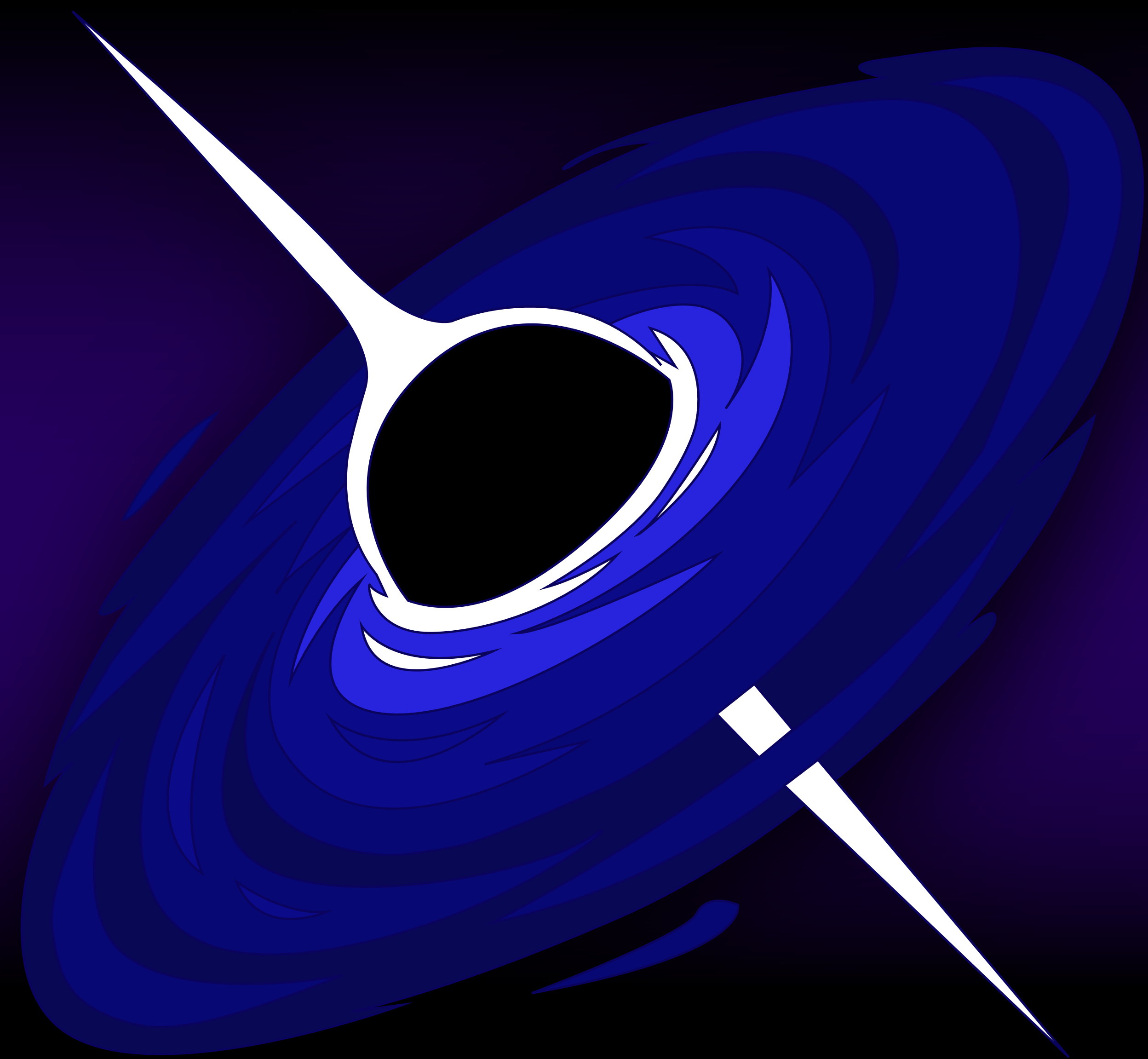
THE BLACK HOLE THEORY

September 10, 2025



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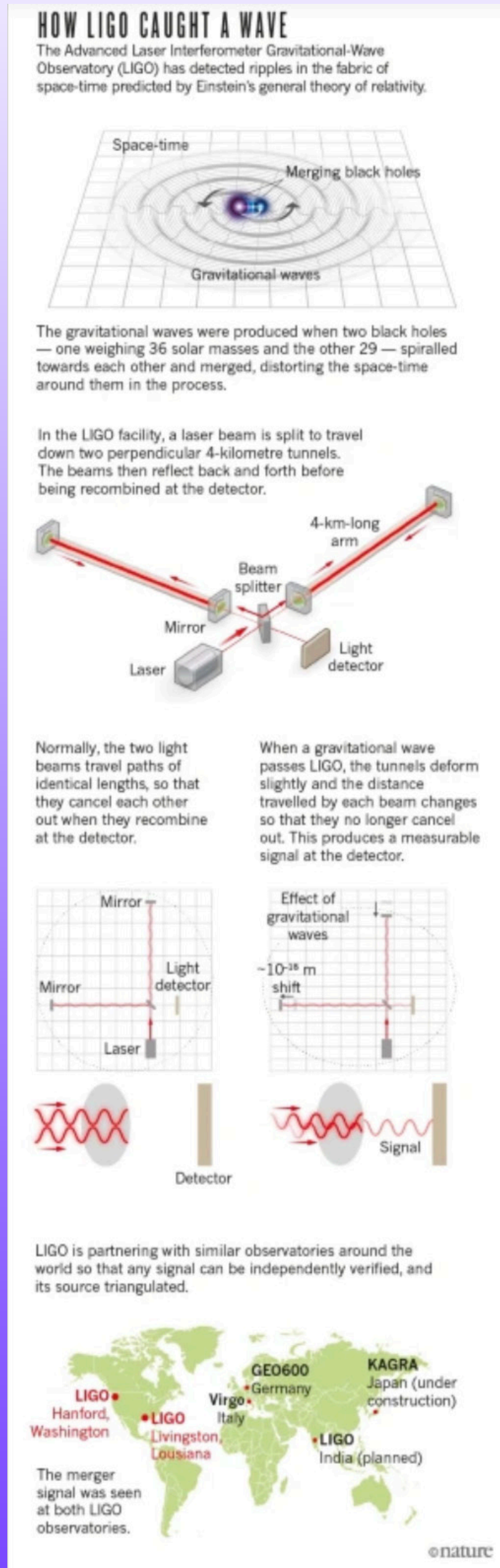


The songs of the cosmos, now that we can finally hear them, might seem anti-climactic — more faint chirp than grand symphonic melody. But, over the past decade, those songs have helped scientists to fathom some of the biggest, strangest and most powerful events in the Universe.

Almost exactly ten years ago, the Laser Interferometer Gravitational-Wave Observatory (LIGO) became the first detector to 'hear' gravitational waves: ripples that waft through the fabric of space-time after being unleashed by the Universe's most-violent collisions.

The first detection, on 14 September 2015, recorded the tune sung by two black holes coalescing into one, and it confirmed Albert Einstein's prediction that such gravitational waves exist. Now, LIGO, alongside other detectors, has detected some 300 gravitational-wave events, including one announced today that supports a theorem by cosmologist Stephen Hawking in the 1970s.

At each of LIGO's twin installations — in Livingston, Louisiana, and Hanford, Washington — laser beams bounce down two arms, arranged in an L shape, that are each 4 kilometres long.

A hairsbreadth misalignment of the beams indicates a squeezing and stretching of space-time, which registers as a wave on a computer read-out. When rendered as an audible sound, the wave resembles a bird's chirp.

To celebrate LIGO's first decade of discoveries, Nature asked gravitational-wave researchers about their favourite detections so far. Here are LIGO's greatest hits, according to specialists.

Einstein Gravitational History

One hundred years after Albert Einstein predicted the existence of gravitational waves, scientists have finally spotted these elusive ripples in space-time.

In a highly anticipated announcement, physicists with the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) revealed on 11 February that their twin detectors have heard the gravitational 'ringing' produced by the collision of two black holes about 400 megaparsecs (1.3 billion light-years) from Earth1,2.

"Ladies and gentlemen, we have detected gravitational waves," David Reitze, the executive director of the LIGO Laboratory, said at a Washington DC press conference. "We did it!"

One black hole was about 36 times the mass of the Sun, and the other was about 29 solar masses. As they spiralled inexorably into one another, they merged into a single, more-massive gravitational sink in space-time that weighed 62 solar masses, the LIGO team estimates.

"These amazing observations are the confirmation of a lot of theoretical work, including Einstein's general theory of relativity, which predicts gravitational waves," says physicist Stephen Hawking of the University of Cambridge, UK. Hawking noted that Einstein himself never believed in black holes.

This is the first black-hole merger that scientists have observed. The violent event temporarily radiated more energy — in the form of gravitational waves — than all the stars in the observable Universe emitted as light in the same amount of time.

When played as an audible sound, the waves make an unmistakeable 'chirp' — a rapidly rising tone — followed by a 'ringdown', the radiation pattern from the merged black hole. The 'loudness' of the recorded signal also provides a rough measure of when the merger occurred: between 600 million and 1.8 billion years ago. The work will be published in a series of papers in Physical Review Letters1 and the Astrophysical Journal.

The historic discovery, which physicists say will probably lead shortly to a Nobel prize opens up the new field of gravitational-wave astronomy, in which scientists will listen to the waves to learn more about the objects that can produce them, including black holes, neutron stars and supernovae.

"This is just the first step in a much larger and more exciting development," says Ilya Mandel, a theoretical physicist at the University of Birmingham, UK. Gravitational waves will join γ-rays, X-rays and radio waves as "part of the toolkit that we have for understanding the universe", he says.

It is also a long-sought victory for the LIGO experiment, which had spent a decade searching for the signal in the 2000s before a US$200-million upgrade improved the sensitivity of its twin detectors, one in Livingston, Louisiana, and the other in Hanford, Washington.

Wave of Discovery

The discovery itself was made before the upgraded version, Advanced LIGO, had officially begun to take scientific data. At 11:50 a.m. Central European Time on 14 September, during the experiment's first observing run, LIGO physicist Marco Drago at the Max Planck Institute for Gravitational Physics in Hannover, Germany, saw a strange signal on his computer.

Software that analyses data in real time was indicating that both interferometers had seen a wave resembling the chirp of a bird with a rapidly increasing pitch. Within an hour, the news had reached Drago's boss, physicist Bruce Allen. The recording looked too good to be true. "When I first saw it I said, 'Oh, it's an injection, obviously,'" Allen says.

It was an oscillation that began at 35 cycles per second (hertz) and rapidly increased to 250 hertz. It then became chaotic and rapidly died down; the whole thing was over within one-fourth of a second. Crucially, both detectors saw it at roughly the same time — Livingston first and Hanford 7 milliseconds later. That delay is an indication of how the waves swept through the Earth.

Other gravitational-wave detectors — the Virgo interferometer near Pisa, Italy, and the GEO600 interferometer near Hannover — were not operating at the time and so could not confirm the signal. Had Advanced Virgo been on, it would have probably detected the event as well, says its spokesperson, Fulvio Ricci, a physicist at the University of Rome La Sapienza. LIGO scientists have run a series of careful checks to ensure that the signal is real and means what they think it does.

In the past, a few senior members of the LIGO team have tested the group's ability to validate a potential discovery by secretly inserting 'blind injections' of fake gravitational waves into the data stream to test whether the research team can differentiate between real and fake signals. But the September detection happened before blind injections were being made, so it is thought to be a signal from a real astrophysical phenomenon in the Universe.

To pinpoint the source of gravitational waves, researchers have to triangulate a signal spotted by different machines spread around Earth. When both LIGO detectors are operating along with Virgo or GEO600, scientists expect to be better able to locate future gravitational-wave sources. Another interferometer in Japan is under development, and a third LIGO site in India has been proposed. A greater geographic spread of detectors would strengthen confidence in any signals.

Direct Detection

Einstein's general theory of relativity predicts that any cosmic event that disturbs the fabric of spacetime with sufficient force should produce gravitational ripples that propagate through the Universe. Earth should be awash with such waves but by the time they reach us, the disturbances that they produce are minute.

In 1974, physicists Joseph Taylor and Russell Hulse at the University of Massachusetts Amherst indirectly confirmed the existence of gravitational waves by watching radio flashes emitted by a pair of neutron stars whirling around one another; the shifts in the flashes' timing matched Einstein's predictions of how gravitational waves would carry energy away from the event. That discovery won them the 1993 Nobel Prize in Physics (see: 'The hundredyear quest for gravitational waves — in pictures').

But direct detection of the waves had to await the sensitivity achieved by Advanced LIGO, which can detect stretches and compressions of spacetime that are as small as one part in 1022 — comparable to a hair'swidth change in the distance from the Sun to Alpha Centauri, the nearest star to the Solar System.

LIGO's twin interferometers bounce laser beams between mirrors at the opposite ends of 4kilometrelong vacuum pipes that are set perpendicularly to each other. A gravitational wave passing through will alter the length of one of the arms, causing the laser beams to shift slightly out of sync.

Paid for by the US National Science Foundation, the machines were designed and built by teams at the California Institute of Technology (Caltech) in Pasadena and the Massachusetts Institute of Technology (MIT) in Cambridge. Caltech's Kip Thorne and Ronald Drever, along with MIT's Rainer Weiss, were the original founders.

More than 1,000 scientists now belong to the LIGO collaboration. By studying gravitational waves, this next generation of researchers expects to probe entirely new realms of physics, including strongfield gravity, the very early Universe and how matter behaves at extremely high densities.

Hawking says that he would like to use gravitational waves to test his area theorem: that "the area of the final black hole is greater than the sum of the areas of the internal black holes." He adds: "This is satisfied by the observations."

"It's the very real dawn of a new era," says Mansi Kasliwal, an astronomer at Caltech.

The Ring Tone

Reported today in Physical Review Letters, LIGO's latest finding stems from the clearest gravitational-wave signal yet.

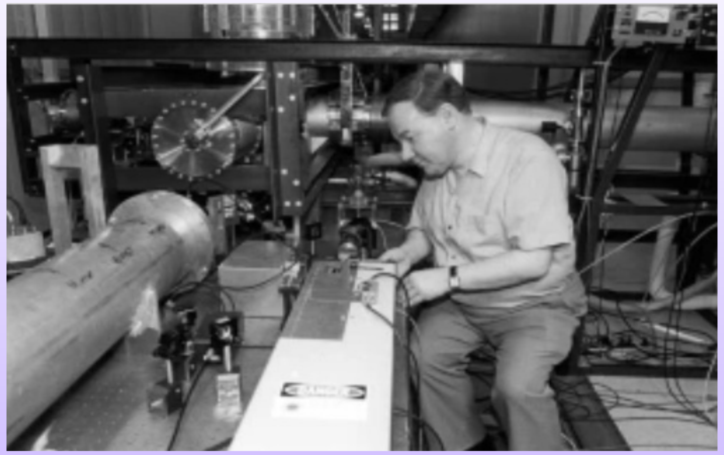
As the telltale signs of a gravitational wave on 14 January emerged from the noise of LIGO's observations, researchers listened to two black holes fusing together. This time, however, they could also detect the vibrations produced by the single black hole spawned by the collision.

Typically, it's difficult to pick out this 'ringdown' from the merger itself. But thanks to the ten years spent fine-tuning LIGO's instruments, scientists made their most-sensitive measurements so far.

Analysis of the ringdown showed that the two parent black holes, which had a combined surface area of 240,000 square kilometres, birthed a much larger one, with a surface area of 400,000 square kilometres.

The clear increase in size lends more credence to Hawking's black-hole-area theorem, which posits that the surface areas of these bodies can never decrease. Although Hawking died before he could witness this confirmation, he said in 2016 that he thought LIGO would be capable of such a feat.

This detection will quickly "become one of my favourites", says David Reitze, executive director of the LIGO laboratory at the California Institute of Technology in Pasadena. "It was the perfect ten-year anniversary gift," adds his colleague Katerina Chatziioannou, a LIGO physicist.



The First Chrip

LIGO began operations in 2002, but it wasn't until after an upgrade that wrapped up in 2015 that it picked up the first-ever murmurs of a gravitational-wave event. And it was an event, indeed. After five months of checking repeatedly that the signal wasn't just background noise or a fake chirp, planted to test the detector, researchers announced their discovery with much jubilation at press conferences around the world. For the first time, scientists had proved that they could "listen to the thundering cosmos", says Reitze, "even though the thunder was a tiny little blip by the time it got to Earth". That blip came from a black-hole merger 1.3 billion years ago. That was how long it took for the collision's subsequent ripples in space-time to cascade all the way to Earth. The detection "was the first observational evidence for the existence of binary black-hole systems", the pairs of black holes that produce these cosmic crashes, says Gabriela González, a physicist at Louisiana State University in Baton Rouge and LIGO's spokesperson at the time of the discovery. The detection won the 2017 Nobel Prize for confirming the century-old prediction of gravitational waves from Einstein's general theory of relativity. Einstein got one thing wrong, however: he thought gravitational waves would never actually be detected.

The Light Show

Mere seconds after LIGO felt the rumble of a gravitational-wave event on 17 August 2017, NASA's Fermi Gamma-Ray Space Telescope spotted a flash of high-energy photons 40 million parsecs away. The two detections were anything but a coincidence. Scientists concluded that both events were made by the collision of two neutron stars, the ultra-dense, leftover cores of stars that have become supernovae. As the two bodies swirled into each other, they emitted gravitational waves that weren't consistent with a black-hole collision. The impact also created an eruption of light called a γ-ray burst, the Universe's most-powerful type of explosion, supporting the idea that the colliding bodies were indeed neutron stars. The discovery wasn't just the first detection of a neutron-star merger, but the first joint appearance of gravitational waves and light. It solidified the theory that neutron-star mergers create γ-ray bursts and confirmed that gravitational waves and light travel at the same speed (as Einstein predicted). It also revealed that such mergers forge heavy elements, including gold and platinum. That's why researchers herald this discovery as a 'gold mine' event. "It turned out to be a very rich discovery in terms of gravitational waves, astrophysics and nuclear physics," says Peter Fritschel, associate director for LIGO at the Massachusetts Institute of Technology in Cambridge. "It was the source we had been waiting for, and it came with fireworks," says González.

The Monster Merger

On 23 November 2023, LIGO listened to a merger of black holes that weighed in at 100 and 140 times the mass of the Sun. Never before had LIGO detected a collision between two such massive objects. The resulting giant black hole was a whopping 225 solar masses.The two parent black holes also spun remarkably fast, with one "warping the surrounding space-time in a manner reminiscent of a tornado", says Alessandra Buonanno, director of the Max Planck Institute for Gravitational Physics in Potsdam, Germany. Researchers think the two bodies were themselves spawned from mergers, making the black hole resulting from the latest merger a grandchild of sorts. All signs "hint at a potentially intricate formation history".

Monster Merger is Unmatched

Physicists have detected the biggest ever merger of colliding black holes. The discovery has major implications for researchers' understanding of how such bodies grow in the Universe. "It's super exciting," says Priyamvada Natarajan, a theoretical astrophysicist at Yale University in New Haven, Connecticut, who was not involved in the research. The merger was between black holes with masses too big for physicists to easily explain. "We're seeing these forbidden high-mass black holes," she says.The discovery was made by the Laser Interferometer Gravitational-Wave Observatory (LIGO), a facility involving two detectors in the United States. It comes at a time when US funding for gravitational-wave detection faces devastating cuts. The results, released as a preprint on the arXiv server, were presented at the GR-Amaldi gravitational-waves meeting in Glasgow, UK, on 14 July.

Forbidden Mass

LIGO detects gravitational waves by firing lasers down long, L-shaped arms. Minuscule changes in arm length reveal the passage of gravitational waves through the planet. The waves are ripples in space-time, caused by massive bodies accelerating, such as when two inspiralling black holes or neutron stars merge. Hundreds of these mergers have been observed using gravitational waves since LIGO's first detection in 2015. But this latest detection, made in November 2023, is the biggest yet. By modelling the signal detected by LIGO, scientists have calculated that the event, dubbed GW231123, was caused by two black holes with masses of about 100 and 140 times that of the Sun merging to form a final black hole weighing in at some 225 solar masses.

"It's the most massive [merger] so far," says Mark Hannam, a physicist at Cardiff University, UK, and part of the LVK Collaboration, a wider network of gravitational-wave detectors that encompasses LIGO, Virgo in Italy and KAGRA in Japan. It's "about 50% more than the previous record holder", he says.

Most of the events captured by LIGO involve stellar-mass black holes — those ranging from a few to 100 times the mass of the Sun — which are thought to form when massive stars end their lives as supernovae. However, the two black holes involved in GW231123 fall in or near a predicted range, of 60–130 solar masses, at which this process isn't expected to work, with theories instead predicting that the stars should be blown apart. "So they probably didn't form by this normal mechanism," says Hannam.

Instead, the two black holes probably formed from earlier merger events — hierarchical mergers of massive bodies that led to the event detected by LIGO, which is estimated to have happened 0.7 billion to 4.1 billion parsecs (2.3 billion to 13.4 billion light years) away.

It's like "four grandparents merging into two parents merging into one baby black hole", says Alan Weinstein, a physicist at the California Institute of Technology in Pasadena and also part of the LVK Collaboration. Models of the black holes also suggest that they were spinning exceedingly fast — about 40 times per second, which is near the limit of what Einstein's general theory of relativity predicts black holes can reach while remaining stable. "They're spinning very close to the maximal spin allowable," says Weinstein.

Both the spin and the mass could provide clues to how black holes grow. One of the biggest questions in astronomy is how the largest black holes, the supermassive ones found at the centres of galaxies such as the Milky Way, grew in the early cosmos.

Although there is plenty of evidence for the existence of stellar-mass black holes and supermassive black holes — those of more than a million solar masses intermediate-mass black holes in the range of 100 to 100,000 solar masses have been harder to find. "We don't see them," says Natarajan.

The latest detection might tell us that "these intermediate-mass black holes of several hundred solar masses play a role in the evolution of galaxies", says Hannam, perhaps through hierarchical mergers, which could increase the spin speed, as well as the mass, of the resulting black holes. "Little by little, we're building up a list of the kind of black holes that are out there," he says.

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