News

ATOM & COSMOS

Physicists detect gravitational waves

LIGO experiment's discovery opens new window to the cosmos

BY ANDREW GRANT

WASHINGTON — Tremors in the cosmic fabric of space and time have finally been detected, opening a new avenue for exploring the universe.

The historic discovery of those tremors, known as gravitational waves, comes almost exactly a century after Albert Einstein first posited their existence. Researchers with the Advanced Laser Interferometer Gravitational-Wave Observatory, or Advanced LIGO, announced the seminal detection February 11 at a news conference and in a paper in *Physical Review Letters*. The gravitational swell originated more than 750 million light-years away, where the high-speed dance of two converging black holes shook the very foundation upon which planets, stars and galaxies reside.

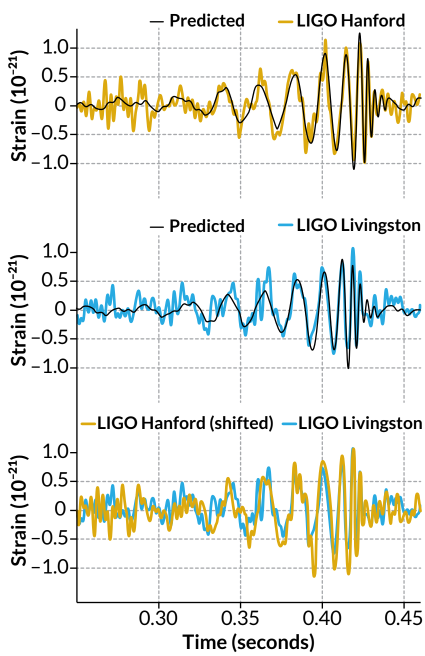
"It's the first time the universe has spoken to us through gravitational waves," LIGO laboratory executive director David Reitze said.

The discovery immediately becomes a likely candidate for a Nobel Prize, and not just because it ties a neat bow around decades of evidence supporting a major prediction of Einstein's 1915 general theory of relativity. "Gravitational waves allow us to look at the universe not just with light but with gravity," says astrophysicist Shane Larson of Northwestern University in Evanston, Ill. Gravitational waves can expose the gory details of black holes and other extreme phenomena that can't be obtained with traditional telescopes. With this discovery, the era of gravitational wave astronomy has begun.

The detection occurred September 14, 2015, four days before the official start of observations for the newly upgraded LIGO. Striking gold so quickly raises hopes for an impending flurry of sightings.

The fleeting burst of waves arrived on Earth long after two black holes, one about 36 times the mass of the sun and the other roughly 29, spiraled toward each other and coalesced. If Isaac Newton had been right about gravity, then the mass of the two black holes would have exerted an invisible force that pulled the objects together. But general relativity maintains that those black holes merged because their mass indented the fabric of space and time (*SN: 10/17/15, p. 16*). As the black holes drew near in a deepening pit of spacetime, they also churned up that fabric, emitting gravitational radiation (or gravity waves, as scientists often call them). Unlike more familiar kinds of waves, these gravitational ripples don't travel "through" space; they are vibrations of spacetime itself, propagating outward in all directions at the speed of light.

Nearly every instance of an object accelerating generates gravity waves — you produce feeble ones getting out of bed in the morning. Advanced LIGO is fine-tuned to home in on more detectable (and scientifically relevant) fare: waves emitted from regions where a lot of mass is packed into small spaces and moving very quickly. The colliding black holes certainly qualify. Their tremendous mass was packed into spheres about 150 kilometers in diameter. By the time the black holes experienced their final unifying plunge, they were circling each other at about half the speed of light. On September 14 at 4:50 a.m. Eastern time, the gravity waves emitted by the black holes during their last fractions of a second of independence encountered the two L-shaped LIGO detectors.



Clear signal The LIGO detectors registered nearly identical signals (top and middle) almost simultaneously as gravity waves from a black hole collision passed by the Earth. The signals closely match predictions.

LIGO's detectors in Hanford, Wash., and Livingston, La., newly reactivated after five years of upgrades, each consist of a powerful laser that splits into two perpendicular, 4-kilometer-long beams (see Page 22). When the gravitational waters of spacetime are calm, the beams recombine at the junction and cancel each other out — the troughs of one beam's 1,064-nanometer waves of laser light completely negate the crests of the second beam's waves.

But the gravitational disturbance from the black hole pair distorted spacetime, slightly squeezing one arm of the detector while stretching the other (*SN: 1/8/00, p. 26*). When the beams recombined, the light no longer matched up perfectly. The detectors sensed that crest missed trough by the tiniest of distances, about a thousandth the diameter of a proton.

The LIGO facilities registered the signal just 7 milliseconds apart, indicating a light-speed pulse from deep space rather than a slower-moving vibration from an underground quake or a big rig rumbling along the highway. Physicists used the combined measurements to estimate a distance of 750 million to 1.8 billion light-years to the black holes, with 1.3 billion light-years as the best estimate. At least one more detector, preferably two, would have been needed to triangulate the precise location of the black holes in the sky.

While the black hole rendezvous was millions of years in the making, only the

LIGO

Gravity waves from a black hole collision came from about 1.3 billion light-years away, probably in the direction of the Magellanic clouds.

LIGO

final two-tenths of a second produced gravity waves with the requisite intensity and frequency for detection by Advanced LIGO. Those two-tenths of a second told quite a story. At first, the black holes were circling each other about 17 times a second; by the end, it was 75. The gravity wave frequency and intensity reached a peak, and then the black holes merged.

Combining the wave measurements with computer simulations, the scientists determined that a pair of 36- and 29-solar-mass black holes had become one 62-solar-mass beast. The missing mass had been transformed into energy and carried away as gravity waves. The power output during that mass-energy conversion was 50 times greater than that of all the stars in the universe combined.

The observed LIGO signal matches what physicists expected from a black hole merger almost perfectly. Ingrid Stairs, an astrophysicist at the University of British Columbia in Vancouver who was not involved with LIGO, says she and colleagues were "bowled over by how beautiful it was." Translated into sound, the signal resembled a rumbling followed by a chirp. "It stood out like a sore thumb," says Rainer Weiss, one of the primary architects of LIGO. The 83-year-old physicist had visited Livingston just days before and almost shut down the detector to fix some minor problems. Had he done so, "we would have missed it."

Despite the seeming no-doubt signal, LIGO researchers conducted a series of rigorous statistical tests. The signal survived. "I have great confidence in the team as a whole and everything they've done with the data," Stairs says.

LIGO's announcement falls between two relevant centennials: Einstein's introduction of general relativity (November 1915) and his prediction of gravitational waves (June 1916, though he had to fix the math two years later). Russell Hulse and Joseph Taylor Jr. won the 1993 Nobel Prize in physics for deducing gravity wave emission based on the motion of a stellar corpse called a neutron star and a closely orbiting companion. Now Advanced LIGO has sealed the deal with the first direct measurement.

The observatory achieved what its predecessor, which ran from 2001 to 2010, could not because of an upgrade that enhanced sensitivity by at least a factor of three. Increased sensitivity translates to identifying more distant objects: If the search area of first-generation LIGO included all the space that could fit within a baseball, Advanced LIGO could spot everything inside a basketball. Advanced LIGO's range extends up to 5 billion light-years in all directions for merging objects about 100 times the mass of the sun, project leader David Shoemaker of MIT says. That extended reach, plus a boost in sensitivity at the wave frequencies associated with black holes, enabled the detection.

This ability to examine black holes and other influential dark objects without actually "seeing" them with light has scientists excited about the gravitational wave era. Black holes gobble up some matter and launch the rest away in powerful jets, scattering atoms within and between galaxies; pairs of neutron stars, also targets of Advanced LIGO, may ultimately trigger gamma-ray bursts, among the brightest and most energetic explosions known in the universe.

Yet while the influence of these cosmic troublemakers is sometimes visible with traditional telescopes, the objects themselves are not. Gravity waves offer a direct probe, and as a bonus they don't get impeded by gas, dust and other cosmic absorbers as light does. "It opens up a new window into astronomy that we never had," says John Mather, a Nobel-winning astrophysicist in attendance at the news conference. Before this discovery, scientists had never observed a pair of black holes orbiting each other. A big next step, scientists say, is to observe a nearby supernova or the collision of neutron stars via both gravity waves and light.

Gravitational wave astronomy has begun with the Advanced LIGO detection, but there's lots more to come. LIGO scientists still have three months of data to sort through from their first round of observing, and the analysis of the signal suggests similar events should occur multiple times a year. The researchers are further upgrading the detectors so that they can spot neutron star and black hole collisions even farther away. The observatory should be back up and running by late summer, says LIGO chief detector scientist Peter Fritschel.

Later this year, European partners of the LIGO collaboration plan to restart their revamped gravity wave observatory, Advanced VIRGO, near Pisa, Italy, providing a crucial third ultrasensitive detector for pinpointing gravity wave sources. Similar detectors are in the works for Japan and India.

LIGO was designed to spot waves in the sweet spot for converging black holes and neutron stars, with a frequency ranging from tens of hertz to several thousand. But just as scientists use radio and gamma-ray telescopes to probe different frequencies of light, physicists are building detectors sensitive to a range of gravity wave frequencies. The eLISA mission, consisting of three satellites, will hunt for waves with frequencies under 1 hertz when it launches in the 2030s. The satellite trio should be able to resolve black holes from the early universe and ones millions of times the mass of the sun.

The LIGO result is distinct from the 2014 claim of a gravity wave detection, since rescinded, by scientists with the BICEP2 telescope (*SN: 2/21/15, p. 13*). BICEP2 hunts for gravity waves with a much lower frequency, signaling reverberations from a split-second span just after the Big Bang called inflation, when space expanded very rapidly. Not detectable directly, these inflation-era gravity waves should be encoded in the universe's earliest light.

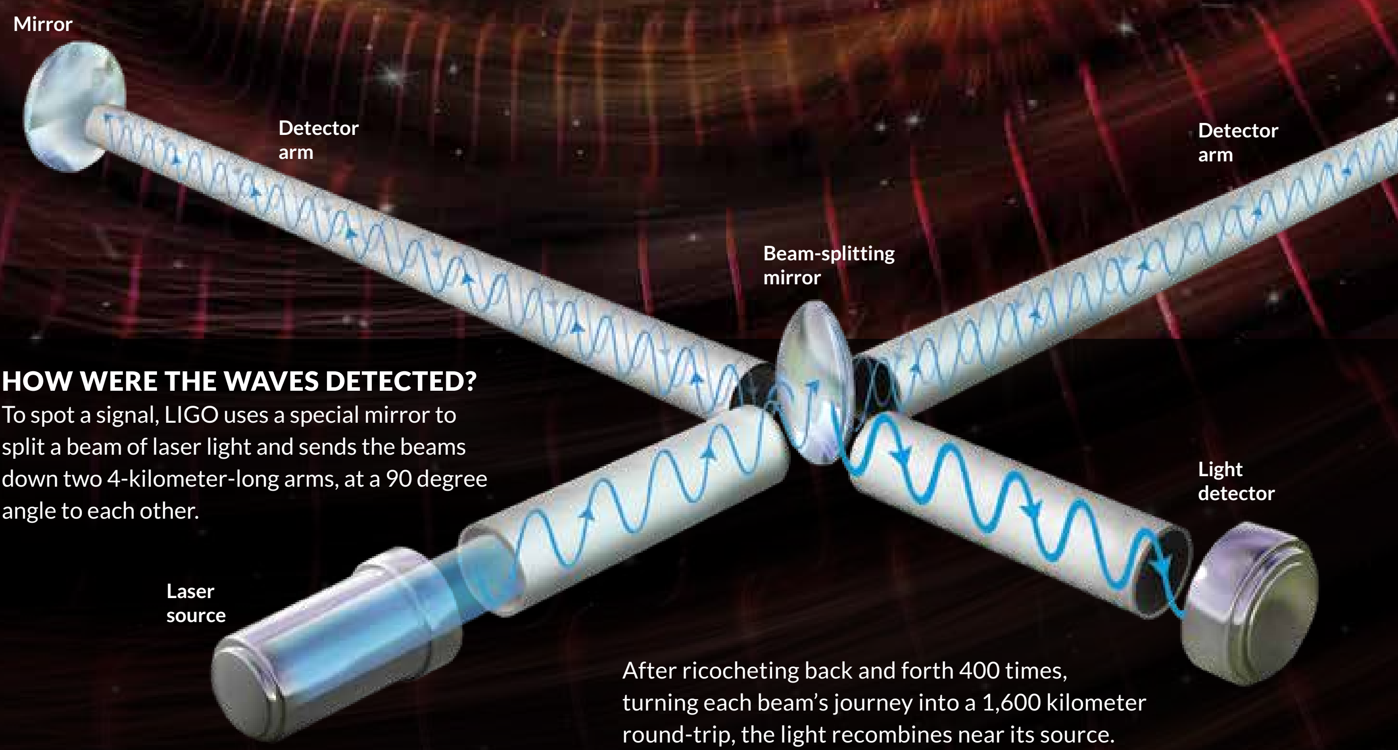
Scientists may well detect those flavors of gravity waves soon. But for now, they can bask in a discovery 100 years in the making. "This was truly a scientific moonshot," Reitze said. "We did it. We landed on the moon." ■

Cosmic **shake-up**

A century after Albert Einstein rewrote our understanding of space and time, physicists have confirmed one of the most elusive predictions of his general theory of relativity. In another galaxy, a billion or so light-years away, two black holes collided, shaking the fabric of spacetime. Here on Earth, two giant detectors on opposite sides of the United States quivered as gravitational waves washed over them. After decades trying to directly detect the waves, the recently upgraded Laser Interferometer Gravitational-Wave Observatory, now known as Advanced LIGO, appears to have succeeded, ushering in a new era of astronomy (see Page 6). — *Christopher Crockett*

WHAT ARE GRAVITATIONAL WAVES?

Colossal cosmic collisions and stellar explosions can rattle spacetime itself. General relativity predicts that ripples in the fabric of spacetime radiate energy away from such catastrophes. The ripples are subtle; by the time they reach Earth, some compress spacetime by as little as one ten-thousandth the width of a proton.



HOW WERE THE WAVES DETECTED?

To spot a signal, LIGO uses a special mirror to split a beam of laser light and sends the beams down two 4-kilometer-long arms, at a 90 degree angle to each other.

After ricocheting back and forth 400 times, turning each beam's journey into a 1,600 kilometer round-trip, the light recombines near its source.

NICOLLE RAGER FULLER

WHERE WERE THE WAVES DETECTED?

LIGO has one detector in Louisiana and another in Washington to ensure the wave is not a local phenomenon and to help identify its source.

WHAT ABOUT OTHER SOURCES?

By studying computer simulations of astrophysical phenomena, scientists can figure out what type of signals to expect from various gravitational wave sources.

Spinning neutron stars

A single spinning neutron star, the core left behind after a massive star explodes, can whip up spacetime at frequencies similar to those produced by colliding black holes.

Supernovas

Powerful explosions known as supernovas, triggered when a massive star dies, can shake up space and blast the cosmos with a burst of high-frequency gravitational waves.

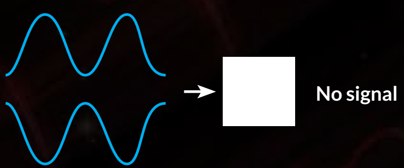
Supermassive black hole pairs

Pairs of gargantuan black holes, more than a million times as massive as the sun and larger than the ones Advanced LIGO detected, radiate long, undulating waves. Though Advanced LIGO can't detect waves at this frequency, scientists might spot them by looking for subtle variations in the steady beats of pulsars.

Big Bang

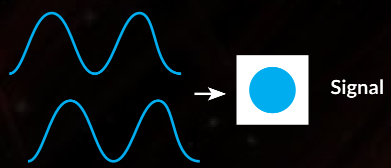
The Big Bang might have triggered universe-sized gravitational waves 13.8 billion years ago. These waves would have left an imprint on the first light released into the cosmos 380,000 years later, and could be seen today in the cosmic microwave background.

Normal situation

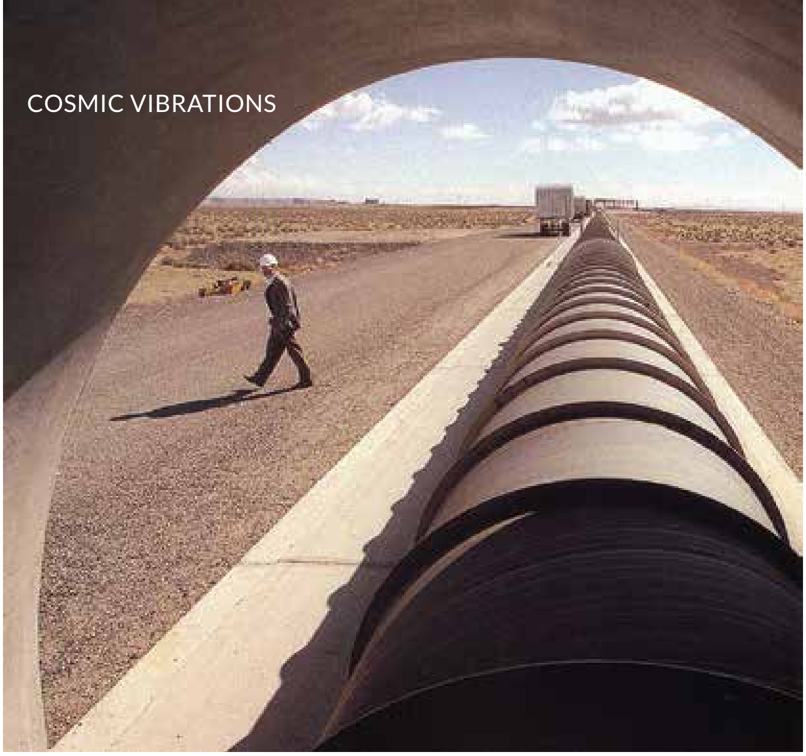


The experiment is designed so that, in normal conditions, the light waves cancel one another out when they recombine, sending no light signal to the nearby detector.

Gravitational wave detection



But a gravitational wave stretches one tube while squeezing the other, altering the distance the two beams travel relative to each other. Because of this difference in distance, the recombining waves are no longer perfectly aligned and therefore don't cancel out. The detector picks up a faint glow, signaling a passing wave.



Listening for GRAVITY WAVES

The long road to detecting rumbles in the fabric of spacetime

By Marcia Bartusiak

Two stainless steel tubes, 4 kilometers long, house laser beams and mirrors to detect waves from space at a LIGO site in Hanford, Wash.

BENJAMIN BENSCHNEIDER/*THE SEATTLE TIMES*

The January e-mail from Syracuse University physicist Peter Saulson caught me off guard. It probably shouldn't have, since I had been anticipating the news for 16 years, ever since I wrote *Einstein's Unfinished Symphony*. The book chronicled the astrophysical community's most cutting-edge start-up: gravity wave astronomy.

Saulson's message meant that Einstein's symphony is no longer "unfinished." A gravitational wave (gravity wave in common parlance), the historic prediction arising from Einstein's equations of general relativity, had never been detected directly. But now, thanks to two colliding black holes, that unfinished task was finally completed, after decades of blood, sweat and immeasurable frustrations. It took that long to get a gravity wave detector working. More than that, the discovery's announcement (see Page 6) was made almost exactly 100 years after Einstein wrote his first paper on gravity waves. "As if those black holes were waiting for that moment," Saulson says.

In papers published in the *Proceedings of the Royal Prussian Academy of Sciences* in 1916 and 1918, Einstein reasoned that just as electromagnetic radiation, such as radio waves, is generated when electric charges travel up and down an antenna, waves of gravitational radiation (what he called *gravitationswellen*) must also be produced when masses move about.

But these waves do not travel through space the way light does; they are literally quakes in spacetime's very framework. Detectable rumbles emanate from the most violent events the universe has to offer — such as the ferocious encounter of two massive black holes (recorded by two gravity wave observatories) merging in a fateful embrace about 1.3 billion years ago. Alternately stretching and squeezing space, the wave right at the clash of the black holes would have stretched a 6-foot man to 12 feet and within a millisecond, squeezed him to 3 feet, before stretching him out once again.

Einstein never imagined such outrageous sources for his waves. Given the relatively quiet nature of the universe assumed in the 1910s, he was picturing waves rippling outward as two stars simply orbited one another. And he and others knew that those spacetime ripples would be feeble, certainly too weak to bother looking for them. Others wondered if his *gravitationswellen* didn't exist at all and were rather just imaginary artifacts of the relativistic mathematics. General relativists argued back and forth over this issue for many years.

Hope and disappointment

But the stalemate shifted in the late 1950s, when a young University of Maryland physicist named Joseph Weber decided to build a gravity wave detector to settle the question. Experimental relativity was undergoing a renaissance at this time, and Weber had been encouraged by Princeton physicist John Archibald Wheeler, then the dean of American general relativity, to hunt for an actual wave.

For his design, Weber surrounded a solid, water heater–sized cylinder of aluminum — a bar — with sensors, figuring that a passing wave would cause the bar to resonate like a bell. The sensors would convert the oscillations into electrical signals registered on a paper chart recorder. Two detectors separated by hundreds of miles, he reasoned, were needed to rule out local noises. In 1969, Weber grandly proclaimed at a relativity conference in Cincinnati that he had simultaneously recorded a signal on two bars, one on the Maryland campus, the other at Argonne National Laboratory near Chicago. Conferees greeted his announcement with applause (*SN: 6/21/69, p. 593*). The popular press heralded his find as the most important event in physics in half a century. “Many laymen will be startled, no doubt,” reported the *New York Times*. A year later, Weber declared that the signal was emanating from the center of the Milky Way galaxy, possibly from a supernova going off or maybe from pulsars, the rapidly spinning neutron stars that had been recently discovered.

Soon other physics groups built their own detectors. They detected no waves whatsoever. Yet they didn’t give up. By the 1980s, teams in various countries had constructed even bigger bar detectors to increase sensitivity. They adjusted the designs, encasing detectors in supercooled fluids to reduce thermal noise. But, again, no signals were recorded. While Weber is still credited with jump-starting the field, the lack of verification damaged his reputation, although he insisted until his death in 2000 that his detectors were recording waves. Today, physicists put the claim down to noise and believe Weber didn’t fully understand the natural noises emanating within his bars.

But while the bar technology was maturing, a new gravity wave–detecting strategy surfaced — a method known as laser interferometry. Two researchers in the Soviet Union, Mikhail Gertsenshtein and V.I. Pustovoit, first published the idea in 1962, but no one outside their country became aware of it. Weber, too, briefly thought of the technique but never published. In 1966, Rainer Weiss at MIT also came up with the scheme independently — and in an offbeat way.

Bouncing lasers

Asked to teach a course on general relativity, Weiss, who worked on gravity as an experimentalist, not a theorist, scrambled. “I couldn’t admit that I didn’t know it. I was just one exercise ahead of my students,” he said in 1999. Arriving at the topic of gravity waves, and wanting to understand them from a more hands-on perspective, he came up with a homework assignment. Imagine, he told his students, three masses suspended above the ground, their orientation forming an L shape. How would the distances between those masses change as a gravity wave passed by? He knew that a gravity wave compresses space in one direction (say, north-south), while expanding it in the other (east-west). A millisecond later, as the wave passes by, the effect reverses. By the time Weiss worked out the solution for himself, he knew that he had a darn good experiment in mind. Continually bounce laser beams between the masses, have the beams eventually recombine (optically “interfere” with one another) to measure the gravity wave shifts, and you have a detector! And it had one great advantage over the bars. Whereas bars could be tuned to only one frequency, laser interferometers could register a wider range of frequencies, increasing the chances of detecting a source.

By 1972, Weiss had written a landmark report for MIT’s Research Laboratory of Electronics identifying all the fundamental sources of noise that could mask a signal in such a setup. The paper is still consulted today by gravity wave researchers. From that point on, Weiss devoted a large part of his career to getting a laser interferometer constructed and to finding the means to reduce those noises. There was extra incentive to do so: In 1974 radio astronomers Joseph Taylor and Russell Hulse, then at the University of Massachusetts Amherst, found a neutron star orbiting a dense companion, the two drawing closer and closer by about a few meters each year — just the change in distance physicists expect if the binary pair is losing orbital energy as gravity waves. Though the proof was indirect (and the waves themselves too weak to measure), it greatly encouraged the gravity wave astronomy community that sources would be available.

By the 1980s, Weiss joined forces with Caltech theorist Kip Thorne, the world’s top expert on the physics of gravity waves, and Scottish experimentalist Ronald Drever, also at Caltech, to leapfrog the small, laboratory prototypes being built and erect two sizable

The 100-year wait Physicists’ efforts to detect gravity waves paid off one century after Einstein predicted the waves existed.

1915 Einstein presents his general theory of relativity

1916 Einstein writes papers in the *Proceedings of the Royal Prussian Academy of Sciences* describing the possibility of gravity waves

Late 1950s Joseph Weber begins work on a gravity wave detector

1966 Rainer Weiss at MIT conceives laser interferometry method to detect gravity waves

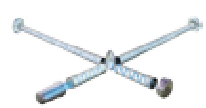
1969 Weber (pictured in *Science News*) announces detection of a gravity wave (it was never confirmed)

1974 Joseph Taylor and Russell Hulse find a binary pulsar system later shown to be losing energy consistent with the emission of gravity waves

1992 National Science Foundation selects sites in Washington and Louisiana for the Laser Interferometer Gravitational-Wave Observatory, or LIGO

1994 Construction begins at the two LIGO sites

2001 LIGO begins operating



2008 Construction begins on Advanced LIGO

2010 LIGO ends operations; Advanced LIGO installation begins

September 2015 Advanced LIGO begins observations and detects a wave

FROM TOP: SCIENCE NEWS ARCHIVES; LIGO; LIGO; NICOLLE RAGER FULLER detectors with lengthy arms instead. A nearly simultaneous reception at a pair of detectors set far apart geographically would verify a wave passed through at the speed of light. Increasing the laser light's path in the arms would magnify the detector's sensitivity. Astrophysical sources, such as supernovas exploding or black holes colliding, generate ripples in spacetime that would be deadly near the event, but by the time those waves reach Earth, they would wiggle the interferometer masses less than the width of a proton. Kilometers-long arms would be needed to measure such subtle movements.

A feasibility study for this daring proposal (later dubbed the Laser Interferometer Gravitational-Wave Observatory) was completed in 1983. The report ultimately convinced the National Science Foundation (in particular NSF administrators Marcel Bardon and Richard Isaacson) to take a chance on going big. But so high was LIGO's estimated construction cost (it rose to nearly $300 million) that it was the first time that the NSF had to go to Congress to get approval for a project. When astronomers and physicists heard about the proposal, a few became very vocal, angered that the NSF was proposing to use precious funds on a gamble rather than a proven technology. As a result, the LIGO proposal went through innumerable ups and downs and was almost canceled more than once (*SN: 6/26/93, p. 408; SN: 1/8/00, p. 26*).

A crucial turning point occurred in 1992 when Caltech physicist Rochus Vogt, then the LIGO director, wrangled a meeting with Louisiana Sen. J. Bennett Johnston, who later

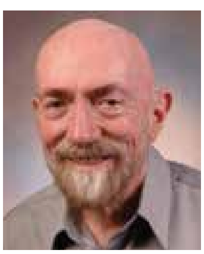
Joseph Weber, in 1969, working on his gravity wave detector at the University of Maryland in College Park.

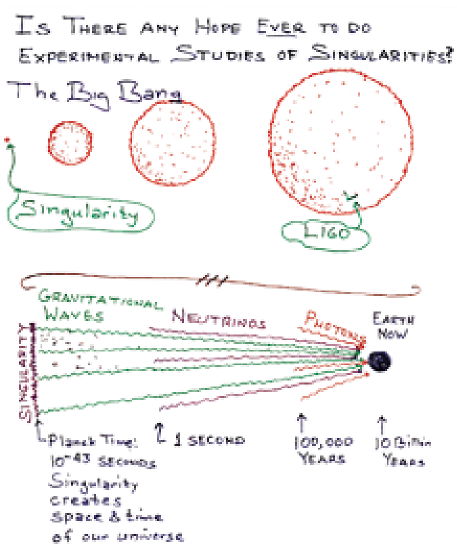
became an ardent supporter of the project. Vogt originally had only 20 minutes, but his tales of cosmology so captivated Johnston that the senator canceled his next three appointments. For several hours, the two huddled over the senator's coffee table, while Vogt drew pictures of curved spacetime. Once again, Einstein's name worked magic. Congress eventually authorized funds to build two detectors, each with 4-kilometer-long arms: one situated in Livingston, La., the other 1,900 miles to the northwest in Hanford, Wash.

Ground was broken for those first-generation detectors in 1994. Both were up and running by 2001. Primarily a test bed to try out the novel technologies needed to find a gravity wave, the first LIGO wasn't expected to register any waves. But it still did its job. What LIGO collaborators learned from each detector's performance went into the design of innovative instrumentation, which was gradually installed over the last five years. This upgrade, called Advanced LIGO, led to an increased sensitivity that, bingo, found a gravity wave as soon as it began operation last fall.

Instruments around the globe are already joining LIGO's quest. A LIGO-like detector known as VIRGO, run by a European collaboration, has been operating on the vast alluvial plain outside Pisa, Italy, since 2007. (VIRGO was offline for instrumentation improvements when Advanced LIGO registered its first gravity wave.) A smaller interferometer named GEO600, with 600-meter-long arms, operates in Germany. Other detectors are under construction in Japan and planned for India.

But laser interferometers on Earth are limited in the frequencies they can register (roughly 10 to several thousand hertz), much the way an optical telescope cannot see radio waves or X-rays. To expand that range so gravity wave events from a variety of sources can be detected, gravity wave astronomers are





Kip Thorne (above) drew this sketch of gravity waves being emitted from the Big Bang for a 1999 lecture.

FROM TOP: SPECIAL COLLECTIONS/UNIV. OF MARYLAND LIBRARIES; CALTECH; K. THORNE/CALTECH pursuing other methods as well. One clever scheme is based on well-studied astronomical objects — pulsars, the most exquisite timepieces in the universe due to the unvarying rhythm of beeps emitted by the rapidly spinning neutron stars (*SN: 10/17/15, p. 24*). By closely monitoring the pulses arriving from an array of particularly fast pulsars situated around the sky, astronomers are on the lookout for slight changes in the pulsing due to an extremely low-frequency gravity wave (10^{-9} to 10^{-6} hertz) passing between the pulsar and the earthbound detector. Supermassive black hole binaries would emit these tremendously long waves as they slowly orbit in the centers of merging galaxies. And ultimately, researchers hope to send laser interferometers into space. The European Space Agency is working on a proposal called the Evolved Laser Interferometer Space Antenna (*SN Online: 12/3/15*), which would enable the detection of weaker gravity waves.

A new astronomy

What the world is witnessing is the birth of a new astronomy. Detecting the ripples of those two black holes, uniting in the distant universe, is like Galileo's first peek at the heavens through a telescope in 1609. Galileo discovered moons orbiting Jupiter and jagged mountains and craters on the moon, amazing wonders to 17th century eyes. Now, gravity wave astronomy is poised to offer its own radically new visions.

Electromagnetic waves, be they visible light, radio, infrared or X-rays, are released by individual atoms and electrons. Such radiation reveals a celestial object's physical condition — how hot it is, how old it is, what it looks like and what it is made of. Gravity waves convey much different information. They will tell about the overall motions of massive objects, indicating how they move, twirl and collide throughout the universe, especially for objects that are too small to be seen directly, such as neutron stars and stellar black holes.

"We've now embarked on an era of exploring phenomena in the universe that are made from warped spacetime," Thorne says. "I like to call it the warped side of the universe." In due course, this new method of observing may be able to record the remnant rumble of the first nanosecond of creation, by gathering the residual gravity waves emitted by the awesome spacetime jolt of the Big Bang itself.

M. TELFER

Global gravity wave detectors

A global quest
Gravity wave detectors are operating in the United States, Germany and Italy, with two more in the works in India and Japan. Researchers expect an expanded network to improve detection confidence and source localization accuracy.

After more than four long and turbulent decades, Weiss has at last seen his experimental dream come true. Did he ever despair? "No," he says without hesitation today. "The reason you don't worry about the end result is this: The problems were interesting, you enjoyed the people you were working with, and it was fun to do!" Ever the experimentalist, Weiss, now 83, continues to travel to observatories, roll up his sleeves and check out the equipment.

He worked on the initial idea in the 1970s with just a few colleagues and students; today, more than 1,000 people are involved — LIGO/VIRGO collaborators at universities and institutes around the world advancing both the theory and the technology.

At the dedication of LIGO's Louisiana observatory in 1999, Rita Colwell, then director of the NSF, noted that those gathered were "breaking a bottle of champagne over the figurative bow of a modern-day galleon — a gravity wave observatory that may ultimately take us farther back in time than we've ever been." With their first signal, a crescendo that when converted to audio starts as a deep bass and heads toward middle C, LIGO scientists are beginning their journey, now able to listen for the myriad events that await detection.

With that in mind, I take back what I said at the opening to this essay. Einstein's symphony will never be finished. ■

Marcia Bartusiak is a professor of science writing at MIT and the author of six books on astrophysics and the history of astronomy.