA will all work flawlessly, paving the way for a LISA launch by the end of the 2020s. For more information, see http://lisamission.org .

Very Low Frequency Window — Periods: Years to Decades



Gravitational waves with these periods can be detected by monitoring tens of millisecond pulsars using radio telescopes. Each pulsar-Earth system responds to a gravitational wave much like each arm of a LIGO interferometer, but replaces the laser beam with radio waves, and the arm’s two mirrors with the radio-emitting pulsar far away in our galaxy and the radio telescope on Earth. Gravitational waves passing through Earth cause minuscule oscillations in the ticking rates of clocks on earth, and thence oscillations in the measured rates of arrival of pulses — similar and simultaneous oscillations for all the pulsars. The set of pulsars is called an “array,” and the set of radio telescopes and pulsars used in the gravitational wave search is called a Pulsar Timing Array (PTA).

An International PTA collaboration--IPTA, which includes American, Australian and European radio astronomers and telescopes--is likely to open this gravitational window within the next decade. The

American telescopes that contribute most effectively are the Arecibo Observatory in Puerto Rico and the Green Bank Telescope in West Virginia.

The IPTA is likely to see very low frequency gravitational waves from the inspiral and merger of gigantic black holes, tens to hundreds of times heavier than those observed by LISA, and may also see gravitational waves from vibrating cosmic strings. These cosmic-length strings are thought to have been created shortly after the Big Bang by the inflationary expansion of fundamental strings — the building blocks of all matter.

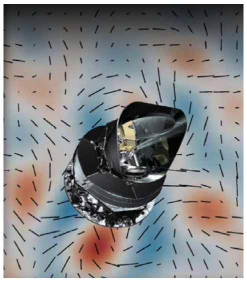
For more information, see http://www.ipta4gw.org/ and http://www.nanograv.org/ .

Binary Pulsar and the First Discovery of Gravitational Waves

The IPTA builds on technology that was developed several decades ago to detect gravitational waves at their source. In 1974 Russell Hulse and Joseph Taylor discovered radio pulses from a pulsar (a spinning neutron star) orbiting a second neutron star — a so-called "binary pulsar." Over the next eight years, Taylor and Joel Weissberg measured changes in the pulses' rate of arrival, and from those changes they inferred that the two neutron stars were spiraling inward toward each other at just the rate that relativity predicts due to loss of energy to gravitational waves. This discovery, announced in 1982, was the first demonstration of the existence of gravitational waves. Hulse and Taylor received the 1993 Nobel Prize for discovering this binary pulsar and for realizing that it could be a powerful observational tool for studying gravity.

Extremely Low Frequency Window — Periods: Billions of Years

A gravitational wave with a billion year period will vary imperceptibly during a human lifetime, so such waves appear as a frozen pattern on the sky. Gravitational waves in this extremely low frequency window are predicted to have been produced in the earliest moments of our universe, when fluctuations from the Big Bang were amplified by an exceedingly rapid inflation of our universe's size. If the resulting "primordial" gravitational waves can be detected and measured, they will reveal details of our universe's inflation, details that are considered a holy grail of cosmology today.



The primordial gravitational waves are predicted to have stretched and squeezed the hot gas that filled the universe 280,000 years after the Big Bang, when that gas was giving rise to the cosmic microwave background radiation (CMB) — electromagnetic waves that we see filling the universe today. This stretching and squeezing is predicted to have placed a swirling "B-mode" imprint on the polarization pattern across the sky. Such an imprint was discovered two years ago by the BICEP2 telescope at the South Pole, but some or all of it could have been produced by microwaves from intergalactic dust, rather than by primordial gravitational waves.

Removing dust's influence requires measurements of the CMB polarization over a much wider range of electromagnetic wavelengths than heretofore. This will be done by improved instruments at the South Pole and at high altitudes in Chile, and by others flown to higher altitudes on balloons, and ultimately by instruments flown on a specially designed satellite, a successor to Planck. At some point along this sequence of instruments, the predicted, swirling, B-mode polarization will be measured, free of interfering dust. This will open the extremely low frequency gravitational window on to our universe and reveal details of our universe's inflationary epoch — an epoch when the universe's age was only 10^{-34} seconds (ten trillionths of a trillionth of a trillionth of a second after the Big Bang).

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

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I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions: transverse waves of spatial strain that travel at the speed of light, generated by time variations of the mass quadrupole moment of the source [1,2]. Einstein understood that gravitational-wave amplitudes would be remarkably small; moreover, until the Chapel Hill conference in 1957 there was significant debate about the physical reality of gravitational waves [3].

Also in 1916, Schwarzschild published a solution for the field equations [4] that was later understood to describe a black hole [5,6], and in 1963 Kerr generalized the solution to rotating black holes [7]. Starting in the 1970s theoretical work led to the understanding of black hole quasinormal modes [8–10], and in the 1990s higher-order post-Newtonian calculations [11] preceded extensive analytical studies of relativistic two-body dynamics [12,13]. These advances, together with numerical relativity breakthroughs in the past decade [14–16], have enabled modeling of binary black hole mergers and accurate predictions of their gravitational waveforms. While numerous black hole candidates have now been identified through electromagnetic observations [17–19], black hole mergers have not previously been observed.

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22], led to the recognition that direct observations of the amplitude and phase of gravitational waves would enable studies of additional relativistic systems and provide new tests of general relativity, especially in the dynamic strong-field regime.

Experiments to detect gravitational waves began with Weber and his resonant mass detectors in the 1960s [23], followed by an international network of cryogenic resonant detectors [24]. Interferometric detectors were first suggested in the early 1960s [25] and the 1970s [26]. A study of the noise and performance of such detectors [27], and further concepts to improve them [28], led to proposals for long-baseline broadband laser interferometers with the potential for significantly increased sensitivity [29–32]. By the early 2000s, a set of initial detectors was completed, including TAMA 300 in Japan, GEO 600 in Germany, the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States, and Virgo in Italy. Combinations of these detectors made joint observations from 2002 through 2011, setting upper limits on a variety of gravitational-wave sources while evolving into a global network. In 2015, Advanced LIGO became the first of a significantly more sensitive network of advanced detectors to begin observations [33–36].

A century after the fundamental predictions of Einstein and Schwarzschild, we report the first direct detection of gravitational waves and the first direct observation of a binary black hole system merging to form a single black hole. Our observations provide unique access to the

*Full author list given at the end of the article.

properties of space-time in the strong-field, high-velocity regime and confirm predictions of general relativity for the nonlinear dynamics of highly disturbed black holes.

II. OBSERVATION

On September 14, 2015 at 09:50:45 UTC, the LIGO Hanford, WA, and Livingston, LA, observatories detected the coincident signal GW150914 shown in Fig. 1. The initial detection was made by low-latency searches for generic gravitational-wave transients [41] and was reported within three minutes of data acquisition [43]. Subsequently, matched-filter analyses that use relativistic models of compact binary waveforms [44] recovered GW150914 as the most significant event from each detector for the observations reported here. Occurring within the 10-ms intersite

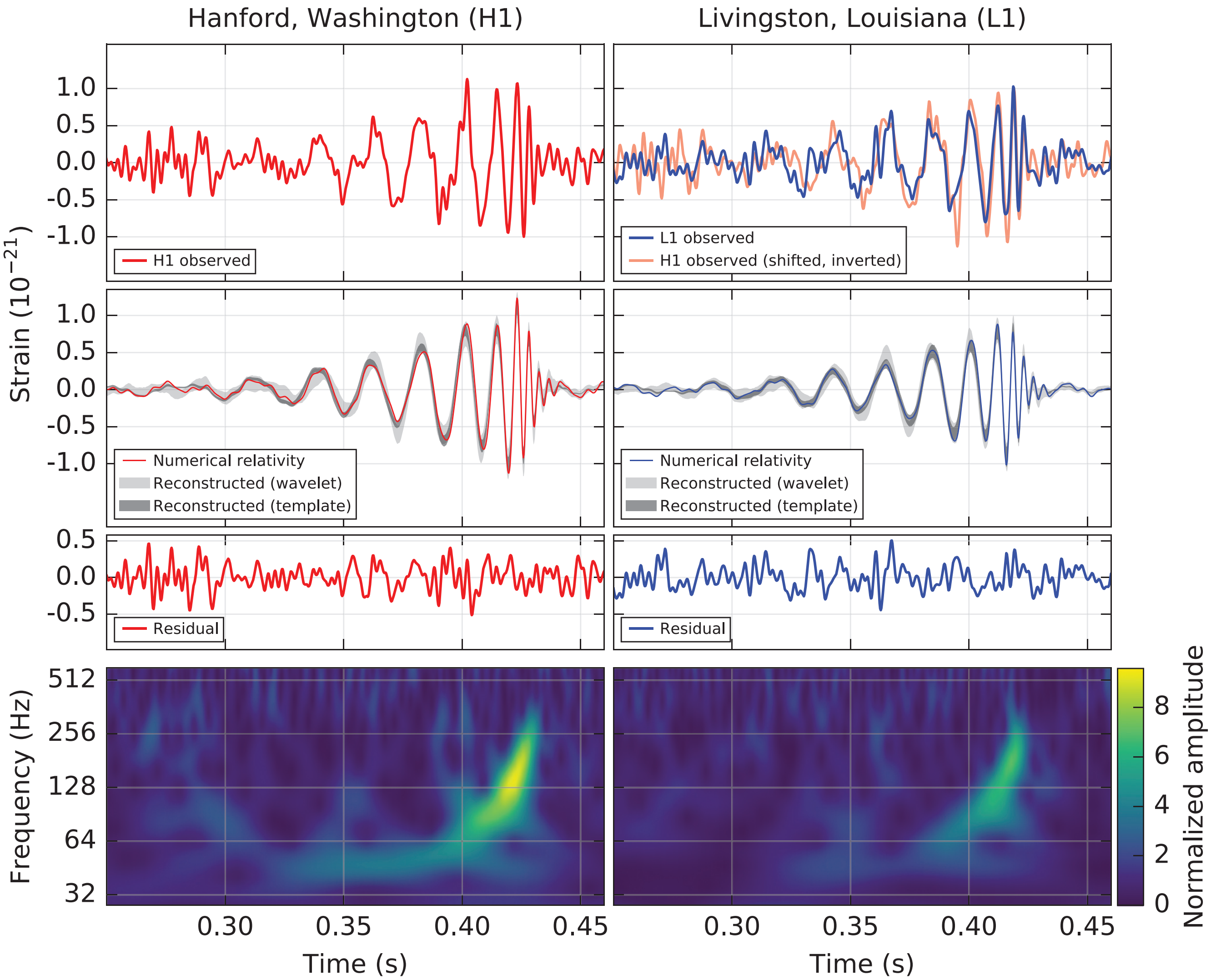

FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left:* H1 strain. *Top row, right:* L1 strain. GW150914 arrived first at L1 and $6.9^{+0.5}_{-0.4}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). *Second row:* Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [15]. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine-Gaussian wavelets [40,41]. These reconstructions have a 94% overlap, as shown in [39]. *Third row:* Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. *Bottom row:* A time-frequency representation [42] of the strain data, showing the signal frequency increasing over time.

propagation time, the events have a combined signal-to-noise ratio (SNR) of 24 [45].

Only the LIGO detectors were observing at the time of GW150914. The Virgo detector was being upgraded, and GEO 600, though not sufficiently sensitive to detect this event, was operating but not in observational mode. With only two detectors the source position is primarily determined by the relative arrival time and localized to an area of approximately 600 deg^2 (90% credible region) [39,46].

The basic features of GW150914 point to it being produced by the coalescence of two black holes—i.e., their orbital inspiral and merger, and subsequent final black hole ringdown. Over 0.2 s, the signal increases in frequency and amplitude in about 8 cycles from 35 to 150 Hz, where the amplitude reaches a maximum. The most plausible explanation for this evolution is the inspiral of two orbiting masses, m_1 and m_2, due to gravitational-wave emission. At the lower frequencies, such evolution is characterized by the chirp mass [11]

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5},$$

where f and $\dot{f}$ are the observed frequency and its time derivative and G and c are the gravitational constant and speed of light. Estimating f and $\dot{f}$ from the data in Fig. 1, we obtain a chirp mass of $\mathcal{M} \simeq 30 M_\odot$, implying that the total mass $M = m_1 + m_2$ is $\gtrsim 70 M_\odot$ in the detector frame. This bounds the sum of the Schwarzschild radii of the binary components to $2GM/c^2 \gtrsim 210$ km. To reach an orbital frequency of 75 Hz (half the gravitational-wave frequency) the objects must have been very close and very compact; equal Newtonian point masses orbiting at this frequency would be only $\simeq 350$ km apart. A pair of neutron stars, while compact, would not have the required mass, while a black hole neutron star binary with the deduced chirp mass would have a very large total mass, and would thus merge at much lower frequency. This leaves black holes as the only known objects compact enough to reach an orbital frequency of 75 Hz without contact. Furthermore, the decay of the waveform after it peaks is consistent with the damped oscillations of a black hole relaxing to a final stationary Kerr configuration. Below, we present a general-relativistic analysis of GW150914; Fig. 2 shows the calculated waveform using the resulting source parameters.

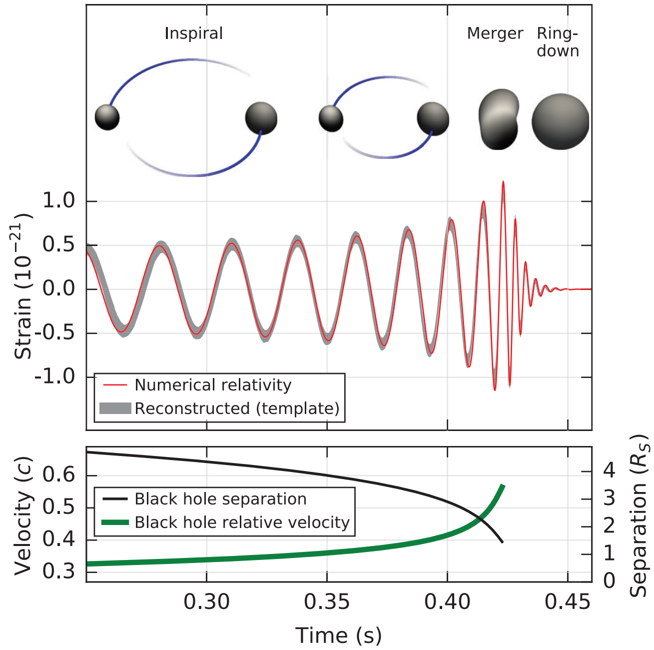

FIG. 2. *Top:* Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 1. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. *Bottom:* The Keplerian effective black hole separation in units of Schwarzschild radii ($R_S = 2GM/c^2$) and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$, where f is the gravitational-wave frequency calculated with numerical relativity and M is the total mass (value from Table I).

III. DETECTORS

Gravitational-wave astronomy exploits multiple, widely separated detectors to distinguish gravitational waves from local instrumental and environmental noise, to provide source sky localization, and to measure wave polarizations. The LIGO sites each operate a single Advanced LIGO detector [33], a modified Michelson interferometer (see Fig. 3) that measures gravitational-wave strain as a difference in length of its orthogonal arms. Each arm is formed by two mirrors, acting as test masses, separated by $L_x = L_y = L = 4$ km. A passing gravitational wave effectively alters the arm lengths such that the measured difference is $\Delta L(t) = \delta L_x - \delta L_y = h(t)L$, where h is the gravitational-wave strain amplitude projected onto the detector. This differential length variation alters the phase difference between the two light fields returning to the beam splitter, transmitting an optical signal proportional to the gravitational-wave strain to the output photodetector.

To achieve sufficient sensitivity to measure gravitational waves, the detectors include several enhancements to the basic Michelson interferometer. First, each arm contains a resonant optical cavity, formed by its two test mass mirrors, that multiplies the effect of a gravitational wave on the light phase by a factor of 300 [48]. Second, a partially transmissive power-recycling mirror at the input provides additional resonant buildup of the laser light in the interferometer as a whole [49,50]: 20 W of laser input is increased to 700 W incident on the beam splitter, which is further increased to 100 kW circulating in each arm cavity. Third, a partially transmissive signal-recycling mirror at the output optimizes

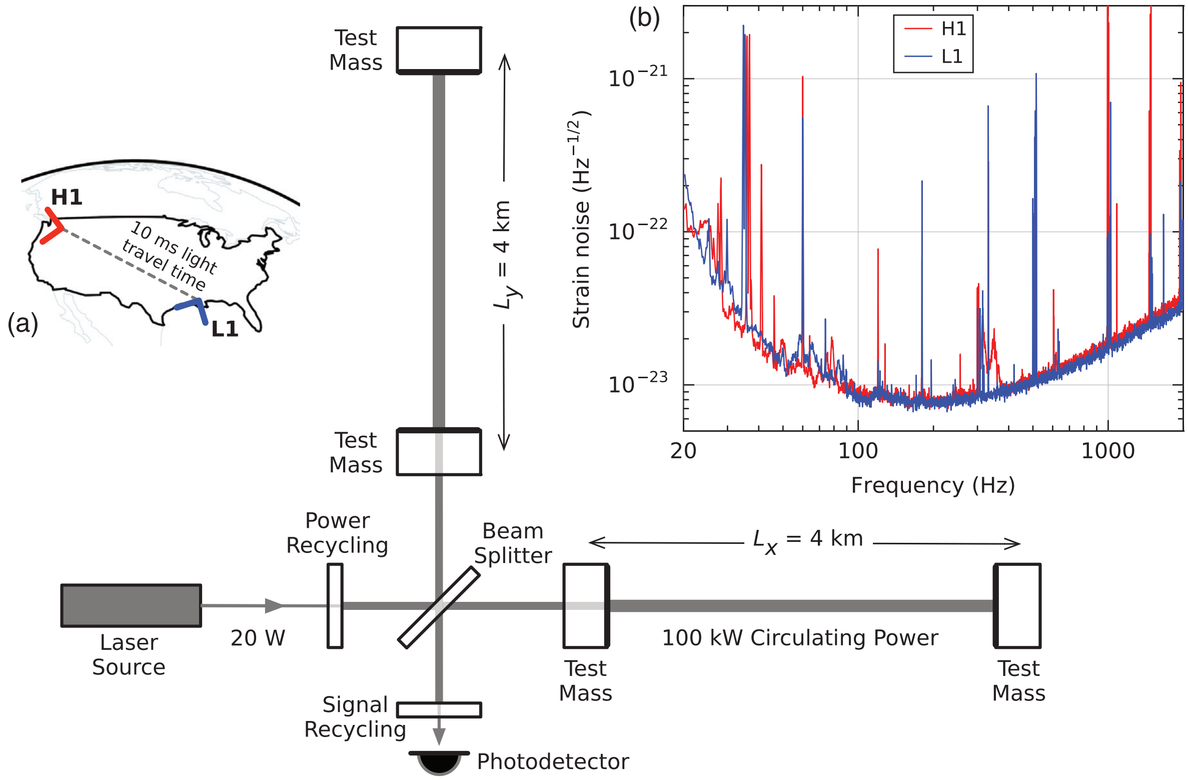

FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). *Inset (b):* The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies [47]. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

the gravitational-wave signal extraction by broadening the bandwidth of the arm cavities [51,52]. The interferometer is illuminated with a 1064-nm wavelength Nd:YAG laser, stabilized in amplitude, frequency, and beam geometry [53,54]. The gravitational-wave signal is extracted at the output port using a homodyne readout [55].

These interferometry techniques are designed to maximize the conversion of strain to optical signal, thereby minimizing the impact of photon shot noise (the principal noise at high frequencies). High strain sensitivity also requires that the test masses have low displacement noise, which is achieved by isolating them from seismic noise (low frequencies) and designing them to have low thermal noise (intermediate frequencies). Each test mass is suspended as the final stage of a quadruple-pendulum system [56], supported by an active seismic isolation platform [57]. These systems collectively provide more than 10 orders of magnitude of isolation from ground motion for frequencies above 10 Hz. Thermal noise is minimized by using low-mechanical-loss materials in the test masses and their suspensions: the test masses are 40-kg fused silica substrates with low-loss dielectric optical coatings [58,59], and are suspended with fused silica fibers from the stage above [60].

To minimize additional noise sources, all components other than the laser source are mounted on vibration isolation stages in ultrahigh vacuum. To reduce optical phase fluctuations caused by Rayleigh scattering, the pressure in the 1.2-m diameter tubes containing the arm-cavity beams is maintained below 1 μPa.

Servo controls are used to hold the arm cavities on resonance [61] and maintain proper alignment of the optical components [62]. The detector output is calibrated in strain by measuring its response to test mass motion induced by photon pressure from a modulated calibration laser beam [63]. The calibration is established to an uncertainty (1σ) of less than 10% in amplitude and 10 degrees in phase, and is continuously monitored with calibration laser excitations at selected frequencies. Two alternative methods are used to validate the absolute calibration, one referenced to the main laser wavelength and the other to a radio-frequency oscillator

[64]. Additionally, the detector response to gravitational waves is tested by injecting simulated waveforms with the calibration laser.

To monitor environmental disturbances and their influence on the detectors, each observatory site is equipped with an array of sensors: seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, ac-power line monitors, and a cosmic-ray detector [65]. Another $\sim 10^5$ channels record the interferometer's operating point and the state of the control systems. Data collection is synchronized to Global Positioning System (GPS) time to better than 10 μs [66]. Timing accuracy is verified with an atomic clock and a secondary GPS receiver at each observatory site.

In their most sensitive band, 100–300 Hz, the current LIGO detectors are 3 to 5 times more sensitive to strain than initial LIGO [67]; at lower frequencies, the improvement is even greater, with more than ten times better sensitivity below 60 Hz. Because the detectors respond proportionally to gravitational-wave amplitude, at low redshift the volume of space to which they are sensitive increases as the cube of strain sensitivity. For binary black holes with masses similar to GW150914, the space-time volume surveyed by the observations reported here surpasses previous observations by an order of magnitude [68].

IV. DETECTOR VALIDATION

Both detectors were in steady state operation for several hours around GW150914. All performance measures, in particular their average sensitivity and transient noise behavior, were typical of the full analysis period [69,70].

Exhaustive investigations of instrumental and environmental disturbances were performed, giving no evidence to suggest that GW150914 could be an instrumental artifact [69]. The detectors' susceptibility to environmental disturbances was quantified by measuring their response to specially generated magnetic, radio-frequency, acoustic, and vibration excitations. These tests indicated that any external disturbance large enough to have caused the observed signal would have been clearly recorded by the array of environmental sensors. None of the environmental sensors recorded any disturbances that evolved in time and frequency like GW150914, and all environmental fluctuations during the second that contained GW150914 were too small to account for more than 6% of its strain amplitude. Special care was taken to search for long-range correlated disturbances that might produce nearly simultaneous signals at the two sites. No significant disturbances were found.

The detector strain data exhibit non-Gaussian noise transients that arise from a variety of instrumental mechanisms. Many have distinct signatures, visible in auxiliary data channels that are not sensitive to gravitational waves; such instrumental transients are removed from our analyses [69]. Any instrumental transients that remain in the data are accounted for in the estimated detector backgrounds described below. There is no evidence for instrumental transients that are temporally correlated between the two detectors.

V. SEARCHES

We present the analysis of 16 days of coincident observations between the two LIGO detectors from September 12 to October 20, 2015. This is a subset of the data from Advanced LIGO's first observational period that ended on January 12, 2016.

GW150914 is confidently detected by two different types of searches. One aims to recover signals from the coalescence of compact objects, using optimal matched filtering with waveforms predicted by general relativity. The other search targets a broad range of generic transient signals, with minimal assumptions about waveforms. These searches use independent methods, and their response to detector noise consists of different, uncorrelated, events. However, strong signals from binary black hole mergers are expected to be detected by both searches.

Each search identifies candidate events that are detected at both observatories consistent with the intersite propagation time. Events are assigned a detection-statistic value that ranks their likelihood of being a gravitational-wave signal. The significance of a candidate event is determined by the search background—the rate at which detector noise produces events with a detection-statistic value equal to or higher than the candidate event. Estimating this background is challenging for two reasons: the detector noise is nonstationary and non-Gaussian, so its properties must be empirically determined; and it is not possible to shield the detector from gravitational waves to directly measure a signal-free background. The specific procedure used to estimate the background is slightly different for the two searches, but both use a time-shift technique: the time stamps of one detector's data are artificially shifted by an offset that is large compared to the intersite propagation time, and a new set of events is produced based on this time-shifted data set. For instrumental noise that is uncorrelated between detectors this is an effective way to estimate the background. In this process a gravitational-wave signal in one detector may coincide with time-shifted noise transients in the other detector, thereby contributing to the background estimate. This leads to an overestimate of the noise background and therefore to a more conservative assessment of the significance of candidate events.

The characteristics of non-Gaussian noise vary between different time-frequency regions. This means that the search backgrounds are not uniform across the space of signals being searched. To maximize sensitivity and provide a better estimate of event significance, the searches sort both their background estimates and their event candidates into different classes according to their time-frequency morphology. The significance of a candidate event is measured against the background of its class. To account for having searched multiple classes, this significance is decreased by a trials factor equal to the number of classes [71].

A. Generic transient search

Designed to operate without a specific waveform model, this search identifies coincident excess power in time-frequency representations of the detector strain data [43,72], for signal frequencies up to 1 kHz and durations up to a few seconds.

The search reconstructs signal waveforms consistent with a common gravitational-wave signal in both detectors using a multidetector maximum likelihood method. Each event is ranked according to the detection statistic $\eta_c = \sqrt{2E_c/(1 + E_n/E_c)}$, where E_c is the dimensionless coherent signal energy obtained by cross-correlating the two reconstructed waveforms, and E_n is the dimensionless residual noise energy after the reconstructed signal is subtracted from the data. The statistic η_c thus quantifies the SNR of the event and the consistency of the data between the two detectors.

Based on their time-frequency morphology, the events are divided into three mutually exclusive search classes, as described in [41]: events with time-frequency morphology of known populations of noise transients (class C1), events with frequency that increases with time (class C3), and all remaining events (class C2).

Detected with $\eta_c = 20.0$, GW150914 is the strongest event of the entire search. Consistent with its coalescence signal signature, it is found in the search class C3 of events with increasing time-frequency evolution. Measured on a background equivalent to over 67 400 years of data and including a trials factor of 3 to account for the search classes, its false alarm rate is lower than 1 in 22 500 years. This corresponds to a probability $< 2 \times 10^{-6}$ of observing one or more noise events as strong as GW150914 during the analysis time, equivalent to 4.6σ. The left panel of Fig. 4 shows the C3 class results and background.

The selection criteria that define the search class C3 reduce the background by introducing a constraint on the signal morphology. In order to illustrate the significance of GW150914 against a background of events with arbitrary shapes, we also show the results of a search that uses the same set of events as the one described above but without this constraint. Specifically, we use only two search classes: the C1 class and the union of C2 and C3 classes (C2 + C3). In this two-class search the GW150914 event is found in the C2 + C3 class. The left panel of Fig. 4 shows the C2 + C3 class results and background. In the background of this class there are four events with $\eta_c \geq 32.1$, yielding a false alarm rate for GW150914 of 1 in 8 400 years. This corresponds to a false alarm probability of 5×10^{-6} equivalent to 4.4σ.

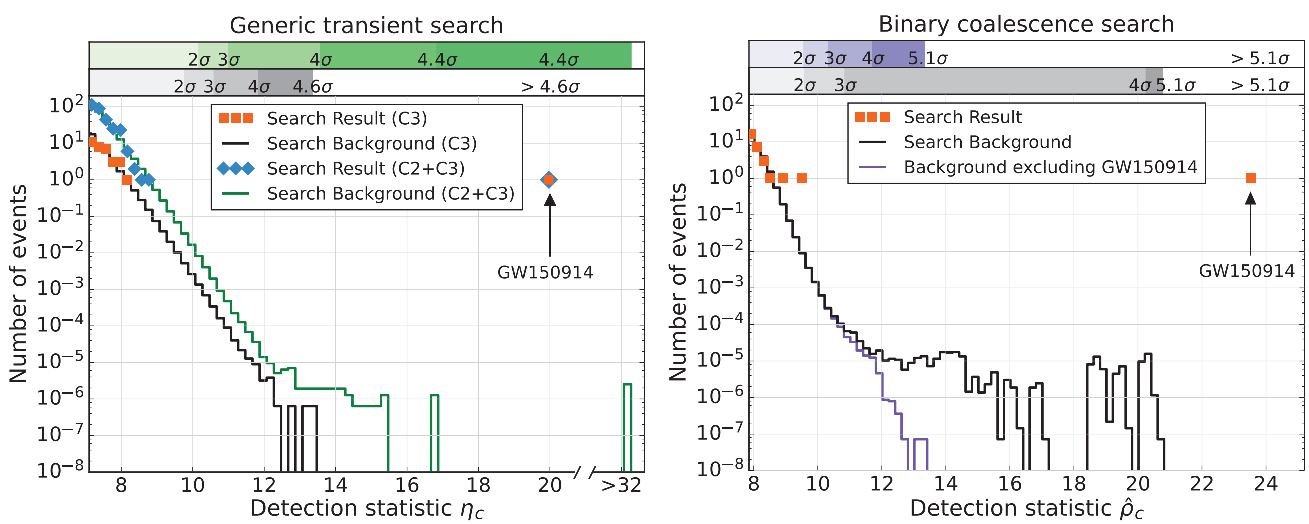

FIG. 4. Search results from the generic transient search (left) and the binary coalescence search (right). These histograms show the number of candidate events (orange markers) and the mean number of background events (black lines) in the search class where GW150914 was found as a function of the search detection statistic and with a bin width of 0.2. The scales on the top give the significance of an event in Gaussian standard deviations based on the corresponding noise background. The significance of GW150914 is greater than 5.1σ and 4.6σ for the binary coalescence and the generic transient searches, respectively. *Left:* Along with the primary search (C3) we also show the results (blue markers) and background (green curve) for an alternative search that treats events independently of their frequency evolution (C2 + C3). The classes C2 and C3 are defined in the text. *Right:* The tail in the black-line background of the binary coalescence search is due to random coincidences of GW150914 in one detector with noise in the other detector. (This type of event is practically absent in the generic transient search background because they do not pass the time-frequency consistency requirements used in that search.) The purple curve is the background excluding those coincidences, which is used to assess the significance of the second strongest event.

For robustness and validation, we also use other generic transient search algorithms [41]. A different search [73] and a parameter estimation follow-up [74] detected GW150914 with consistent significance and signal parameters.

B. Binary coalescence search

This search targets gravitational-wave emission from binary systems with individual masses from 1 to $99M_\odot$, total mass less than $100M_\odot$, and dimensionless spins up to 0.99 [44]. To model systems with total mass larger than $4M_\odot$, we use the effective-one-body formalism [75], which combines results from the post-Newtonian approach [11,76] with results from black hole perturbation theory and numerical relativity. The waveform model [77,78] assumes that the spins of the merging objects are aligned with the orbital angular momentum, but the resulting templates can, nonetheless, effectively recover systems with misaligned spins in the parameter region of GW150914 [44]. Approximately 250 000 template waveforms are used to cover this parameter space.

The search calculates the matched-filter signal-to-noise ratio $\rho(t)$ for each template in each detector and identifies maxima of $\rho(t)$ with respect to the time of arrival of the signal [79–81]. For each maximum we calculate a chi-squared statistic χ_r^2 to test whether the data in several different frequency bands are consistent with the matching template [82]. Values of χ_r^2 near unity indicate that the signal is consistent with a coalescence. If χ_r^2 is greater than unity, $\rho(t)$ is reweighted as $\hat{\rho} = \rho/\{[1 + (\chi_r^2)^3]/2\}^{1/6}$ [83,84]. The final step enforces coincidence between detectors by selecting event pairs that occur within a 15-ms window and come from the same template. The 15-ms window is determined by the 10-ms intersite propagation time plus 5 ms for uncertainty in arrival time of weak signals. We rank coincident events based on the quadrature sum $\hat{\rho}_c$ of the $\hat{\rho}$ from both detectors [45].

To produce background data for this search the SNR maxima of one detector are time shifted and a new set of coincident events is computed. Repeating this procedure $\sim 10^7$ times produces a noise background analysis time equivalent to 608 000 years.

To account for the search background noise varying across the target signal space, candidate and background events are divided into three search classes based on template length. The right panel of Fig. 4 shows the background for the search class of GW150914. The GW150914 detection-statistic value of $\hat{\rho}_c = 23.6$ is larger than any background event, so only an upper bound can be placed on its false alarm rate. Across the three search classes this bound is 1 in 203 000 years. This translates to a false alarm probability $< 2 \times 10^{-7}$, corresponding to 5.1σ.

A second, independent matched-filter analysis that uses a different method for estimating the significance of its events [85,86], also detected GW150914 with identical signal parameters and consistent significance.

TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1 + z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

When an event is confidently identified as a real gravitational-wave signal, as for GW150914, the background used to determine the significance of other events is reestimated without the contribution of this event. This is the background distribution shown as a purple line in the right panel of Fig. 4. Based on this, the second most significant event has a false alarm rate of 1 per 2.3 years and corresponding Poissonian false alarm probability of 0.02. Waveform analysis of this event indicates that if it is astrophysical in origin it is also a binary black hole merger [44].

VI. SOURCE DISCUSSION

The matched-filter search is optimized for detecting signals, but it provides only approximate estimates of the source parameters. To refine them we use general relativity-based models [77,78,87,88], some of which include spin precession, and for each model perform a coherent Bayesian analysis to derive posterior distributions of the source parameters [89]. The initial and final masses, final spin, distance, and redshift of the source are shown in Table I. The spin of the primary black hole is constrained to be < 0.7 (90% credible interval) indicating it is not maximally spinning, while the spin of the secondary is only weakly constrained. These source parameters are discussed in detail in [39]. The parameter uncertainties include statistical errors and systematic errors from averaging the results of different waveform models.

Using the fits to numerical simulations of binary black hole mergers in [92,93], we provide estimates of the mass and spin of the final black hole, the total energy radiated in gravitational waves, and the peak gravitational-wave luminosity [39]. The estimated total energy radiated in gravitational waves is $3.0^{+0.5}_{-0.5} M_\odot c^2$. The system reached a peak gravitational-wave luminosity of $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s, equivalent to $200^{+30}_{-20} M_\odot c^2/\mathrm{s}$.

Several analyses have been performed to determine whether or not GW150914 is consistent with a binary black hole system in general relativity [94]. A first consistency check involves the mass and spin of the final black hole. In general relativity, the end product of a black hole binary coalescence is a Kerr black hole, which is fully described by its mass and spin. For quasicircular inspirals, these are predicted uniquely by Einstein's equations as a function of the masses and spins of the two progenitor black holes. Using fitting formulas calibrated to numerical relativity simulations [92], we verified that the remnant mass and spin deduced from the early stage of the coalescence and those inferred independently from the late stage are consistent with each other, with no evidence for disagreement from general relativity.

Within the post-Newtonian formalism, the phase of the gravitational waveform during the inspiral can be expressed as a power series in $f^{1/3}$. The coefficients of this expansion can be computed in general relativity. Thus, we can test for consistency with general relativity [95,96] by allowing the coefficients to deviate from the nominal values, and seeing if the resulting waveform is consistent with the data. In this second check [94] we place constraints on these deviations, finding no evidence for violations of general relativity.

Finally, assuming a modified dispersion relation for gravitational waves [97], our observations constrain the Compton wavelength of the graviton to be $\lambda_g > 10^{13}$ km, which could be interpreted as a bound on the graviton mass $m_g < 1.2 \times 10^{-22}$ eV$/c^2$. This improves on Solar System and binary pulsar bounds [98,99] by factors of a few and a thousand, respectively, but does not improve on the model-dependent bounds derived from the dynamics of Galaxy clusters [100] and weak lensing observations [101]. In summary, all three tests are consistent with the predictions of general relativity in the strong-field regime of gravity.

GW150914 demonstrates the existence of stellar-mass black holes more massive than $\simeq 25 M_\odot$, and establishes that binary black holes can form in nature and merge within a Hubble time. Binary black holes have been predicted to form both in isolated binaries [102–104] and in dense environments by dynamical interactions [105–107]. The formation of such massive black holes from stellar evolution requires weak massive-star winds, which are possible in stellar environments with metallicity lower than $\simeq 1/2$ the solar value [108,109]. Further astrophysical implications of this binary black hole discovery are discussed in [110].

These observational results constrain the rate of stellar-mass binary black hole mergers in the local universe. Using several different models of the underlying binary black hole mass distribution, we obtain rate estimates ranging from 2–400 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ in the comoving frame [111–113]. This is consistent with a broad range of rate predictions as reviewed in [114], with only the lowest event rates being excluded.

Binary black hole systems at larger distances contribute to a stochastic background of gravitational waves from the superposition of unresolved systems. Predictions for such a background are presented in [115]. If the signal from such a population were detected, it would provide information about the evolution of such binary systems over the history of the universe.

VII. OUTLOOK

Further details about these results and associated data releases are available at [116]. Analysis results for the entire first observational period will be reported in future publications. Efforts are under way to enhance significantly the global gravitational-wave detector network [117]. These include further commissioning of the Advanced LIGO detectors to reach design sensitivity, which will allow detection of binaries like GW150914 with 3 times higher SNR. Additionally, Advanced Virgo, KAGRA, and a possible third LIGO detector in India [118] will extend the network and significantly improve the position reconstruction and parameter estimation of sources.

VIII. CONCLUSION

The LIGO detectors have observed gravitational waves from the merger of two stellar-mass black holes. The detected waveform matches the predictions of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

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[1] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. **1**, 688 (1916).
[2] A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. **1**, 154 (1918).
[3] P. R. Saulson, Gen. Relativ. Gravit. **43**, 3289 (2011).
[4] K. Schwarzschild, Sitzungsber. K. Preuss. Akad. Wiss. **1**, 189 (1916).
[5] D. Finkelstein, Phys. Rev. **110**, 965 (1958).
[6] M. D. Kruskal, Phys. Rev. **119**, 1743 (1960).
[7] R. P. Kerr, Phys. Rev. Lett. **11**, 237 (1963).
[8] C. V. Vishveshwara, Nature (London) **227**, 936 (1970).
[9] W. H. Press, Astrophys. J. **170**, L105 (1971).
[10] S. Chandrasekhar and S. L. Detweiler, Proc. R. Soc. A **344**, 441 (1975).
[11] L. Blanchet, T. Damour, B. R. Iyer, C. M. Will, and A. G. Wiseman, Phys. Rev. Lett. **74**, 3515 (1995).
[12] L. Blanchet, Living Rev. Relativity **17**, 2 (2014).
[13] A. Buonanno and T. Damour, Phys. Rev. D **59**, 084006 (1999).
[14] F. Pretorius, Phys. Rev. Lett. **95**, 121101 (2005).
[15] M. Campanelli, C. O. Lousto, P. Marronetti, and Y. Zlochower, Phys. Rev. Lett. **96**, 111101 (2006).
[16] J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, and J. van Meter, Phys. Rev. Lett. **96**, 111102 (2006).
[17] B. L. Webster and P. Murdin, Nature (London) **235**, 37 (1972).
[18] C. T. Bolton, Nature (London) **240**, 124 (1972).
[19] J. Casares and P. G. Jonker, Space Sci. Rev. **183**, 223 (2014).
[20] R. A. Hulse and J. H. Taylor, Astrophys. J. **195**, L51 (1975).
[21] J. H. Taylor and J. M. Weisberg, Astrophys. J. **253**, 908 (1982).
[22] W. Press and K. Thorne, Annu. Rev. Astron. Astrophys. **10**, 335 (1972).
[23] J. Weber, Phys. Rev. **117**, 306 (1960).
[24] P. Astone *et al.*, Phys. Rev. D **82**, 022003 (2010).
[25] M. E. Gertsenshtein and V. I. Pustovoit, Sov. Phys. JETP **16**, 433 (1962).
[26] G. E. Moss, L. R. Miller, and R. L. Forward, Appl. Opt. **10**, 2495 (1971).
[27] R. Weiss, Electromagnetically coupled broadband gravitational antenna, Quarterly Report of the Research Laboratory for Electronics, MIT Report No. 105, 1972, https://dcc.ligo.org/LIGO-P720002/public/main.
[28] R. W. P. Drever, in *Gravitational Radiation*, edited by N. Deruelle and T. Piran (North-Holland, Amsterdam, 1983), p. 321.
[29] R. W. P. Drever, F. J. Raab, K. S. Thorne, R. Vogt, and R. Weiss, Laser Interferometer Gravitational-wave Observatory (LIGO) Technical Report, 1989, https://dcc.ligo.org/LIGO-M890001/public/main.
[30] A. Abramovici *et al.*, Science **256**, 325 (1992).
[31] A. Brillet, A. Giazotto *et al.*, Virgo Project Technical Report No. VIR-0517A-15, 1989, https://tds.ego-gw.it/ql/?c=11247.
[32] J. Hough *et al.*, Proposal for a joint German-British interferometric gravitational wave detector, MPQ Technical Report 147, No. GWD/137/JH(89), 1989, http://eprints.gla.ac.uk/114852.
[33] J. Aasi *et al.*, Classical Quantum Gravity **32**, 074001 (2015).
[34] F. Acernese *et al.*, Classical Quantum Gravity **32**, 024001 (2015).
[35] C. Affeldt *et al.*, Classical Quantum Gravity **31**, 224002 (2014).
[36] Y. Aso, Y. Michimura, K. Somiya, M. Ando, O. Miyakawa, T. Sekiguchi, D. Tatsumi, and H. Yamamoto, Phys. Rev. D **88**, 043007 (2013).
[37] The waveform shown is SXS:BBH:0305, available for download at http://www.black-holes.org/waveforms.
[38] A. H. Mroué *et al.*, Phys. Rev. Lett. **111**, 241104 (2013).
[39] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500218/public/main.
[40] N. J. Cornish and T. B. Littenberg, Classical Quantum Gravity **32**, 135012 (2015).
[41] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500229/public/main.
[42] S. Chatterji, L. Blackburn, G. Martin, and E. Katsavounidis, Classical Quantum Gravity **21**, S1809 (2004).
[43] S. Klimenko *et al.*, arXiv:1511.05999 [Phys. Rev. D (to be published)].
[44] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500269/public/main.
[45] S. A. Usman *et al.*, arXiv:1508.02357.
[46] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500227/public/main.
[47] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500237/public/main.
[48] R. W. P. Drever, *The Detection of Gravitational Waves*, edited by D. G. Blair (Cambridge University Press, Cambridge, England, 1991).
[49] R. W. P. Drever *et al.*, in *Quantum Optics, Experimental Gravity, and Measurement Theory*, edited by P. Meystre and M. O. Scully, NATO ASI, Ser. B, Vol. 94 (Plenum Press, New York, 1983), pp. 503–514.
[50] R. Schilling (unpublished).
[51] B. J. Meers, Phys. Rev. D **38**, 2317 (1988).

[52] J. Mizuno, K. A. Strain, P. G. Nelson, J. M. Chen, R. Schilling, A. Rüdiger, W. Winkler, and K. Danzmann, Phys. Lett. A **175**, 273 (1993).
[53] P. Kwee *et al.*, Opt. Express **20**, 10617 (2012).
[54] C. L. Mueller *et al.*, Rev. Sci. Instrum. **87**, 014502 (2016).
[55] T. T. Fricke *et al.*, Classical Quantum Gravity **29**, 065005 (2012).
[56] S. M. Aston *et al.*, Classical Quantum Gravity **29**, 235004 (2012).
[57] F. Matichard *et al.*, Classical Quantum Gravity **32**, 185003 (2015).
[58] G. M. Harry *et al.*, Classical Quantum Gravity **24**, 405 (2007).
[59] M. Granata *et al.*, Phys. Rev. D **93**, 012007 (2016).
[60] A. V. Cumming *et al.*, Classical Quantum Gravity **29**, 035003 (2012).
[61] A. Staley *et al.*, Classical Quantum Gravity **31**, 245010 (2014).
[62] L. Barsotti, M. Evans, and P. Fritschel, Classical Quantum Gravity **27**, 084026 (2010).
[63] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500248/public/main.
[64] E. Goetz *et al.*, in *Gravitational Waves: Proceedings, of the 8th Edoardo Amaldi Conference, Amaldi, New York, 2009*; E. Goetz and R. L. Savage Jr., Classical Quantum Gravity **27**, 084024 (2010).
[65] A. Effler, R. M. S. Schofield, V. V. Frolov, G. González, K. Kawabe, J. R. Smith, J. Birch, and R. McCarthy, Classical Quantum Gravity **32**, 035017 (2015).
[66] I. Bartos, R. Bork, M. Factourovich, J. Heefner, S. Márka, Z. Márka, Z. Raics, P. Schwinberg, and D. Sigg, Classical Quantum Gravity **27**, 084025 (2010).
[67] J. Aasi *et al.*, Classical Quantum Gravity **32**, 115012 (2015).
[68] J. Aasi *et al.*, Phys. Rev. D **87**, 022002 (2013).
[69] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500238/public/main.
[70] L. Nuttall *et al.*, Classical Quantum Gravity **32**, 245005 (2015).
[71] L. Lyons, Ann. Appl. Stat. **2**, 887 (2008).
[72] S. Klimenko, I. Yakushin, A. Mercer, and G. Mitselmakher, Classical Quantum Gravity **25**, 114029 (2008).
[73] R. Lynch, S. Vitale, R. Essick, E. Katsavounidis, and F. Robinet, arXiv:1511.05955.
[74] J. Kanner, T. B. Littenberg, N. Cornish, M. Millhouse, E. Xhakaj, F. Salemi, M. Drago, G. Vedovato, and S. Klimenko, Phys. Rev. D **93**, 022002 (2016).
[75] A. Buonanno and T. Damour, Phys. Rev. D **62**, 064015 (2000).
[76] L. Blanchet, T. Damour, G. Esposito-Farèse, and B. R. Iyer, Phys. Rev. Lett. **93**, 091101 (2004).
[77] A. Taracchini *et al.*, Phys. Rev. D **89**, 061502 (2014).
[78] M. Pürrer, Classical Quantum Gravity **31**, 195010 (2014).
[79] B. Allen, W. G. Anderson, P. R. Brady, D. A. Brown, and J. D. E. Creighton, Phys. Rev. D **85**, 122006 (2012).
[80] B. S. Sathyaprakash and S. V. Dhurandhar, Phys. Rev. D **44**, 3819 (1991).
[81] B. J. Owen and B. S. Sathyaprakash, Phys. Rev. D **60**, 022002 (1999).
[82] B. Allen, Phys. Rev. D **71**, 062001 (2005).
[83] J. Abadie *et al.*, Phys. Rev. D **85**, 082002 (2012).
[84] S. Babak *et al.*, Phys. Rev. D **87**, 024033 (2013).
[85] K. Cannon *et al.*, Astrophys. J. **748**, 136 (2012).
[86] S. Privitera, S. R. P. Mohapatra, P. Ajith, K. Cannon, N. Fotopoulos, M. A. Frei, C. Hanna, A. J. Weinstein, and J. T. Whelan, Phys. Rev. D **89**, 024003 (2014),
[87] M. Hannam, P. Schmidt, A. Bohé, L. Haegel, S. Husa, F. Ohme, G. Pratten, and M. Pürrer, Phys. Rev. Lett. **113**, 151101 (2014).
[88] S. Khan, S. Husa, M. Hannam, F. Ohme, M. Pürrer, X. Jiménez Forteza, and A. Bohé, Phys. Rev. D **93**, 044007 (2016).
[89] J. Veitch *et al.*, Phys. Rev. D **91**, 042003 (2015).
[90] A. Krolak and B. F. Schutz, Gen. Relativ. Gravit. **19**, 1163 (1987).
[91] P. A. R. Ade *et al.*, arXiv:1502.01589.
[92] J. Healy, C. O. Lousto, and Y. Zlochower, Phys. Rev. D **90**, 104004 (2014).
[93] S. Husa, S. Khan, M. Hannam, M. Pürrer, F. Ohme, X. Jiménez Forteza, and A. Bohé, Phys. Rev. D **93**, 044006 (2016).
[94] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500213/public/main.
[95] C. K. Mishra, K. G. Arun, B. R. Iyer, and B. S. Sathyaprakash, Phys. Rev. D **82**, 064010 (2010).
[96] T. G. F. Li, W. Del Pozzo, S. Vitale, C. Van Den Broeck, M. Agathos, J. Veitch, K. Grover, T. Sidery, R. Sturani, and A. Vecchio, Phys. Rev. D **85**, 082003 (2012),
[97] C. M. Will, Phys. Rev. D **57**, 2061 (1998).
[98] C. Talmadge, J. P. Berthias, R. W. Hellings, and E. M. Standish, Phys. Rev. Lett. **61**, 1159 (1988).
[99] L. S. Finn and P. J. Sutton, Phys. Rev. D **65**, 044022 (2002).
[100] A. S. Goldhaber and M. M. Nieto, Phys. Rev. D **9**, 1119 (1974).
[101] S. Choudhury and S. SenGupta, Eur. Phys. J. C **74**, 3159 (2014).
[102] A. Tutukov and L. Yungelson, Nauchnye Informatsii **27**, 70 (1973).
[103] V. M. Lipunov, K. A. Postnov, and M. E. Prokhorov, Mon. Not. R. Astron. Soc. **288**, 245 (1997).
[104] K. Belczynski, S. Repetto, D. Holz, R. O'Shaughnessy, T. Bulik, E. Berti, C. Fryer, M. Dominik, arXiv:1510.04615 [Astrophys. J. (to be published)].
[105] S. Sigurdsson and L. Hernquist, Nature (London) **364**, 423 (1993).
[106] S. F. Portegies Zwart and S. L. W. McMillan, Astrophys. J. Lett. **528**, L17 (2000).
[107] C. L. Rodriguez, M. Morscher, B. Pattabiraman, S. Chatterjee, C.-J. Haster, and F. A. Rasio, Phys. Rev. Lett. **115**, 051101 (2015),
[108] K. Belczynski, T. Bulik, C. L. Fryer, A. Ruiter, F. Valsecchi, J. S. Vink, and J. R. Hurley, Astrophys. J. **714**, 1217 (2010).
[109] M. Spera, M. Mapelli, and A. Bressan, Mon. Not. R. Astron. Soc. **451**, 4086 (2015).
[110] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500262/public/main [Astrophys. J. Lett. (to be published)].
[111] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500217/public/main.

[112] C. Kim, V. Kalogera, and D. R. Lorimer, Astrophys. J. **584**, 985 (2003).
[113] W. M. Farr, J. R. Gair, I. Mandel, and C. Cutler, Phys. Rev. D **91**, 023005 (2015).
[114] J. Abadie *et al.*, Classical Quantum Gravity **27**, 173001 (2010).
[115] B. Abbott *et al.*, https://dcc.ligo.org/LIGO-P1500222/public/main.
[116] LIGO Open Science Center (LOSC), https://losc.ligo.org/events/GW150914/.
[117] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Living Rev. Relativity **19**, 1 (2016).
[118] B. Iyer *et al.*, LIGO-India Technical Report No. LIGO-M1100296, 2011, https://dcc.ligo.org/LIGO-M1100296/public/main.

B. P. Abbott,[1] R. Abbott,[1] T. D. Abbott,[2] M. R. Abernathy,[1] F. Acernese,[3,4] K. Ackley,[5] C. Adams,[6] T. Adams,[7] P. Addesso,[3] R. X. Adhikari,[1] V. B. Adya,[8] C. Affeldt,[8] M. Agathos,[9] K. Agatsuma,[9] N. Aggarwal,[10] O. D. Aguiar,[11] L. Aiello,[12,13] A. Ain,[14] P. Ajith,[15] B. Allen,[8,16,17] A. Allocca,[18,19] P. A. Altin,[20] S. B. Anderson,[1] W. G. Anderson,[16] K. Arai,[1] M. A. Arain,[5] M. C. Araya,[1] C. C. Arceneaux,[21] J. S. Areeda,[22] N. Arnaud,[23] K. G. Arun,[24] S. Ascenzi,[25,13] G. Ashton,[26] M. Ast,[27] S. M. Aston,[6] P. Astone,[28] P. Aufmuth,[8] C. Aulbert,[8] S. Babak,[29] P. Bacon,[30] M. K. M. Bader,[9] P. T. Baker,[31] F. Baldaccini,[32,33] G. Ballardin,[34] S. W. Ballmer,[35] J. C. Barayoga,[1] S. E. Barclay,[36] B. C. Barish,[1] D. Barker,[37] F. Barone,[3,4] B. Barr,[36] L. Barsotti,[10] M. Barsuglia,[30] D. Barta,[38] J. Bartlett,[37] M. A. Barton,[37] I. Bartos,[39] R. Bassiri,[40] A. Basti,[18,19] J. C. Batch,[37] C. Baune,[8] V. Bavigadda,[34] M. Bazzan,[41,42] B. Behnke,[29] M. Bejger,[43] C. Belczynski,[44] A. S. Bell,[36] C. J. Bell,[36] B. K. Berger,[1] J. Bergman,[37] G. Bergmann,[8] C. P. L. Berry,[45] D. Bersanetti,[46,47] A. Bertolini,[9] J. Betzwieser,[6] S. Bhagwat,[35] R. Bhandare,[48] I. A. Bilenko,[49] G. Billingsley,[1] J. Birch,[6] R. Birney,[50] O. Birnholtz,[8] S. Biscans,[10] A. Bisht,[8,17] M. Bitossi,[34] C. Biwer,[35] M. A. Bizouard,[23] J. K. Blackburn,[1] C. D. Blair,[51] D. G. Blair,[51] R. M. Blair,[37] S. Bloemen,[52] O. Bock,[8] T. P. Bodiya,[10] M. Boer,[53] G. Bogaert,[53] C. Bogan,[8] A. Bohe,[29] P. Bojtos,[54] C. Bond,[45] F. Bondu,[55] R. Bonnand,[7] B. A. Boom,[9] R. Bork,[1] V. Boschi,[18,19] S. Bose,[56,14] Y. Bouffanais,[30] A. Bozzi,[34] C. Bradaschia,[19] P. R. Brady,[16] V. B. Braginsky,[49] M. Branchesi,[57,58] J. E. Brau,[59] T. Briant,[60] A. Brillet,[53] M. Brinkmann,[8] V. Brisson,[23] P. Brockill,[16] A. F. Brooks,[1] D. A. Brown,[35] D. D. 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Coccia,[25,12,13] P.-F. Cohadon,[60] A. Colla,[79,28] C. G. Collette,[80] L. Cominsky,[81] M. Constancio Jr.,[11] A. Conte,[79,28] L. Conti,[42] D. Cook,[37] T. R. Corbitt,[2] N. Cornish,[31] A. Corsi,[71] S. Cortese,[34] C. A. Costa,[11] M. W. Coughlin,[78] S. B. Coughlin,[82] J.-P. Coulon,[53] S. T. Countryman,[39] P. Couvares,[1] E. E. Cowan,[63] D. M. Coward,[51] M. J. Cowart,[6] D. C. Coyne,[1] R. Coyne,[71] K. Craig,[36] J. D. E. Creighton,[16] T. D. Creighton,[83] J. Cripe,[2] S. G. Crowder,[84] A. M. Cruise,[45] A. Cumming,[36] L. Cunningham,[36] E. Cuoco,[34] T. Dal Canton,[8] S. L. Danilishin,[36] S. D'Antonio,[13] K. Danzmann,[17,8] N. S. Darman,[85] C. F. Da Silva Costa,[5] V. Dattilo,[34] I. Dave,[48] H. P. Daveloza,[83] M. Davier,[23] G. S. Davies,[36] E. J. Daw,[86] R. Day,[34] S. De,[35] D. DeBra,[40] G. Debreczeni,[38] J. Degallaix,[65] M. De Laurentis,[67,4] S. Deléglise,[60] W. Del Pozzo,[45] T. Denker,[8,17] T. Dent,[8] H. Dereli,[53] V. Dergachev,[1] R. T. DeRosa,[6] R. De Rosa,[67,4] R. DeSalvo,[87] S. Dhurandhar,[14] M. C. Díaz,[83] L. Di Fiore,[4] M. Di Giovanni,[79,28] A. Di Lieto,[18,19] S. Di Pace,[79,28] I. Di Palma,[29,8] A. Di Virgilio,[19] G. Dojcinoski,[88] V. Dolique,[65] F. Donovan,[10] K. L. Dooley,[21] S. Doravari,[6,8] R. Douglas,[36] T. P. Downes,[16] M. Drago,[8,89,90] R. W. P. Drever,[1] J. C. Driggers,[37] Z. Du,[70] M. Ducrot,[7] S. E. Dwyer,[37] T. B. Edo,[86] M. C. Edwards,[78] A. Effler,[6] H.-B. Eggenstein,[8] P. Ehrens,[1] J. Eichholz,[5] S. S. Eikenberry,[5] W. Engels,[76] R. C. Essick,[10] T. Etzel,[1] M. Evans,[10] T. M. Evans,[6] R. Everett,[72] M. Factourovich,[39] V. Fafone,[25,13,12] H. Fair,[35] S. Fairhurst,[91] X. Fan,[70] Q. Fang,[51] S. Farinon,[47] B. Farr,[75] W. M. Farr,[45] M. Favata,[88] M. Fays,[91] H. Fehrmann,[8] M. M. Fejer,[40] D. Feldbaum,[5] I. Ferrante,[18,19] E. C. Ferreira,[11] F. Ferrini,[34] F. Fidecaro,[18,19] L. S. Finn,[72] I. Fiori,[34] D. Fiorucci,[30] R. P. Fisher,[35] R. Flaminio,[65,92] M. Fletcher,[36] H. Fong,[69] J.-D. Fournier,[53] S. Franco,[23] S. Frasca,[79,28] F. Frasconi,[19] M. Frede,[8] Z. Frei,[54] A. Freise,[45] R. Frey,[59] V. Frey,[23] T. T. Fricke,[8] P. Fritschel,[10] V. V. Frolov,[6] P. Fulda,[5] M. Fyffe,[6] H. A. G. Gabbard,[21] J. R. Gair,[93] L. Gammaitoni,[32,33] S. G. Gaonkar,[14] F. Garufi,[67,4] A. Gatto,[30] G. Gaur,[94,95]

N. Gehrels,[68] G. Gemme,[47] B. Gendre,[53] E. Genin,[34] A. Gennai,[19] J. George,[48] L. Gergely,[96] V. Germain,[7] Abhirup Ghosh,[15] Archisman Ghosh,[15] S. Ghosh,[52,9] J. A. Giaime,[2,6] K. D. Giardina,[6] A. Giazotto,[19] K. Gill,[97] A. Glaefke,[36] J. R. Gleason,[5] E. Goetz,[98] R. Goetz,[5] L. Gondan,[54] G. González,[2] J. M. Gonzalez Castro,[18,19] A. Gopakumar,[99] N. A. Gordon,[36] M. L. Gorodetsky,[49] S. E. Gossan,[1] M. Gosselin,[34] R. Gouaty,[7] C. Graef,[36] P. B. Graff,[62] M. Granata,[65] A. Grant,[36] S. Gras,[10] C. Gray,[37] G. Greco,[57,58] A. C. Green,[45] R. J. S. Greenhalgh,[100] P. Groot,[52] H. Grote,[8] S. Grunewald,[29] G. M. Guidi,[57,58] X. Guo,[70] A. Gupta,[14] M. K. Gupta,[95] K. E. Gushwa,[1] E. K. Gustafson,[1] R. Gustafson,[98] J. J. Hacker,[22] B. R. Hall,[56] E. D. Hall,[1] G. Hammond,[36] M. Haney,[99] M. M. Hanke,[8] J. Hanks,[37] C. Hanna,[72] M. D. Hannam,[91] J. Hanson,[6] T. Hardwick,[2] J. Harms,[57,58] G. M. Harry,[101] I. W. Harry,[29] M. J. Hart,[36] M. T. Hartman,[5] C.-J. Haster,[45] K. Haughian,[36] J. Healy,[102] J. Heefner,[1,a] A. Heidmann,[60] M. C. Heintze,[5,6] G. Heinzel,[8] H. Heitmann,[53] P. Hello,[23] G. Hemming,[34] M. Hendry,[36] I. S. Heng,[36] J. Hennig,[36] A. W. Heptonstall,[1] M. Heurs,[8,17] S. Hild,[36] D. Hoak,[103] K. A. Hodge,[1] D. Hofman,[65] S. E. Hollitt,[104] K. Holt,[6] D. E. Holz,[75] P. Hopkins,[91] D. J. Hosken,[104] J. Hough,[36] E. A. Houston,[36] E. J. Howell,[51] Y. M. Hu,[36] S. Huang,[73] E. A. Huerta,[105,82] D. Huet,[23] B. Hughey,[97] S. Husa,[66] S. H. Huttner,[36] T. Huynh-Dinh,[6] A. Idrisy,[72] N. Indik,[8] D. R. Ingram,[37] R. Inta,[71] H. N. Isa,[36] J.-M. Isac,[60] M. Isi,[1] G. Islas,[22] T. Isogai,[10] B. R. Iyer,[15] K. Izumi,[37] M. B. Jacobson,[1] T. Jacqmin,[60] H. Jang,[77] K. Jani,[63] P. Jaranowski,[106] S. Jawahar,[107] F. Jiménez-Forteza,[66] W. W. Johnson,[2] N. K. Johnson-McDaniel,[15] D. I. Jones,[26] R. Jones,[36] R. J. G. Jonker,[9] L. Ju,[51] K. Haris,[108] C. V. Kalaghatgi,[24,91] V. Kalogera,[82] S. Kandhasamy,[21] G. Kang,[77] J. B. Kanner,[1] S. Karki,[59] M. Kasprzack,[2,23,34] E. Katsavounidis,[10] W. Katzman,[6] S. Kaufer,[17] T. Kaur,[51] K. Kawabe,[37] F. Kawazoe,[8,17] F. Kéfélian,[53] M. S. Kehl,[69] D. Keitel,[8,66] D. B. Kelley,[35] W. Kells,[1] R. Kennedy,[86] D. G. Keppel,[8] J. S. Key,[83] A. Khalaidovski,[8] F. Y. Khalili,[49] I. Khan,[12] S. Khan,[91] Z. Khan,[95] E. A. Khazanov,[109] N. Kijbunchoo,[37] C. Kim,[77] J. Kim,[110] K. Kim,[111] Nam-Gyu Kim,[77] Namjun Kim,[40] Y.-M. Kim,[110] E. J. King,[104] P. J. King,[37] D. L. Kinzel,[6] J. S. Kissel,[37] L. Kleybolte,[27] S. Klimenko,[5] S. M. Koehlenbeck,[8] K. Kokeyama,[2] S. Koley,[9] V. Kondrashov,[1] A. Kontos,[10] S. Koranda,[16] M. Korobko,[27] W. Z. Korth,[1] I. Kowalska,[44] D. B. Kozak,[1] V. Kringel,[8] B. Krishnan,[8] A. Królak,[112,113] C. Krueger,[17] G. Kuehn,[8] P. Kumar,[69] R. Kumar,[36] L. Kuo,[73] A. Kutynia,[112] P. Kwee,[8] B. D. Lackey,[35] M. Landry,[37] J. Lange,[102] B. Lantz,[40] P. D. Lasky,[114] A. Lazzarini,[1] C. Lazzaro,[63,42] P. Leaci,[29,79,28] S. Leavey,[36] E. O. Lebigot,[30,70] C. H. Lee,[110] H. K. Lee,[111] H. M. Lee,[115] K. Lee,[36] A. Lenon,[35] M. Leonardi,[89,90] J. R. Leong,[8] N. Leroy,[23] N. Letendre,[7] Y. Levin,[114] B. M. Levine,[37] T. G. F. Li,[1] A. Libson,[10] T. B. Littenberg,[116] N. A. Lockerbie,[107] J. Logue,[36] A. L. Lombardi,[103] L. T. London,[91] J. E. Lord,[35] M. Lorenzini,[12,13] V. Loriette,[117] M. Lormand,[6] G. Losurdo,[58] J. D. Lough,[8,17] C. O. Lousto,[102] G. Lovelace,[22] H. Lück,[17,8] A. P. Lundgren,[8] J. Luo,[78] R. Lynch,[10] Y. Ma,[51] T. MacDonald,[40] B. Machenschalk,[8] M. MacInnis,[10] D. M. Macleod,[2] F. Magaña-Sandoval,[35] R. M. Magee,[56] M. Mageswaran,[1] E. Majorana,[28] I. Maksimovic,[117] V. Malvezzi,[25,13] N. Man,[53] I. Mandel,[45] V. Mandic,[84] V. Mangano,[36] G. L. Mansell,[20] M. Manske,[16] M. Mantovani,[34] F. 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[a]Deceased, April 2012.
[b]Deceased, May 2015.
[c]Deceased, March 2015.

VIEWPOINT

The First Sounds of Merging Black Holes

Gravitational waves emitted by the merger of two black holes have been detected, setting the course for a new era of observational astrophysics.

by Emanuele Berti*,†

For decades, scientists have hoped they could "listen in" on violent astrophysical events by detecting their emission of gravitational waves. The waves, which can be described as oscillating distortions in the geometry of spacetime, were first predicted to exist by Einstein in 1916, but they have never been observed directly. Now, in an extraordinary paper, scientists report that they have detected the waves at the Laser Interferometer Gravitational-wave Observatory (LIGO) [1]. From an analysis of the signal, researchers from LIGO in the US, and their collaborators from the Virgo interferometer in Italy, infer that the gravitational waves were produced by the inspiral and merger of two black holes (Fig. 1), each with a mass that is more than 25 times greater than that of our Sun. Their finding provides the first observational evidence that black hole binary systems can form and merge in the Universe.

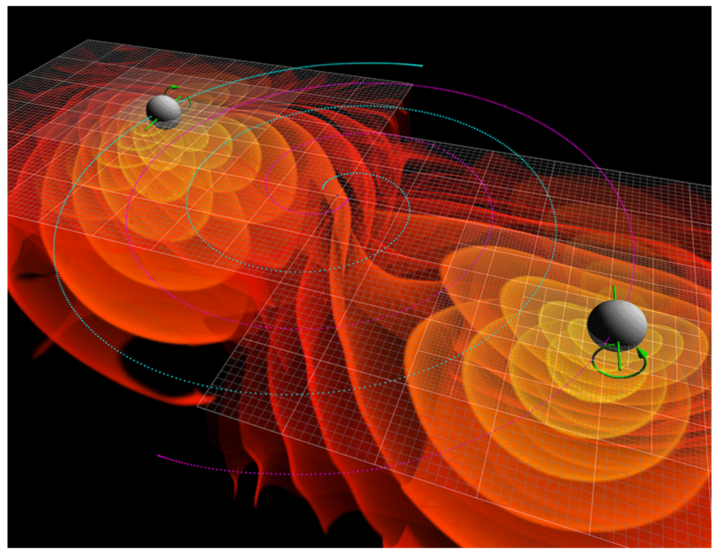

Figure 1: Numerical simulations of the gravitational waves emitted by the inspiral and merger of two black holes. The colored contours around each black hole represent the amplitude of the gravitational radiation; the blue lines represent the orbits of the black holes and the green arrows represent their spins. (C. Henze/NASA Ames Research Center)

Gravitational waves are produced by moving masses, and like electromagnetic waves, they travel at the speed of light. As they travel, the waves squash and stretch spacetime in the plane perpendicular to their direction of propagation (see inset, Video 1). Detecting them, however, is exceptionally hard because they induce very small distortions: even the strongest gravitational waves from astrophysical events are only expected to produce relative length variations of order 10^{-21}.

"Advanced" LIGO, as the recently upgraded version of the experiment is called, consists of two detectors, one in Hanford, Washington, and one in Livingston, Louisiana. Each detector is a Michelson interferometer, consisting of two 4-km-long optical cavities, or "arms," that are arranged in an L shape. The interferometer is designed so that, in the absence of gravitational waves, laser beams traveling in the two arms arrive at a photodetector exactly 180° out of phase, yielding no signal. A gravitational wave propagating perpendicular to the detector plane disrupts this perfect destructive interference. During its first half-cycle, the wave will lengthen one arm and shorten the other; during its second half-cycle, these changes are reversed (see Video 1). These length variations alter the phase difference between the laser beams, allowing optical power—a signal—to reach the photodetector. With two such interferometers, LIGO can rule out spurious signals (from, say, a local seismic wave) that appear in one detector but not in the other.

LIGO's sensitivity is exceptional: it can detect length differences between the arms that are smaller than the size of an atomic nucleus. The biggest challenge for LIGO is detector noise, primarily from seismic waves, thermal motion, and photon shot noise. These disturbances can easily mask the small signal expected from gravitational waves.

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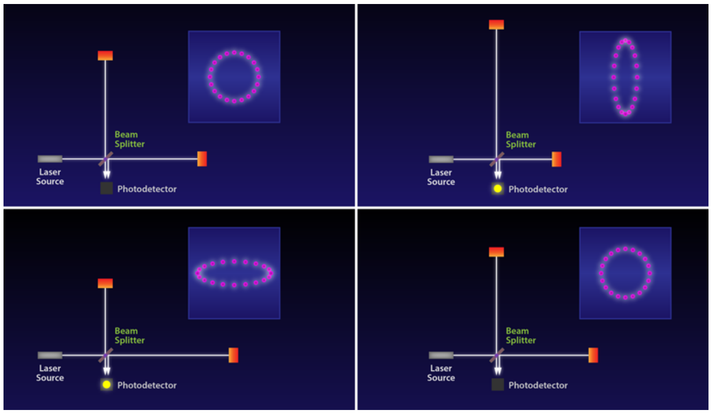

Video 1: (Animation appears online only.) A schematic depiction of LIGO's interferometric gravitational wave detector. Light from a laser is split in two by a beam splitter; one half travels down the vertical arm of the interferometer, the other half travels down the horizontal arm. The detector is designed so that in the absence of gravitational waves (top left) the light takes the same time to travel back and forth along the two arms and interferes destructively at the photodetector, producing no signal. As the wave passes (moving clockwise from top right) the travel times for the lasers change, and a signal appears in the photodetector. (The actual distortions are extremely small, but are exaggerated here for easier viewing.) Inset: The elongations in a ring of particles show the effects of a gravitational wave on spacetime. (APS/Alan Stonebraker)

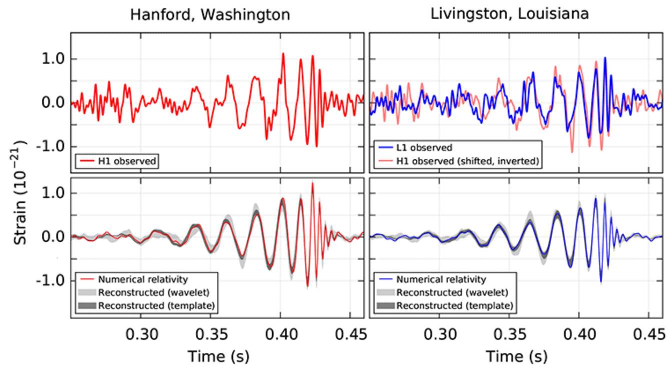

Figure 2: On September 14, 2015, similar signals were observed in both of LIGO's interferometers. The top panels show the measured signal in the Hanford (top left) and Livingston (top right) detectors. The bottom panels show the expected signal produced by the merger of two black holes, based on numerical simulations. (B. P. Abbott *et al.* [1].)

The upgrade, completed in 2015, improved the detector's sensitivity by a factor of 3–5 for waves in the 100–300 Hz frequency band and by more than a factor of 10 below 60 Hz. These improvements have enhanced the detector's sensitivity to more distant sources and were crucial to the discovery of gravitational waves.

On September 14, 2015, within the first two days of Advanced LIGO's operation, the researchers detected a signal so strong that it could be seen by eye (Fig. 2). The most intense portion of the signal lasted for about 0.2 s and was observed in both detectors, with a combined signal-to-noise ratio of 24. Fittingly, this first gravitational wave signal, dubbed GW150914, arrived less than two months before the 100-year anniversary of the publication of Einstein's general relativity theory.

Up until a few decades ago, detecting gravitational waves was considered an impossible task. In fact, in the 1950s, physicists were still heatedly debating whether the waves were actual physical entities and whether they could carry energy. The turning point was a 1957 conference in Chapel Hill, North Carolina [2, 3]. There, the theorist Felix Pirani pointed out a connection between Newton's second law and the equation of geodesic deviation, which describes the effect of tidal forces in general relativity. This connection allowed him to show that the relative accelerations of neighboring particles in the presence of a gravitational wave provide a physically meaningful—and measurable—way to observe it. Sadly, Pirani, who laid the groundwork for our modern thinking about gravitational waves and how to detect them, passed away on December 31, 2015, just weeks before the LIGO scientists announced their discovery.

Other prominent physicists at the meeting, including Joseph Weber, Richard Feynman, and Hermann Bondi, were instrumental in pushing Pirani's ideas forward. Feynman and Bondi, in particular, developed Pirani's observation into what is now known as the "sticky bead" thought experiment. They argued that if beads sliding on a sticky rod accelerated under the effect of a passing gravitational wave, then they must surely also transfer heat to the rod by friction. This heat transfer is proof that gravitational waves must indeed carry energy, and are therefore, in principle, detectable.

Interest in carrying out such experiments wasn't immediate. As Pirani noted in his 1964 lectures on gravitational radiation [4], Weber thought that meaningful laboratory experiments were "impossible by several orders of magnitude." At about the same time, William Fowler (the future Nobel laureate) suggested that a large fraction of the energy emitted by so-called massive double quasars—what we now know as black hole binaries—might be in the form of gravitational radiation. Pirani, however, felt that the direct observation of gravitational waves was not "necessary or sufficient" to justify a corresponding theory, arguing that unless physicists figured out a way to quantize gravity, such a theory would not "have much to do with physics" [4].

What galvanized the field was a 1969 paper from Weber, who claimed he had detected gravitational radiation with a resonant bar detector (see 22 December 2005 Focus story). The finding was controversial—physicists could not duplicate it and by the mid-1970s, most agreed that Weber had likely been incorrect. However, a few years later a young professor at the Massachusetts Institute of Technology named Rainer Weiss was preparing for his course on relativity when he came across a proposal by Pirani for detecting gravitational waves. Pirani had suggested using light signals to see the variations in the positions of neighboring particles when a wave passed. His idea, with one key modification, led to the genesis of LIGO: rather than using the timing of short light pulses, Weiss proposed to make phase measurements in a Michelson interferometer [5]. Ronald Drever, Kip Thorne, and many others made crucial contributions to developing this idea into what LIGO is today. (See Ref. [2] for a historical account.)

Now, what was once considered "impossible by several orders of magnitude" is a reality. To confirm the gravitational-wave nature of their signal, the researchers used two different data analysis methods. The first was to determine whether the excess power in the photodetector could be caused by a signal, given their best estimate of the noise, but without any assumptions about the origin of the signal itself. From this analysis, they could say that a transient, "unmodeled" signal was observed with a statistical significance greater than 4.6σ. The second method involved comparing the instrumental output (signal plus noise) with a theoretical signal from numerical simulations of merging black holes using general relativity. From this so-called matched-filtering search, the researchers concluded that the significance of the observation was greater than 5.1σ.

The most exciting conclusions come from comparing the observed signal's amplitude and phase with numerical relativity predictions, which allows the LIGO researchers to estimate parameters describing the gravitational-wave source. The waveform is consistent with a black hole binary system whose component masses are 36 and 29 times the mass of the Sun. These stellar-mass black holes—so named because they likely formed from collapsing stars—are the largest of their kind to have been observed. Moreover, no binary system other than black holes can have component masses large enough to explain the observed signal. (The most plausible competitors would be two neutron stars, or a black hole and a neutron star.) The binary is approximately 1.3 billion light years from Earth, or equivalently, at a luminosity distance of 400 megaparsecs (redshift of $z \sim 0.1$). The researchers estimate that about 4.6% of the binary's energy was radiated in gravitational waves, leading to a rotating black hole remnant with mass 62 times the mass of the Sun and dimensionless spin of 0.67.

From the signal, the researchers were also able to perform two consistency tests of general relativity and put a bound on the mass of the graviton—the hypothetical quantum particle that mediates gravity. In the first test, they used general relativity to estimate the black hole remnant's mass and spin from the pre-merger parameters. They then also determined the remnant's mass and spin from the oscillations in the wave produced by the final black hole [6]. They found that the values inferred from these oscillations agreed with those they had calculated. The second test was to analyze the phase of the wave generated by the black holes as they spiraled inward towards one another. This phase can be written as a series expansion in v/c, where v is the speed of the orbiting black holes, and the authors verified that the coefficients of this expansion were consistent with general relativity predictions. By assuming that a graviton with mass would modify the phase of the waves, they determined an upper bound on the particle's mass of 1.2×10^{-22} eV$/c^2$, improving the bounds from measurements in our Solar System and from observations of binary pulsars. These findings will be discussed in detail in later papers.

In physics, we live and breathe for discoveries like the one reported by LIGO, but the best is yet to come. As Kip Thorne recently said in a BBC interview, recording a gravitational wave for the first time was never LIGO's main goal. The motivation was always to open a new window onto the Universe.

Gravitational wave detection will allow new and more precise measurements of astrophysical sources. For example, the spins of two merging black holes hold clues to their formation mechanism. Although Advanced LIGO wasn't able to measure the magnitude of these spins very accurately, better measurements might be possible with improved models of the signal, better data analysis techniques, or more sensitive detectors. Once Advanced LIGO reaches design sensitivity, it should be capable of detecting binaries like the one that produced GW150914 with 3 times its current signal-to-noise ratio, allowing more accurate determinations of source parameters such as mass and spin.

The upcoming network of Earth-based detectors, comprising Advanced Virgo, KAGRA in Japan, and possibly a third LIGO detector in India, will help scientists determine the locations of sources in the sky. This would tell us where to aim "traditional" telescopes that collect electromagnetic radiation or neutrinos. Combining observational tools in this way would be the basis for a new research field, sometimes referred to as "multimessenger astronomy" [7]. Soon we will also collect the first results from LISA Pathfinder, a spacecraft experiment serving as a testbed for eLISA, a space-based interferometer. eLISA will enable us to peer deeper into the cosmos than ground-based detectors, allowing studies of the formation of more massive black holes and investigations of the strong-field behavior of gravity at cosmological distances [8].

With Advanced LIGO's result, we are entering the dawn of the age of gravitational wave astronomy: with this new tool, it is as though we are able to hear, when before we could only see. It is very significant that the first "sound" picked up by Advanced LIGO came from the merger of two black holes. These are objects we can't see with electromagnetic radiation. The implications of gravitational-wave astronomy for astrophysics in the near future are dazzling. Multiple detections will allow us to study how often black holes merge in the cosmos and to test astrophysical models that describe the formation of binary systems [9, 10]. In this respect, it's encouraging to note that LIGO may have already detected a second event; a very preliminary analysis suggests that if this event proves to have an astrophysical origin, then it is likely to also be from a black hole binary system. The detection of strong signals will also allow physicists to test the so-called no-hair theorem, which says that a black hole's structure and dynamics depend only on its mass and spin. Observing gravitational waves from black holes might also tell us about the nature of gravity. Does gravity really behave as predicted by Einstein in the vicinity of black holes, where the fields are very strong? Can dark energy and the acceleration of the Universe be explained if we modify Einstein's gravity? We are only just beginning to answer these questions [11, 12].

REFERENCES

[1] B. P. Abbott *et al.* (LIGO Scientific Collaboration and the Virgo Collaboration), "Observation of Gravitational Waves from a Binary Black Hole Merger," Phys. Rev. Lett. **116** (2016).

[2] D. Kennefick, Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves (Princeton University Press, Princeton), p. 2007.

[3] P. R. Saulson, "Josh Goldberg and the Physical Reality of Gravitational Waves," Gen. Relativ. Gravit. **43**, No. 12, 3289 (2011).

[4] F. A. E. Pirani, "Introduction to Gravitational Radiation Theory," in Lectures on General Relativity, 1964, Volume 1. Brandeis Summer Institute of Theoretical Physics, edited by A. Trautman, F. A. E. Pirani, and H. Bondi (Prentice-Hall, Englewood, NJ, 1965), p. 249-273.

[5] R. Weiss, "Electromagnetically Coupled Broadband Gravitational Antenna," Quarterly Progress Report of the MIT Research Laboratory of Electronics, No. 105, 54 (1972), available online at http://dspace.mit.edu/bitstream/handle/1721.1/56271/RLE_QPR_105_V.pdf.

[6] E. Berti, V. Cardoso, and A. O. Starinets, "Quasinormal Modes of Black Holes and Black Branes," Class. Quantum Grav. **26**, 163001 (2009).

[7] B. P. Abbott *et al.*, "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo," Living Rev. Relativity **19**, 1 (2016).

[8] Pau Amaro-Seoane *et al.*, "eLISA: Astrophysics and Cosmology in the Millihertz Regime," arXiv:1201.3621.

[9] M. Dominik, E. Berti, R. O'Shaughnessy, I. Mandel, K. Belczynski, C. Fryer, D. E. Holz, T. Bulik, and F. Pannarale, "Double Compact Objects. III. Gravitational-Wave Detection Rates," Astrophys. J. **806**, 263 (2015).

[10] S. Stevenson, F. Ohme, and S. Fairhurst, "Distinguishing Compact Binary Population Synthesis Models Using Gravitational Wave Observations of Coalescing Binary Black Holes," Astrophys. J. **810**, 58 (2015).

[11] N. Yunes and X. Siemens, "Gravitational-Wave Tests of General Relativity with Ground-Based Detectors and Pulsar-Timing Arrays," Living Rev. Relativity **16**, 9 (2013).

[12] E. Berti *et al.*, "Testing General Relativity with Present and Future Astrophysical Observations," Class. Quantum Grav. **32**, 243001 (2015).

10.1103/Physics.9.17