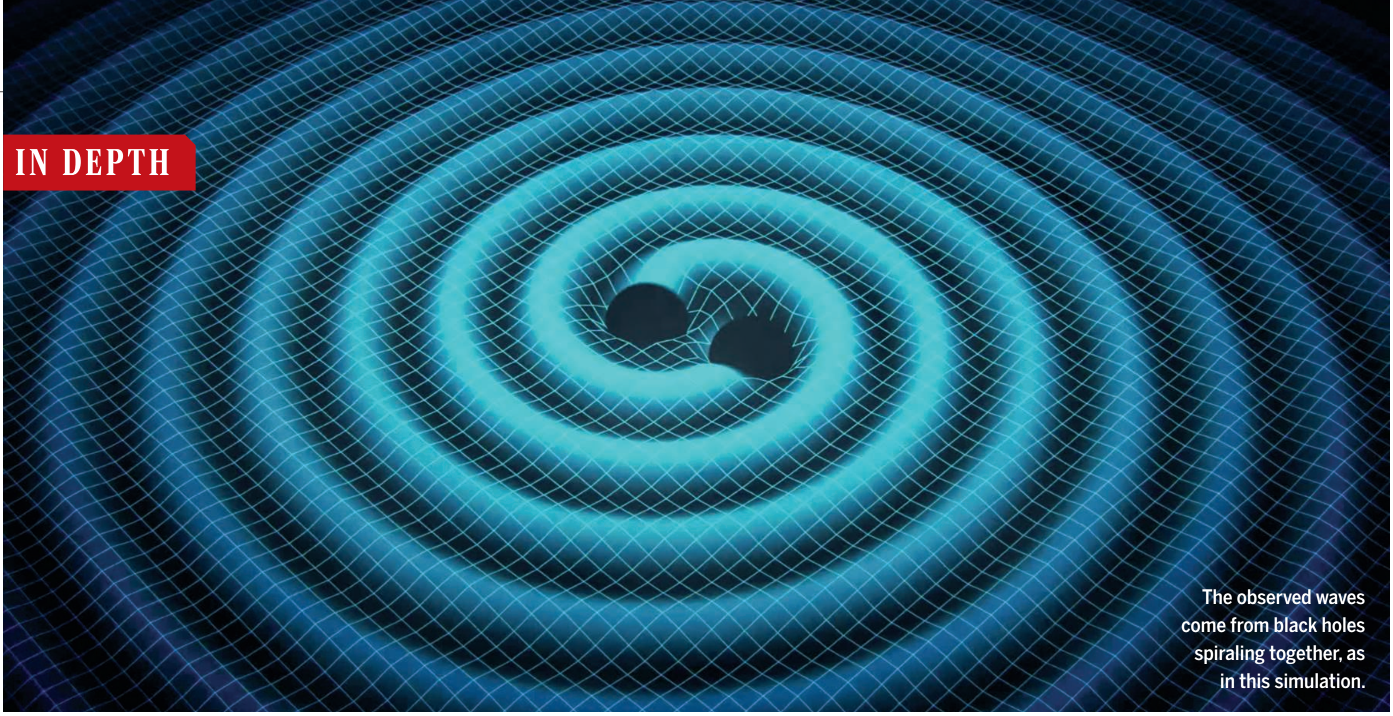


The observed waves come from black holes spiraling together, as in this simulation.

PHYSICS

Triumph for gravitational wave hunt

Observation made with newly detectable radiation clinches case for black holes

By **Adrian Cho**

Long ago, deep in space, two massive black holes—the ultrastrong gravitational fields left behind by gigantic stars that collapsed to infinitesimal points—slowly drew together. The stellar ghosts spiraled ever closer, until, about 1.3 billion years ago, they whirled about each other at half the speed of light and finally merged. The collision sent a shudder through the universe: ripples in the fabric of space and time called gravitational waves. Five months ago, they washed past Earth. And, for the first time, physicists detected the waves, fulfilling a 4-decade quest and opening new eyes on the heavens.

The discovery marks a triumph for the 1000 physicists with the Laser Interferometer Gravitational-Wave Observatory (LIGO), a pair of gigantic instruments in Hanford, Washington, and Livingston, Louisiana. Rumors of the detection had circulated for months. But as *Science* went to press, the LIGO team planned to make it official on 11 February in a press conference in Washington, D.C. "We did it!" says David Reitze, a physicist and LIGO executive director at the California Institute of Technology (Caltech) in Pasadena. "All the rumors swirling around out there got most of it right."

Albert Einstein predicted the existence of gravitational waves 100 years ago, but directly detecting them required mind-boggling technological prowess. LIGO researchers sensed a wave that stretched space by one part in 10^{21}, making the entire Earth expand and contract by 1/100,000 of a nanometer, about the width of an atomic nucleus. The observation tests Einstein's theory of gravity, the general theory of relativity, with unprecedented rigor and provides proof positive that black holes exist. "It will win a Nobel Prize," says Marc Kamionkowski, a theorist at Johns Hopkins University in Baltimore, Maryland.

LIGO watches for a minuscule stretching of space with what amounts to ultraprecise rulers: two L-shaped contraptions called interferometers with arms 4 kilometers long. Mirrors at the ends of each arm form a long "resonant cavity," in which laser light of a precise wavelength bounces back and forth, resonating just as sound of a specific pitch rings in an organ pipe. Where the arms meet, the two beams can overlap. If they have traveled different distances along the arms, their waves will wind up out of step and interfere with each other. That will cause some of the light to warble out through an exit called a dark port in synchrony with undulations of the wave.

From the interference, researchers can compare the relative lengths of the two arms to within 1/10,000 the width of a proton—enough sensitivity to see a passing gravitational wave as it stretches the arms by different amounts. To spot such tiny displacements, however, scientists must damp out vibrations such as the rumble of seismic waves, the thrum of traffic, and the crashing of waves on distant coastlines.

On 14 September 2015, at 9:50:45 universal time—4:50 a.m. in Louisiana and 2:50 a.m. in Washington—LIGO's automated systems detected just such a signal. The oscillation emerged at a frequency of 35 cycles per second, or Hertz, and sped up to 250 Hz before disappearing 0.25 seconds later. The increasing frequency, or chirp, jibes with two massive bodies spiraling into each other. The 0.007-second delay between the signals in Louisiana and Wash-

Signals in synchrony

When shifted by 0.007 seconds, the signal from LIGO's observatory in Washington (red) neatly matches the signal from the one in Louisiana (blue).

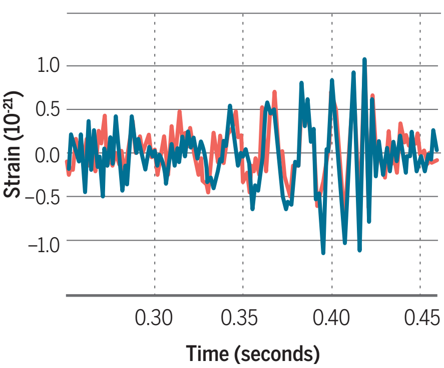


ILLUSTRATION: SWINBURNE ASTRONOMY PRODUCTIONS ington is the right timing for a light-speed wave zipping across both detectors.

The signal exceeds the "five-sigma" standard of statistical significance that physicists use to claim a discovery, LIGO researchers report in a paper scheduled to be published in *Physical Review Letters* to coincide with the press conference. It's so strong it can be seen in the raw data, says Gabriela González, a physicist at Louisiana State University, Baton Rouge, and spokesperson for the LIGO scientific collaboration. "If you filter the data, the signal is obvious to the eye," she says.

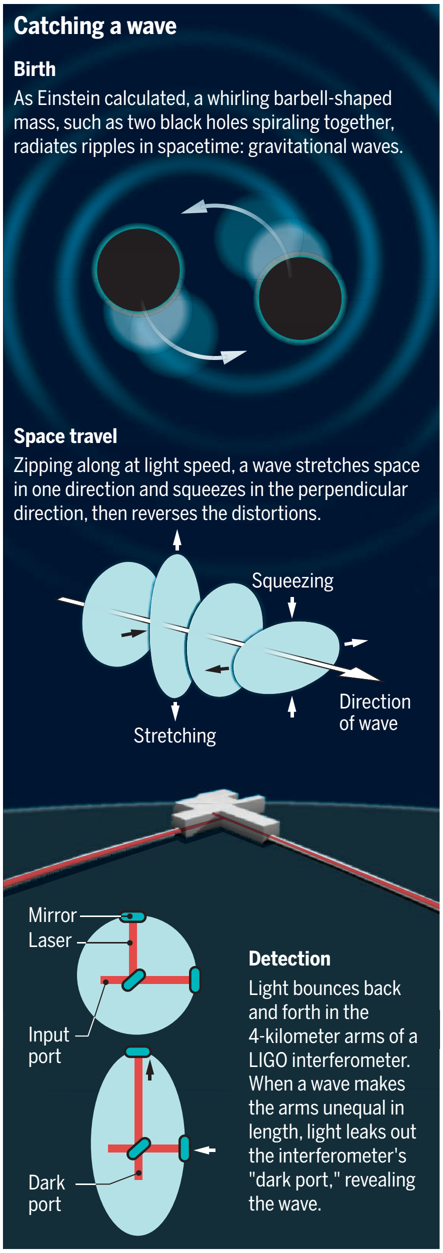
Comparison with computer simulations reveals that the wave came from two objects 29 and 36 times as massive as the sun spiraling to within 210 kilometers of each other before merging. Only a black hole—which is made of pure gravitational energy and gets its mass through Einstein's famous equation $E=mc^2$—can pack so much mass into so little space, says Bruce Allen, a LIGO member at the Max Planck Institute for Gravitational Physics in Hanover, Germany. The observation provides the first evidence for black holes that does not depend on watching hot gas or stars swirl around them at far greater distances. "Before, you could argue in principle whether or not black holes exist," Allen says. "Now you can't."

The collision produced an astounding, invisible explosion. Modeling shows that the final black hole totals 62 solar masses—3 solar masses less than the sum of the initial black holes. The missing mass vanished in gravitational radiation—a conversion of mass to energy that makes an atomic bomb look like a spark. "For a tenth of a second [the collision] shines brighter than all of the stars in all the galaxies," Allen says. "But only in gravitational waves."

For 5 months, LIGO physicists struggled to keep a lid on their pupating discovery. Ordinarily, most team members would not have known whether the signal was real. LIGO regularly salts its data readings with secret false signals called "blind injections" to test the equipment and keep researchers on their toes. But on 14 September 2015, that blind injection system was not running. Physicists had only recently completed a 5-year, $205 million upgrade of the machines, and several systems—including the injection system—were still offline as the team wound up a preliminary "engineering run." As a result, the whole collaboration knew that the observation was likely real. "I was convinced that day," González says.

Still, LIGO physicists had to rule out every alternative, including the possibility that the reading was a malicious hoax. "We spent about a month looking at the ways that somebody could spoof a signal," Reitze says, before deciding it was impossible. For González, making the checks "was a heavy responsibility," she says. "This was the first detection of gravitational waves, so there was no room for a mistake."

Proving that gravitational waves exist may not be LIGO's most important legacy, as there has been compelling indirect evidence for them. In 1974, U.S. astronomers Russell Hulse and Joseph Taylor discovered a pair of radio-emitting neutron stars called pulsars orbiting each other. By timing the pulsars, Taylor and colleague Joel Weisberg demonstrated that they are very slowly spiraling toward each other—as they should if they're radiating gravitational waves.



It is the prospect of the science that might be done with gravitational waves that really excites physicists. For example, says Kamionkowski, the theorist at Johns Hopkins, the first LIGO result shows the power of such radiation to reveal unseen astrophysical objects like the two ill-fated black holes. "This opens a new window on this vast population of stellar remnants that we know are out there but of which we have seen only a tiny fraction," he says.

The observation also paves the way for testing general relativity as never before, Kamionkowski says. Until now, physicists have studied gravity only in conditions where the force is relatively weak. By studying gravitational waves, they can now explore extreme conditions in which the energy in an object's gravitational field accounts for most or all of its mass—the realm of strong gravity so far explored by theorists alone.

With the black hole merger, general relativity has passed the first such test, says Rainer Weiss, a physicist at the Massachusetts Institute of Technology (MIT) in Cambridge, who came up with the original idea for LIGO. "The things you calculate from Einstein's theory look exactly like the signal," he says. "To me, that's a miracle."

The detection of gravitational waves marks the culmination of a decades-long quest that began in 1972, when Weiss wrote a paper outlining the basic design of LIGO. In 1979, the National Science Foundation funded research and development work at both MIT and Caltech, and LIGO construction began in 1994. The $272 million instruments started taking data in 2001, although it was not until the upgrade that physicists expected a signal.

If LIGO's discovery merits a Nobel Prize, who should receive it? Scientists say Weiss is a shoo-in, but he demurs. "I don't like to think of it," he says. "If it wins a Nobel Prize, it shouldn't be for the detection of gravitational waves. Hulse and Taylor did that." Many researchers say other worthy recipients would include Ronald Drever, the first director of the project at Caltech who made key contributions to LIGO's design, and Kip Thorne, the Caltech theorist who championed the project. Thorne also objects. "The people who really deserve the credit are the experimenters who pulled this off, starting with Rai and Ron," he says.

Meanwhile, other detections may come quickly. LIGO researchers are still analyzing data from their first observing run with their upgraded detectors, which ended 12 January, and they plan to start taking data again in July. A team in Italy hopes to turn on its rebuilt VIRGO detector—an interferometer with 3-kilometer arms—later this year. Physicists eagerly await the next wave. ■

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