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A pair of black holes spiral together, unleashing a torrent of gravitational waves that eventually will sweep across the universe.

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Novelty to science

The last three binary black holes opened exotic new realm of astrophysics.
n September 14, 2015, the international LIGO collaboration accomplished the seemingly impossible. Its twin laser interferometers in Louisiana and Washington made the first direct detection of gravitational waves, long-sought deformations in the fabric of space-time predicted a century earlier by Albert Einstein in his general theory of relativity.

LIGO (the Laser Interferometer Gravitational-wave Observatory) caught the final half-second inward spiral and merger of two black holes containing the masses of 29 and 36 Suns. In a fleeting moment, the smash-up created a 62-solar-mass black hole and converted the remaining 3 solar masses into pure gravitational wave energy, a cosmic tsunami that barreled outward at the speed of light. The wave's peak power briefly exceeded the total energy output of the entire visible universe 50 times over, but none of this energy was in any form of light.

As the wave radiated 1.3 billion-light-years in all directions, an infinitesimally tiny portion of its energy passed through Earth. It alternately stretched and compressed the two 2.5-mile-long (4 kilometers) arms in each LIGO facility by 1/1,000 the width of a proton. With their powerful lasers, both LIGO facilities caught these deformations with a precision equivalent to measuring the 4.2-light-year distance to Proxima Centauri to the width of a human hair.

LIGO's scientific and technical breakthrough was so astounding that its February 11, 2016, announcement managed to briefly steal the media limelight from the U.S. presidential election.

LIGO followed up this Nobel-worthy discovery with a second detection on December 25, 2015. This event involved the cataclysmic coalescence of 8- and 14-solar-mass black holes at a distance similar to the first event. LIGO also detected a possible merger October 12, 2015, between black holes of about 13 and 23 solar masses. The team is about 90 percent confident that this event is real, but refrained from claiming it as an official detection.

After shutting down LIGO for 11 months for a series of upgrades, the team began a new science run in late November 2016. Five weeks later, on January 4, 2017, the observatory caught waves from a third black hole coalescence, with objects of 19 and 31 solar masses.

Just two years ago, astronomers had no direct evidence that stellar-mass black holes paired up in binary systems. Now they know for certain that such binaries exist, and that they have finite lifetimes. "The key thing to take away from this third highly confident event is that we're really moving from novelty to a new observational science, a new astronomy of gravitational waves," LIGO spokesman David Shoemaker said at the May 31 discovery press conference.

Analyzing the waves from the three mergers has yielded crucial information about black hole masses and spins. But the field is still in its infancy. In the years ahead, we can expect profound discoveries that would be impossible to make any other way. We'll learn about black hole formation, whether some neutron stars are made of exotic matter, and whether general relativity breaks down in nature's most extreme laboratories.

"After personally working endless hours on LIGO for 18 years, 16 of those seeing nothing, it's nice to live in a world where gravitational wave astronomy is a real thing," says Amber Stover of Villanova University. "And there is still so much more out there to discover."

Heavy black holes
LIGO's latest discovery delighted scientists for several reasons. Like LIGO's first detection, it involves a new class of black holes considerably more massive than the stellar-mass black holes previously detected in binary systems with normal stars. Those earlier known black holes range from about 5 to 15 solar masses, and they presumably formed when the cores of massive stars collapsed and triggered supernovae, which ejected most of their stars' envelopes into space.

Some members of the heavier class that LIGO detected probably arose from prior black hole mergers, but most presumably formed from the deaths of massive stars. Theorists have predicted that heavier black holes can form if their progenitors were deficient in elements heavier than hydrogen and helium. These so-called "low-metallicity" stars were common in the early
universe. They produce weaker stellar winds, so their envelopes retain a high fraction of their mass as the stars age.

When a massive low-metallicity star dies, its core collapses into a neutron star. But sometimes the supernova engine proves too weak to blow off a massive envelope, so the explosion fizzles. The neutron star accretes infalling material for several seconds and collapses into a black hole. A black hole formed in one of these "failed supernova" could gobble up several dozen solar masses.

Coincidentally, just a week before the third LIGO announcement, the Space Telescope Science Institute issued a press release touting a possible failed supernova. Using the Hubble Space Telescope and the Large Binocular Telescope, a team led by Ohio State University astronomers observed a highly luminous star in spiral galaxy NGC 6946 vanish from sight with no supernova. This star apparently collapsed into a black hole — possibly in the heavy mass range seen by LIGO.

LIGO’s merged black holes are also highly significant. The heavier two contain about 62 and 49 solar masses, falling into an intermediate mass range between stellar-mass black holes and the supermassive black holes in the centers of galaxies.

Astronomers have identified several binaries that consist of two supermassive black holes weighing millions or billions of solar masses. These monstrous systems, which arise when galaxies merge, radiate gravitational waves with wavelengths far too long for LIGO to detect. But teams of radio astronomers in the United States, Europe, and Australia are monitoring pulsars — rapidly spinning neutron stars that emit precisely timed pulses — to catch these waves. When gravitational waves from these supermassive binaries cross the space between Earth and these distant pulsars, they slightly affect the arrival time of pulsar pulses. Because pulsar timing is so precise, it’s likely these teams will detect long-wavelength gravitational waves in the next several years.

Forming black hole binaries

LIGO’s recently announced merger also sheds light on the fascinating question of how black holes pair together in binaries. One possibility is that the progenitor stars were always gravitationally bound. The two stars eventually collapsed and left behind black hole corpses that remained locked together. Gravitational waves slowly drained the binary’s orbital energy, inexorably closing the gap between the black holes over billions of years. But only in the final seconds before they collided were the waves powerful enough and in the right wavelength band to be detected from Earth.

But the third LIGO event offers evidence for a different scenario. Just like stars and planets, a black hole spins on its axis. If the black hole progenitors formed together in a binary system, their spin axes should be aligned with their orbital plane.

According to relativity, the two couldn’t merge until they draw extremely close and shed some of the system’s rotational energy. But the LIGO data doesn’t show this slight delay, indicating that the spin axis of one or both black holes was tilted with respect to the orbital plane.

“This finding likely favors the theory that these two black holes formed separately in a dense stellar cluster, sunk to the core of the cluster, and then paired up, rather than being formed together from the collapse of two already-paired stars,” says LIGO team member Laura Cadonati of Georgia Tech University.

As the LIGO team ramps up the interferometers’ sensitivities in the coming years, the instrument will see deeper into space, bringing millions of new galaxies into view. Although black hole mergers are extremely rare events in any given galaxy, extending LIGO’s reach means the two facilities will catch hundreds of black hole mergers each year. By analyzing the statistics of dozens and eventually hundreds of mergers, scientists should be able to determine which mode of black hole binary formation predominates.

Because astronomers don’t expect black hole binaries to radiate much light in any part of the spectrum, there is no other way to observe these incredible systems. As West Virginia University physicist Paul Baker explains, “Studying black hole binaries was one of LIGO’s great selling points. LIGO is probing something that no other instrument has probed before.”
Testing general relativity

The most recent LIGO event was also noteworthy for the relative weakness of its gravitational waves considering the black holes’ high masses. The signal’s faintness yields an estimated distance of 3 billion light-years, more than twice that of the first two detections.

The greater distance gave the LIGO team a golden opportunity to test a key prediction of general relativity: that gravitational waves don’t disperse, meaning all frequencies travel at exactly the same velocity (the speed of light). If gravitational waves disperse, slower frequencies will arrive at the detectors after the faster ones. And the farther away the source, the greater the time lag.

“Our measurements are very sensitive to minute differences in the speeds of different frequencies,” says Bangalore Sathyaprakash of Penn State and Cardiff universities. “But we did not discover any dispersion, once again failing to prove that Einstein was wrong.”

Just as photons transmit the electromagnetic force, hypothetical quantum particles known as gravitons convey the force of gravity. Quantum theory predicts that gravitons should have zero rest mass, just like photons. Any hint of dispersion would indicate that gravitons have mass, so dispersion would contradict quantum theory as well as relativity. The most recent LIGO detection tightened the limits on a possible graviton mass by 30 percent.

Despite the more than $1 billion the National Science Foundation and its international partners have spent on LIGO, the project remains a work in progress. When it ramps up to its final design sensitivity sometime after 2020, LIGO will start detecting hundreds of black hole mergers a year, with many of them at even greater distances. And because the farther the source, the better the chances of seeing any dispersion, scientists should be able to tell whether gravitational waves deviate at all from general relativity’s predictions. Einstein has passed every test so far.

“Black hole mergers are an incredibly dynamic and strong regime to test general relativity. I don’t think anybody is expecting any crazy differences, so any deviations will be subtle,” Penn State astrophysicist Chad Hanna says.

Any such detection would rock the foundations of science, but it could guide physicists toward a long-sought unification of general relativity and quantum theory. As Penn State physicist Abhay Ashtekar says, “I don’t think general relativity is the final word on gravitation because it ignores quantum physics.”

Virgo joins the search

On August 1, less than a month before LIGO closed for about a year for more upgrades, a new partner joined the search: the European Virgo interferometer near Pisa, Italy. With 1.9-mile-long (3km) arms, Virgo will be considerably less sensitive than LIGO at first, but like its sibling, it will undergo improvements over time to extend its range.

Adding a third interferometer will take gravitational wave science to new heights. Most importantly, Virgo will enable scientists to locate a gravitational wave source more precisely, giving astronomers a better chance of catching an electromagnetic signal from the event itself, or from its afterglow. Although expected to be incredibly faint, any kind of electromagnetic counterpart to a gravitational wave source would usher in a revolutionary new era of multi-messenger astronomy. It would allow scientists to
compare the signals and extract detailed information about the physics of the event.

With just the two LIGO detectors, scientists use the slight difference in a wave's arrival time between Louisiana and Washington to narrow down the location of a source to roughly 100 square degrees. But as amateur astronomers know, that's a huge area of sky. Finding an afterglow is essentially hopeless. Scientists would feel confident they had seen an electromagnetic counterpart to a LIGO detection only if they detected a simultaneous supernova or gamma-ray burst (GRB) in the same area. Adding a third interferometer will enable scientists to triangulate some sources to about 10 square degrees. This smaller patch of sky would give astronomers a fighting chance to spot an afterglow.

The LIGO team currently sends out alerts to about 70 astronomical partners only after it has studied a candidate gravitational wave and feels confident it's not an instrumental glitch, a process that takes several minutes. But once the LIGO and Virgo teams have built up confidence with more detections, they will issue public alerts more quickly after they register a promising signal.

Two additional laser interferometers currently under construction will enable researchers to pin down the location of some sources to only 1 square degree. Japan is building its KAGRA interferometer under a mountain. With two 1.9-mile-long (3km) arms, it features some cutting-edge technology, such as cryogenically cooled mirrors that should reduce instrument noise. After a series of significant delays, scientists expect KAGRA — short for Kamioka Gravitational Wave Detector — to join LIGO and Virgo next year.

A clone of the LIGO interferometers will be built in Maharashtra, India, using hardware initially built for LIGO's Washington facility. LIGO-India is scheduled to begin science operations around 2024, with a sensitivity similar to the two U.S. instruments.

**Sky map of mergers**

Scientists may need the more robust capabilities of an expanded network to go beyond black hole mergers. While black hole binaries were only theorized prior to LIGO's first detection, astronomers were 100 percent certain that neutron star binaries existed. In fact, radio astronomers have detected 20 such pairs. And in every case where they can make high-precision measurements, the binary's orbit is shrinking exactly in accordance with Einstein's predictions of how gravitational waves carry away orbital energy. In other words, neutron star binaries are also destined to merge.

LIGO has yet to see any such mergers because neutron stars have lower masses than black holes, so their mergers produce weaker gravitational waves. The observatory can detect neutron star mergers only out to about 290 million light-years. But as the team ramps up LIGO's sensitivity and extends this range to 1.4 billion light-years, it will start catching these rare but highly significant events.

Astronomers suspect that neutron star mergers initiate most GRBs lasting less than two seconds, although some of them might come from mergers between black holes and neutron stars. A simultaneous gravitational wave event and GRB would be immensely important because it would reveal the nature of the progenitor. It also would help answer burning questions about the energy source that powers GRBs, how the merger ejects mass, the angle at which matter gets beamed in jets, and how that material produces gamma rays.

Perhaps even more important: As the two neutron stars draw close, each star's gravity tidally distorts its partner, which, in turn, affects how fast they spiral inward in the final milliseconds prior to merging. Any detection of gravitational waves from this tug-of-war will yield valuable information about the highly compressed nuclear material inside each neutron star.

Recent computer simulations show that the merger itself produces a hypermassive
neutron star with a density several times higher than atomic nuclei. Such an object spins rapidly, producing a centrifugal force that briefly prevents it from collapsing into a black hole. These extraordinarily dense objects shed rotational energy by emitting gravitational waves. LIGO will be challenged to detect these waves, but if scientists luck out and catch a neutron star merger within 100 million light-years, they could gain precious insights into matter as it is compressed to almost unimaginably high densities. “We would be able to witness the final victory of gravity over nuclear forces as the star collapses to form a new black hole,” says Princeton University theorist David Radice.

LIGO also could discover the first known binary consisting of a black hole orbiting a neutron star. Although scientists think such systems are extremely rare, they almost certainly exist. In these systems, the black hole would tidally rip apart the neutron star just before they coalesce, producing strong gravitational waves that would reveal vital information about the neutron star’s composition.

Even solitary neutron stars could give off gravitational waves. With their incredibly high densities, neutron stars should be perfectly symmetrical about their rotation axes. But neutron stars with bulges just a couple of inches high would radiate gravitational waves continuously. LIGO might catch these waves if any of these neutron stars reside in our corner of the Milky Way. Such detections would yield critical evidence about whether neutron star cores are made of conventional nuclear matter or exotic material, such as strange quarks. You can participate in this search by visiting https://einsteinathome.org and letting your computer sift through LIGO and other data while you’re away.

The ultimate cosmic messenger

While LIGO has already identified several black hole mergers, another type of event could prove even more valuable. Our Milky Way is long overdue for a supernova. A galactic event triggered by the collapse of a massive star’s core would be an astrophysicist’s dream come true—a cosmic Rosetta stone of multi-messenger astronomy. Although a core collapse would be phenomenally bright across much of the electromagnetic spectrum, it also would produce on the order of 10$^{50}$ neutrinos representing 99 percent of the supernova’s energy. The world’s various neutrino detectors would register tens of thousands of hits, giving precious insights into the explosion mechanism. And under certain conditions, a collapsing stellar core will unleash gravitational waves that could be detected from Earth.

“The gravitational waves would be emitted at almost exactly the same time as the neutrinos, so you could correlate the two events,” says Princeton astrophysicist Adam Burrows. “If we could get all that information from the signal, we’d really have a window on exactly what was happening in real time.” Theorists would learn about the core’s rotation, density, and mass, and how turbulence and asymmetries affect the explosion.

But how close would that supernova have to be? The mass involved in a collapsing stellar core is tiny compared with that in a binary merger, so the gravitational waves are much weaker. And, Burrows notes, a spherical core collapse wouldn’t produce gravitational waves.

According to Shunsaku Horiuchi of Virginia Tech, the detectable range depends on the symmetry of the collapsing core as well as other factors. A highly asymmetric collapse would produce stronger waves, so LIGO might have an outside shot at hearing such a supernova in a nearby galaxy. But if the collapse is nearly symmetric, it would be a challenge for LIGO even if the explosion occurred well within the Milky Way.

Horiuchi also points out another intriguing possibility: If a massive star in our galaxy collapses into a black hole and fails to produce a supernova, it could be a detectable gravitational wave source with little or no corresponding electromagnetic signal.

The exotic and the unknown

Of all astrophysical objects expected to produce gravitational waves LIGO could detect, cosmic strings are the most speculative and exotic. Some theories of cosmic inflation predict that strings of ultradense matter thinner than atoms formed when the early universe went through a phase transition. Some of these strings could stretch across millions of light-years of intergalactic space.

There is not a shred of observational evidence that cosmic strings even exist. But if they do, they could interact with each other occasionally, causing them to pinch off into loops that should radiate powerful bursts of gravitational waves. LIGO and Virgo might be able to hear these signals, or other phenomena relating to strings. Any such discovery could revolutionize cosmology.

But of all the potential sources that astrophysicists can dream up, the most tantalizing possibility is a completely unexpected type of signal. Any reputable physicist will admit that it’s impossible to imagine that humans, with our itty-bitty brains, have conceived of every possible source that could produce detectable gravitational waves.

Stuver sums up the greatest hope of all: “What I really want is to find a gravitational wave that we know is real but have no idea what made it. The process of discovering its source will be an amazing scientific journey that will revolutionize our understanding of the universe. After all, every time humans have looked at the universe in a new way, it has always revealed something unexpected and exciting!”

Robert Naeye served on the editorial staff of Astronomy from 1995 to 2000. He was editor-in-chief of Sky & Telescope from 2008 to 2014.