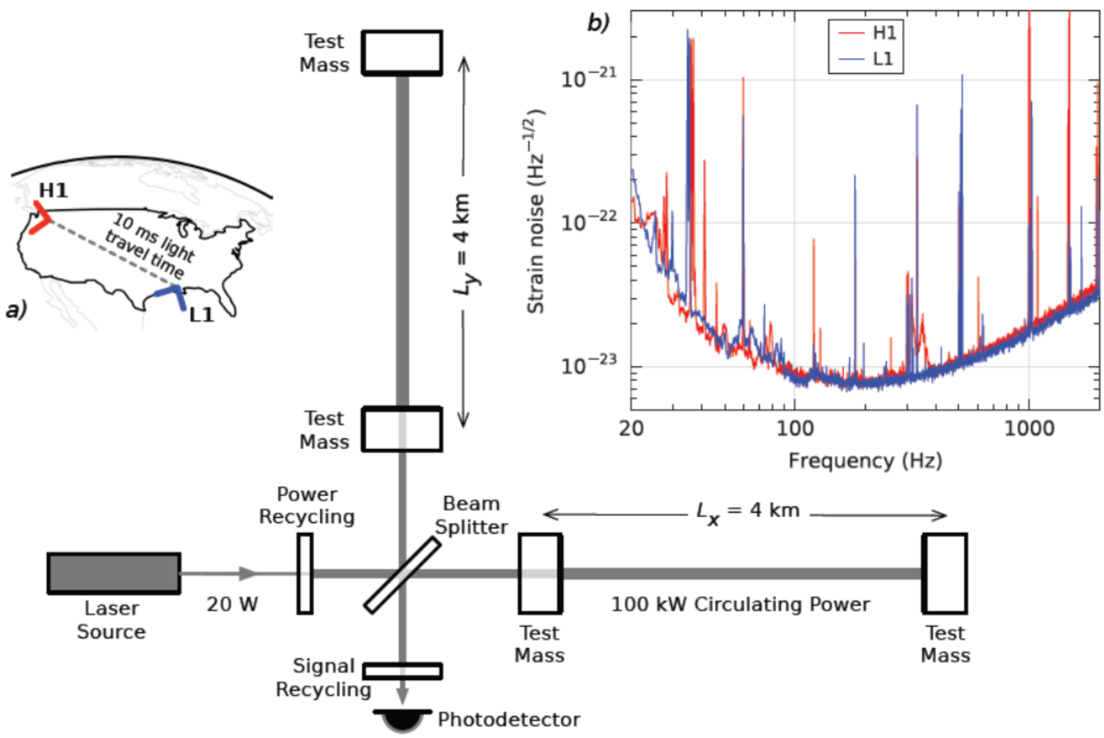
For the first time, scientists have observed ripples in the fabric of spacetime called gravitational waves, arriving at the earth from a cataclysmic event in the distant universe. This confirms a major prediction of Albert Einstein's 1915 general theory of relativity and opens an unprecedented new window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

Gravitational waves carry information about their dramatic origins and about the nature of gravity that cannot otherwise be obtained. 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 September 14, 2015 at 5:51 a.m. Eastern Daylight Time (9:51 UTC) by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington, USA. The LIGO Observatories are funded by the National Science Foundation (NSF), and were conceived, built, and are operated by Caltech and 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.

## How the detection happened

On Sept. 14, 2015, the LIGO Hanford, Wash., and Livingston, La, observatories detected the coincident signal referred to as GW150914. It was just past 4:50 a.m. in Livingston and just past 2:50 a.m. in Hanford, The signal arrived at Livingston about seven-thousandths of a second (0.007 seconds) before it reached Hanford. The initial detection was made by the online search program Coherent WaveBurst, which identifies generic gravitational wave transients in the LIGO data stream. The coincident detection was reported within three minutes of data acquisition.




Simplified diagram of the Advanced LIGO detector. The instrument is essentially an ultrasensitive laser rangefinder, measuring the difference in lengths of two 4-km optical cavities formed by mirror surfaces on the test masses in horizontal (x) and vertical (y) arms. An incident gravitational wave 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. Inset a: Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). Inset b: Instrumental noise versus the frequency of the wave. The detectors are most sensitive around 190 Hz (G below middle C).

The Advanced LIGO detectors construction was finished and accepted by the National Science Foundation in late 2014. An official dedication took place at Hanford in May 2015, transitioning the facilities from a construction project to functioning observatories. By August 2015, the two detectors were working well, only a bit short of their designed sensitivity (as is normal at the early stage of such a complex project).

The diagram above contains a graph of LIGO's sensitivity as a function of the frequency of the wave. The frequencies to which LIGO is sensitive are in the audio frequency range, 30 Hz to 4000 Hz, or B0 (third piano key from the bottom) to B8 (second from top).

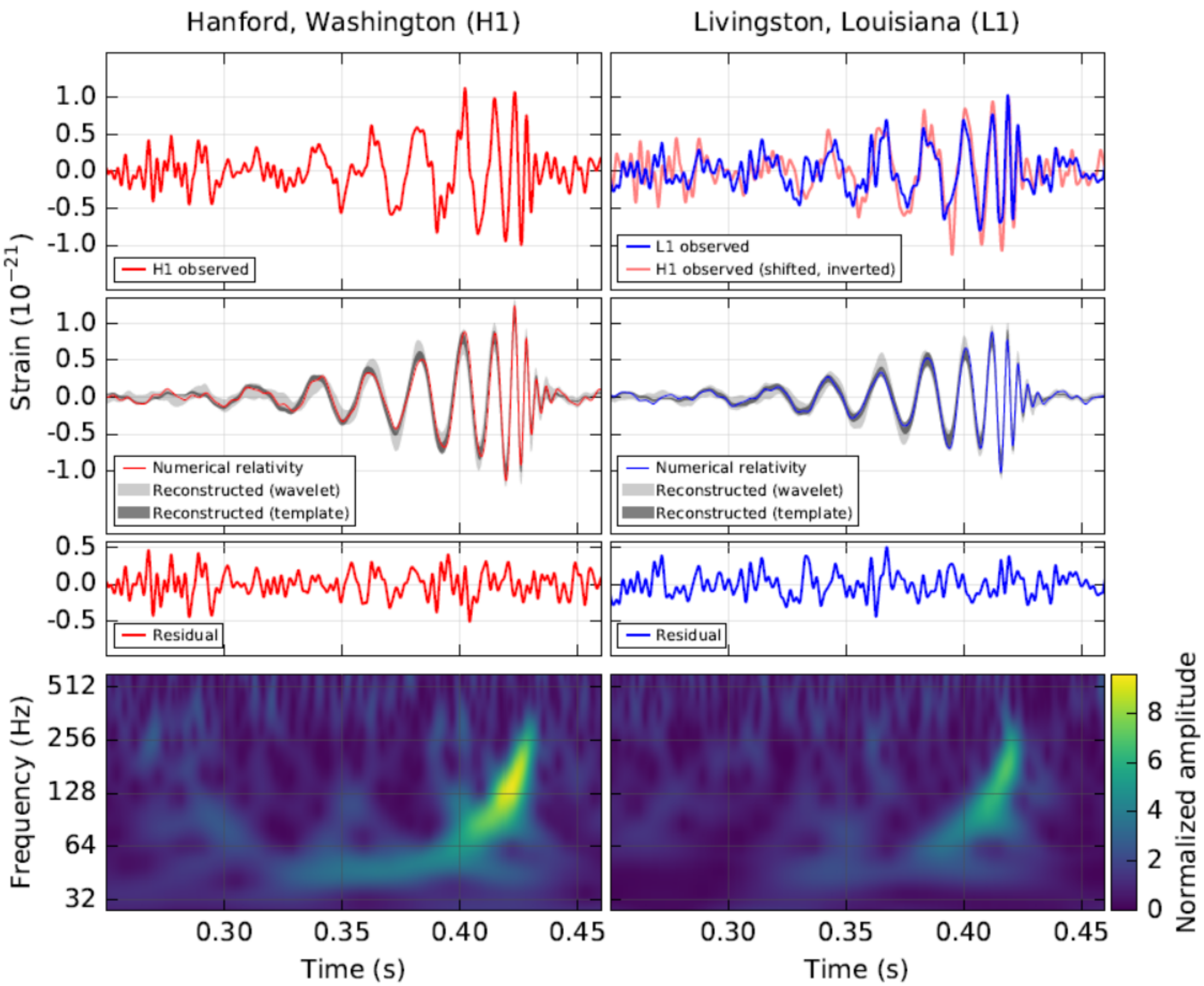
## Details of the detection

On Sept. 14, everything changed.

Even though the detectors were being operated in engineering rather than science mode, data were being recorded and an online analysis program (Coherent WaveBurst) was operating.

Two black holes, orbiting each other more than 20 times per second, emitted an oscillating force field that shook the mirrors by a tiny amount. The shaking was detected because of the sensitivity of the LIGO detectors. (They can detect mirror motions that are 10,000 times less than the diameter of a proton.) The signal shows the two black holes spiraling into each other, moving faster and faster, reaching more than 100 orbits per second. Then, they merged, forming a single, heavier, rapidly spinning black hole, ringing down to invisibility.

The diagram below shows for both observatories the measured signal, simulations using Einstein's theory of general relativity, the background noise, and a false color plot showing signal frequency as a function of time. The duration of the signal was only 0.12 seconds. The strain (the change of arm length divided by the arm length itself) was one part in $10^{21}$, meaning that the arm length changed by 4 attometers. (Atto is a unit prefix in the metric system meaning a factor of $10^{-18}$ or 0.000000000000000001.)




GW150914 (filtered with a 35–350 Hz band-pass filter) as observed by the LIGO Hanford (left) and Livingston (right) detectors. GW150914 arrived first at Livingston and about 0.007 second later at Hanford. Second row: Calculation by Einstein's theory of general relativity of the strain from the inspiral and coalescence of two black holes with mases 29 and 36 times the mass of our Sun. Third row: Background noise. Bottom row: A time-frequency representation of the strain data, showing the signal frequency increasing over time. The total duration of the event was about 0.12 seconds.

This event took place 1.3 billion years ago, long before any multicellular life started on Earth. The space-time ripple produced by this violent event spread out through space at the speed of light, while life on Earth became intelligent enough to build instruments capable of detecting it

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. The US National Science Foundation leads in financial support for 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 have been developed and tested by the German UK GEO collaboration. Significant computer resources have been 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 New York, and Louisiana State University.

## Einstein and gravitational waves

This discovery provides the capstone to Einstein's general theory of relativity. General relativity is a geometric theory of gravitation, expanding and extending Newton's theory of gravity. We know gravity as the force that attracts us to the ground under us, causes oranges to fall from the tree, and keeps the Earth and other planets in orbits around the Sun. Einstein's theory replaces Newton's forces with the notion that gravity is the result of the bending or warping of space-time. The equations of general relativity were first described (to the Prussian Academy of Sciences) by Einstein in November 1915. General relativity makes a number of predictions and most have been confirmed since the theory was published. These include the precession of the orbit of Mercury, gravitational lensing, supermassive black holes, and the warping of time, now an important correction built into global positioning systems. That the theory predicted the emission of gravitational waves by objects orbiting each other was proposed by Einstein in June 1916. The paper was in German, "Näherungsweise Integration der Feldgleichungen der Gravitation," or "Approximate integration of the field equations of gravitation." These waves have been invoked to explain the dynamics of a pulsar in orbit around another star but direct observation of them had up to now eluded physicists. With the observation and the publication of the paper, just under 100 years elapsed between the beginning of the theory and the first capture of gravitational waves. It also is the first evidence for relatively light black holes, ones that are only around 30 times as heavy as our Sun. Moreover, it is the first time two black holes have been seen in orbit around each other. This result will literally change the way we look at the universe.

## A worldwide collaboration

LIGO was originally proposed as a means of detecting these 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.

LIGO research is carried out by the LIGO Scientific Collaboration (LSC), a group of more than 1000 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.

Virgo research is carried out by the Virgo Collaboration, consisting of more than 250 physicists and engineers belonging to 19 different European research groups: 6 from Centre National de la Recherche Scientifique (CNRS) in France; 8 from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; 2 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.