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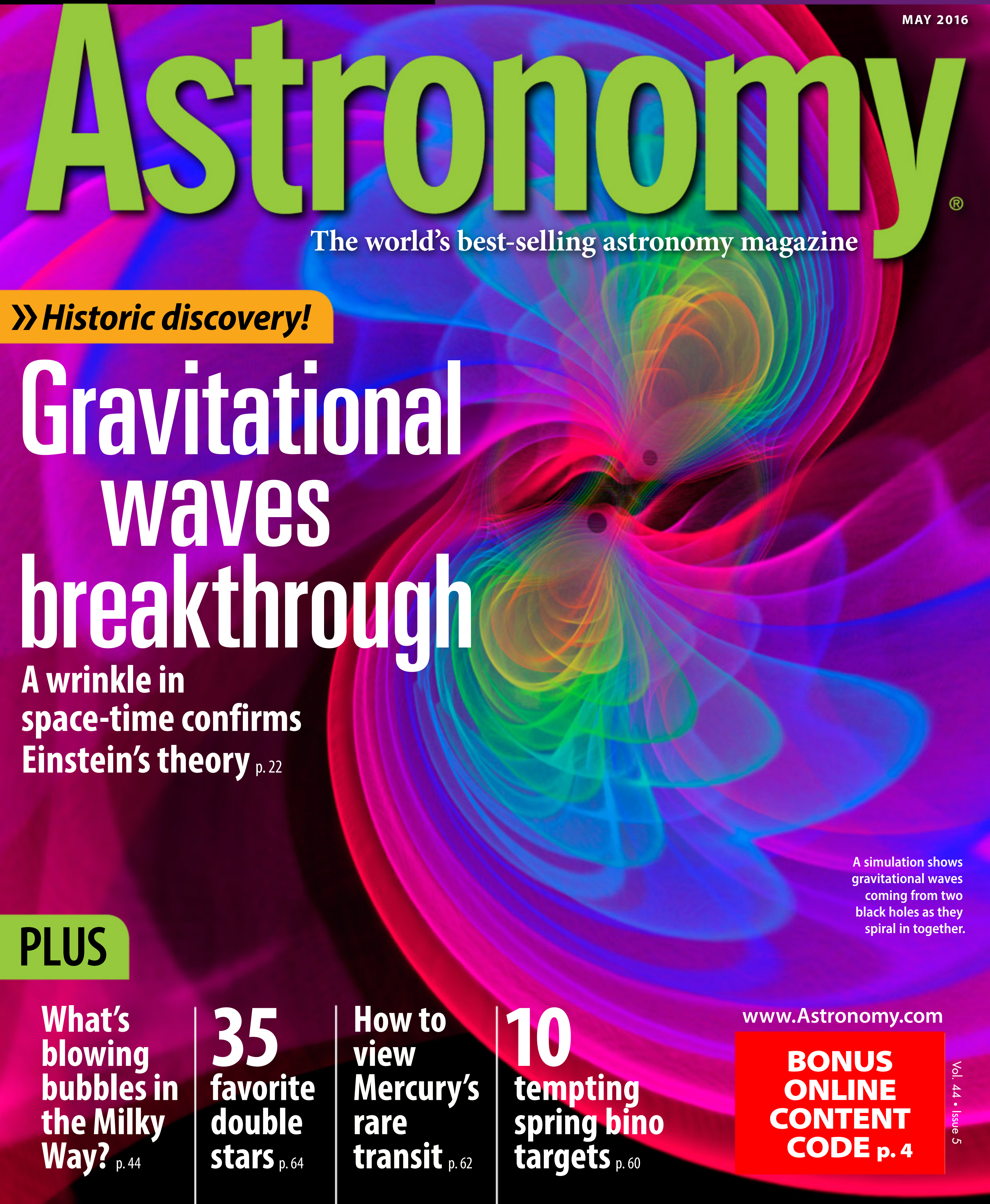

A simulation shows gravitational waves coming from two black holes as they spiral in together.

» Historic discovery!

Gravitational waves breakthrough

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A wrinkle in space–

Astronomers have finally found gravitational waves. Now things can get interesting. **by Korey Haynes and Eric Betz**

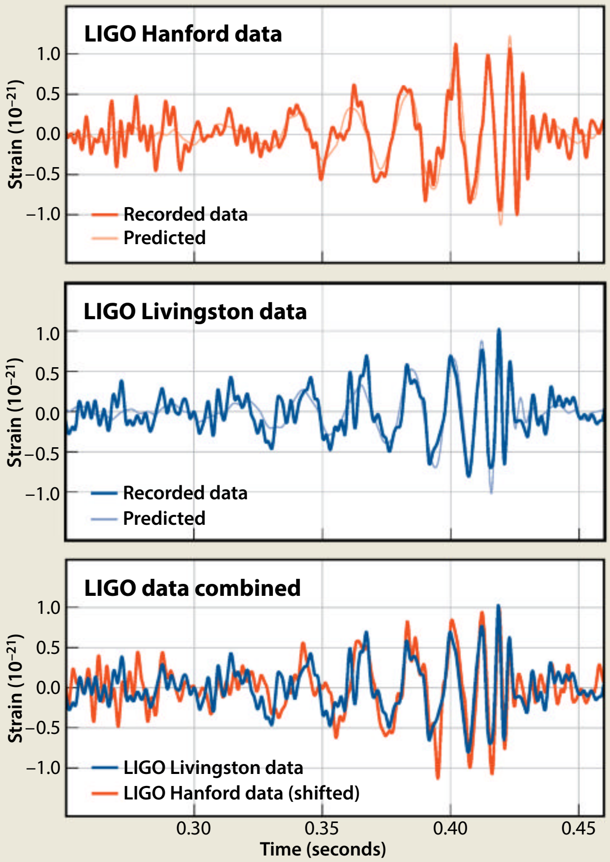
time confirms Einstein's gravitation

"Ladies and gentlemen, we have detected gravitational waves. We did it!" The words from LIGO spokesman David Reitze prompted cheers at the press conference on February 11, and with good reason. The tangibility of gravitational waves has taunted scientists since Albert Einstein first predicted them 100 years ago. In the intervening century, scientists have proved relativity a hundred times over. But no one had ever measured the delicate vibrations of the waves themselves.

These ripples in space-time are currently detectable only when the universe's densest objects — black holes or neutron stars — smash together. And on September 14, 2015, the ripples arrived from two black holes that merged some 1.3 billion light-years away. Despite the cosmos-shaking collision that produced the first recorded signal, LIGO (the Laser Interferometer Gravitational-wave Observatory) had to strain to hear it past the literal earthquakes and even nearby motor traffic that also jounces its detectors.

Merging black holes warp space around them in this artist's illustration, gravitationally lensing background stars and causing the swirls visible around them. SXS

The first detection



This signal from a gravitational wave passed through both LIGO detectors in Hanford, Washington, and Livingston, Louisiana, matching model predictions closely. The wave struck the Livingston site first, and the Hanford site seven-thousandths of a second later, traveling at the speed of light. Space-time between LIGO's beams was stretched by an amount equivalent to the width of a human hair between the Sun and Alpha Centauri. LIGO

"Imagine the instrument as a giant ruler," says Marco Cavaglià, a University of Mississippi astronomer and assistant LIGO spokesman. "We measure distance along two perpendicular arms, and if these distances change, then we can see it with the laser light." Although the gravitational waves are incredibly weak — only enough to warp the distance between Earth and the Sun by the width of a hydrogen atom — LIGO's instruments are extremely sensitive.

The detection of these ripples has opened up a new way to observe the universe, allowing astronomers to "hear" in the darkest regions of space where telescopes yield no information. Black holes, for instance, are impossible to observe directly; they emit no light. But with gravitational waves, astronomers can probe the very hearts of singularities. They stand to discover black holes completely invisible to traditional observatories — and surely other surprises as well.

"It is, of course, the great hope of all the astrophysicists involved here that this new window will allow us to see things that one has not even thought of before," says Albert Einstein Institute senior scientist Albrecht Rüdiger, who spent his entire career developing gravitational wave detectors.

In 1865, James Clerk Maxwell predicted that light travels in waves, but humanity needed Heinrich Hertz's first radio transmitter to unleash modern technology and unveil new types of cosmic phenomena. And radio was simply a different breed of the same species of electromagnetic radiation our eyes see naturally. Measuring cosmic tremors from gravitational waves gives scientists a wholly new sense with which to observe the universe.

And that universe turns out to be a violent place. LIGO witnessed the cosmic collision between black holes 36 and 29 times the Sun's mass. Afterward, the new combined black hole was left with only 62 solar masses. Most of the colossal difference — some 5,000 supernovae worth of energy — radiated away as gravitational waves. Yet it took the most sensitive machine in human history to notice this tsunami in space-time.

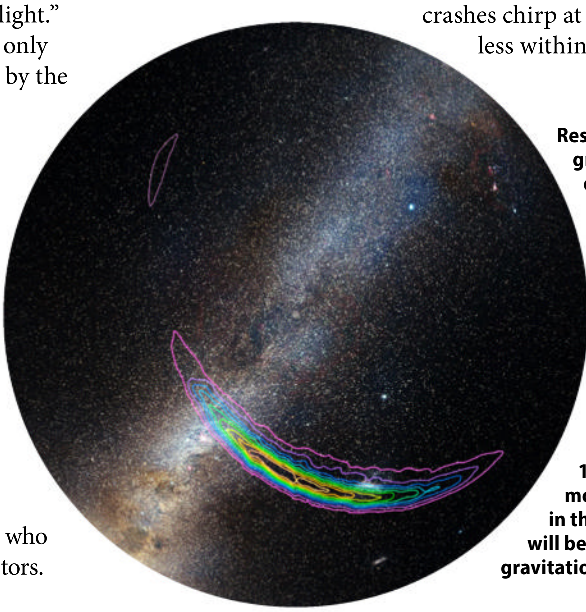
A most violent affair

Einstein's theory of general relativity tells us that gravity is simply the warping of the fabric of space-time by massive objects. He figured out that massive moving objects would create ripples in this fabric, like a child's bounce on a trampoline. What's more, these gravitational waves would spread throughout the universe at the speed of light. The trick is in detecting them.

At the center of LIGO's L-shaped arms sits a laser and beam-splitter that sends light racing toward mirrors at the end of each arm. Normally, light waves take the same amount of time to travel back and forth along both arms. The peaks and troughs should line up when the two beams meet again at the center, perfectly canceling out.

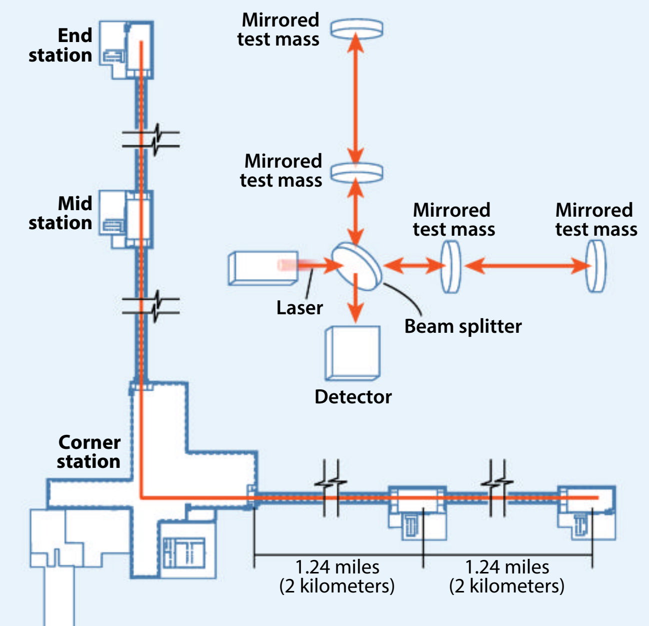
But when a gravitational wave passes, the bunching and squeezing of space-time stretches one arm while compressing the other, changing the distance the light has to travel. Now, when the laser beams rejoin, scientists see interference in the light's pattern, a jarring mismatch of peaks and valleys that spills the secrets of gravitational waves — if scientists can read through the static of local noise that can also jiggle the mirrors and mar the signal.

And just as stars, supernova explosions, and the Big Bang's fading glow all give off different frequencies of light, they also send out different frequencies of gravitational waves. The most extreme events in the universe — colliding supermassive black holes — emit a hum 10,000 times lower than a whale song, too deep for LIGO to hear. Neutron stars are dense stellar corpses with masses a little larger than the Sun crammed into a city-size sphere. Their crashes chirp at frequencies more or less within the range of a piano,



Researchers estimated the gravitational waves' source direction based on the time delay between the two detectors. But this still leaves a wide swath of sky. The measurements indicate 90 percent probability that the source lies somewhere within the purple contours, but the more specific yellow contour holds only 10 percent confidence. As more detectors come online in the coming years, scientists will be able to better pinpoint gravitational wave sources. LIGO

How LIGO works



Each of the LIGO detectors sends laser pulses down two 2.5-mile (4-kilometer) arms and combines their light. By making laser light travel up and down the arms and interfere with itself, scientists are able to deduce very small changes in the light's path from a gravitational wave encounter. *ASTRONOMY*: ROEN KELLY

The LIGO site in Livingston, Louisiana, resides near a large lumber operation. When timber was still being cleared, researchers could pick up the crash of falling trees with their sensitive detectors. CALTECH/MIT/LIGO LAB

and the stellar mass black hole collision LIGO heard last year falls into a similar range.

LIGO was built to hunt compact binary objects. These include pairs of neutron stars, pairs of stellar mass black holes or crashes involving one of each. All the events involve dense objects locked in a death spiral toward one another. Astronomers can watch neutron stars orbit each other for many years using more traditional observatories, and all the while, energy leaks away from the system in the form of invisible gravitational waves. Joseph Taylor and Russell Hulse won the 1993 Nobel Prize in physics for showing such binary neutron stars radiate gravitational energy.

"What turned out to be the most important prediction is that a system like this should lose energy gradually in the form of gravitational waves," says Taylor. "Those waves should be carrying away orbital energy and orbital momentum, and the orbit should gradually evolve."

But the constant radiation of these gravitational waves is too weak for current detectors. And the Hulse-Taylor pulsar pair, designated PSR B1913+16, won't actually collide for hundreds of millions of years. To directly observe gravitational waves, multiple science teams worked for decades to build instruments sensitive enough to detect the ripples emanating from collisions far beyond the Milky Way. LIGO got there first.

"LIGO senses those last few minutes or seconds of the waves generated just before the objects crash into one another," explains Patrick Brady, a professor at the University of Wisconsin-Milwaukee and a member of the LIGO collaboration. LIGO begins to hear the impending collision once the orbits tighten to about five times per second. At that point, the gravitational waves reach a frequency of 10 hertz, or cycles per second, the low end of its range. In the few moments left in their lives (0.2 second for LIGO's black hole pair), the tightening spiral causes the gravitational waves to increase in both frequency and strength. "That means they sweep right through the most sensitive band of the LIGO instruments," Brady says.

Even Einstein had his doubts

LIGO's detection presages the future, but it also caps off a century of speculation and hard work. Even Einstein himself was a prominent doubter. In 1936, 20 years after he introduced the concept, the great physicist took another look at his math and reached a surprising conclusion.

"Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation," he wrote in a letter to friend Max Born.

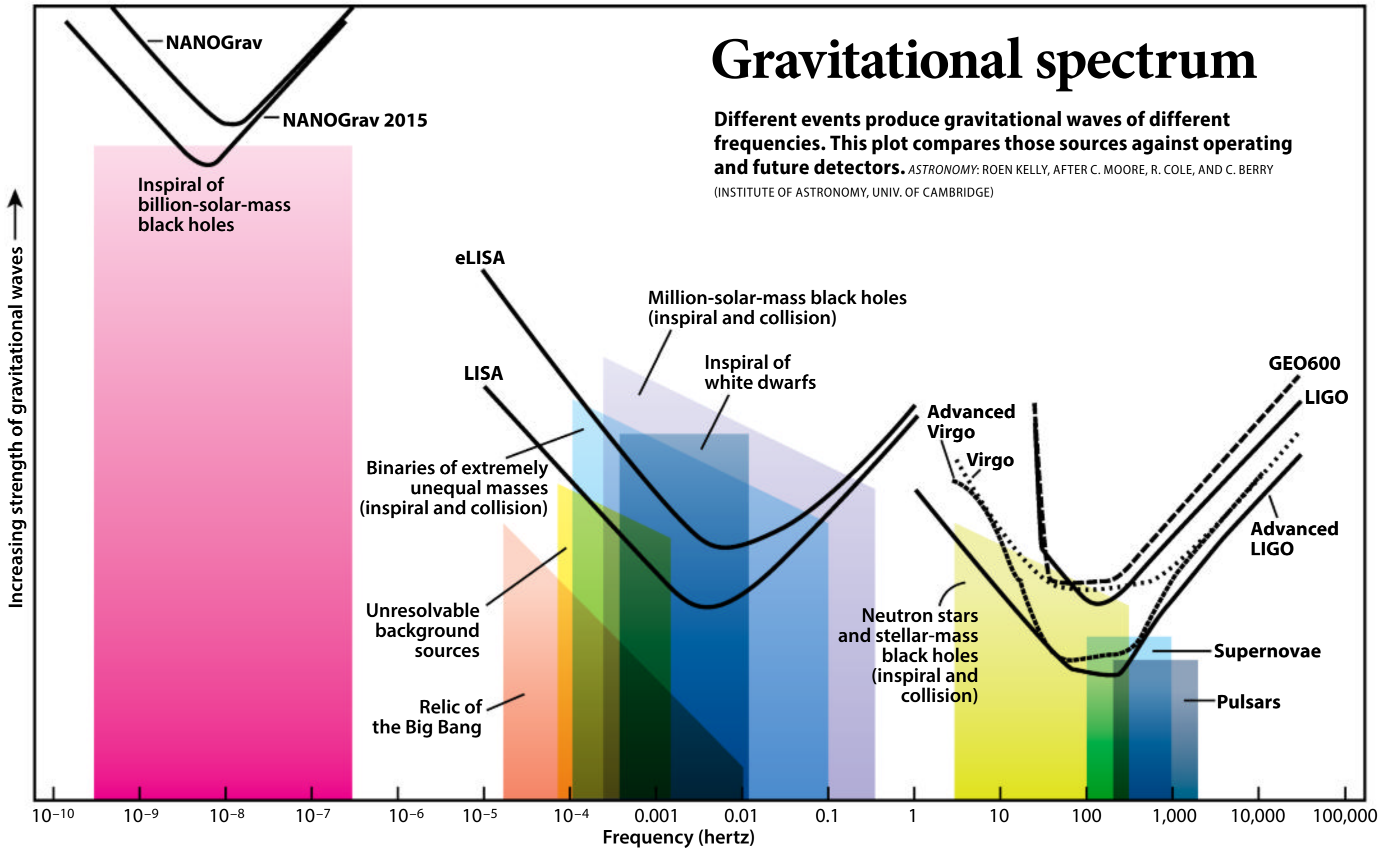
Einstein submitted his change of heart in a paper to the *Physical Review* titled "Do gravitational waves exist?" The reviewer soon poked holes in the math, showing how Einstein's coordinate system lacked imagination when dealing with pesky singularities. Upset, Einstein took his paper to a lesser-known journal, though he was persuaded to change his calculations and his mind just before publication. Although Einstein came back around to accept the existence of gravitational waves, he still didn't expect they'd be strong enough to detect. Many physicists shared that view.

In 1959, Joseph Weber, who was also an early pioneer of the laser, became the first person to actually look for gravitational waves. The experimental physicist used an aluminum bar like a tuning fork and then waited for it to move, staring at the noise for much of a decade. By 1969, he was convinced he'd found gravitational waves, and international headlines followed. But the scientific community was skeptical.

Walter Winkler was just starting his career at the time. Together with his mentor, legendary computer scientist Heinz Billing, they flew from Germany to Pennsylvania to visit Weber. The physicist openly shared his instrument design drawings.

From 1972 to 1975, Winkler's team performed a gravitational wave search that improved on Weber's methods. Their work proved beyond any doubt that Weber was watching extraneous noise and reading patterns into it.

Korey Haynes *and* **Eric Betz** *are* Astronomy *magazine associate editors.* **Carl Engelking** *and* **Bill Andrews** *of* Discover *magazine contributed reporting to this story.*



Gravitational spectrum

Different events produce gravitational waves of different frequencies. This plot compares those sources against operating and future detectors. *ASTRONOMY*: ROEN KELLY, AFTER C. MOORE, R. COLE, AND C. BERRY (INSTITUTE OF ASTRONOMY, UNIV. OF CAMBRIDGE)

"At that time, computers were not so common to everyone," says Winkler. "He worked with a recorder, so he had the output of his detectors written down on long strips of paper, and he sat down watching the detectors. And if you stare into the noise, you can be sure you'll see something. He was a man, not a machine."

Despite the failure to find the waves, Winkler's group continued to seek ever more sensitive detection methods. Across the Atlantic Ocean, another revolutionary experimental physicist had detailed a promising new approach to finding gravitational waves. The Germans took note of an interferometer design published by MIT's Rainer Weiss and built their own. Their first attempt had arms just a foot long. The next spanned a few yards.

As the team built larger interferometers, it became apparent that they'd need an instrument several miles long to actually detect the weak gravitational waves. The German government rejected such a project for its cost.

But in the United States, Weiss had continued his work toward larger interferometers. And in 1992, he co-founded LIGO with Kip Thorne and Ronald Drever of Caltech, thanks to funding from the National Science Foundation. It was NSF's most ambitious and expensive scientific project to date.

The chirp heard 'round the world

The biggest challenge for this sensitive new instrument was learning to see beyond the local chatter. Nearby highway traffic, waves lapping at the shore of the Gulf of Mexico, or a tree falling in the forest near the Louisiana site can all swamp the gravitational waves. Major earthquakes anywhere in the world can knock LIGO offline.

"If a car or a truck drives about 10 miles per hour [16 km/h] near the interferometer site, we can see that," Cavaglià says. "We see the noise of airplanes passing nearby."

Cavaglià likens the task to hunting through static with a car's radio dial for a clear station. "At a certain point, you find a station because you know you hear a voice. Your brain has the template of the voice, and you are able to recognize that there is a signal there," he says.

Researchers have expanded their theories from Einstein's basic framework to detailed models of what the pattern of a gravitational wave should look like. By comparing the data streaming in to models of different potential sources, researchers can pick out the voice of cosmic gravity from the static of earthly mumblings. Astronomers call this signal a "chirp." And the signal LIGO recorded was both clear and complete, encompassing not just the inspiral and collision, but what's called the "ringdown," the aftershock as the black hole settles into its new shape.

No one has ever detected a black hole merger before. So while theory didn't predict any light from the event, observatories across the world immediately checked to see if they might have picked up any simultaneous signals — the scientific method in action. One of them, the Fermi Gamma-ray Space Telescope, did indeed pick up an intriguing gamma-ray burst at just the right time, but a second gamma-ray satellite couldn't confirm the signal.

With only two detectors currently online, pinpointing where this object or future findings are located on the sky is a rough measure at best. Astronomers can triangulate where the signal came from by noting which detector saw the wave first — a difference of mere milliseconds. LIGO allows them to narrow the signal to within a couple hundred degrees on the sky. But backup is on the way.

A new kind of telescope

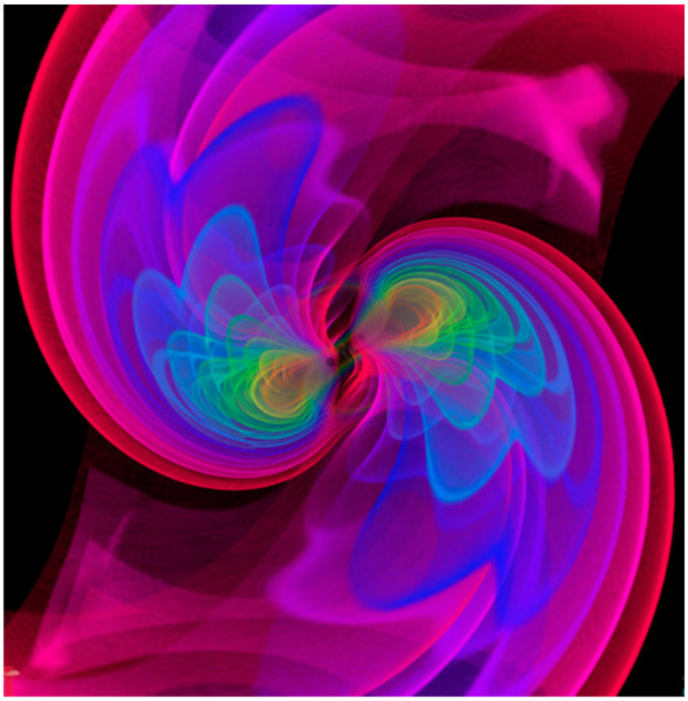
A handful of additional gravitational wave detectors should turn on in the coming decade. These instruments will allow astrophysicists to triangulate the incoming waves and home in on their sources.

An upgraded version of Virgo, the European Gravitational Observatory's primary instrument in Italy, will begin observations in the fall of 2016 in conjunction with LIGO. Advanced Virgo's improvements will increase its sensitivity tenfold, and allow researchers to probe a volume of space 1,000 times larger than before. Virgo could pick up a gravitational wave signal once per month, or even per week, with its enhancements.

And, in the immediate wake of LIGO's detection, the Indian government approved funding for LIGO India, which will serve as the third in the LIGO family and could be operational by 2022. When it comes online, the LIGO group expects they'll be able to place many gravitational wave signals within a few square degrees of sky — an area roughly 10 times the size of the Full Moon.

Meanwhile, in Japan, crews have blasted and excavated tunnels in the abandoned Kamioka mine to make way for the Kamioka Gravitational Wave Detector (KAGRA). The instrument will feature two sets of 1.9-mile (3km) laser interferometric wave detectors. KAGRA is expected to detect signals from neutron star mergers every one or two months once it is fully operational in the 2020s.

The Einstein Telescope represents a third-generation detector that's still in the design phase. It would be 100 times more sensitive than current instruments. Based on the design concept, the Einstein Telescope would be buried underground to reduce noise. The telescope would have three detectors: two for low-frequency signals and one to detect high frequencies.



A simulation shows gravitational waves coming from two black holes as they spiral in together. S. OSSOKINE, A. BUONANNO (MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS), D. STEINHAUSER (AIRBORNE HYDRO MAPPING GMBH)

Above the chatter

These ground-based detectors will observe high frequencies, but to detect lower frequencies, we'll need an extremely quiet place that's sheltered from any disturbances — even gravitational forces as minuscule as those generated by a mosquito.

In December, the European Space Agency launched the Laser Interferometer Space Antenna (LISA) Pathfinder into space 932,000 miles (1.5 million km) from Earth. LISA Pathfinder won't look for gravitational waves, but it will prove that a hypersensitive, space-based wave detector is possible in the decades to come.

"We want to make this the quietest place in the solar system," says Martin Hewitson, LISA Pathfinder scientist. "If we are able to do that, we can build a gravitational wave detector in the future."

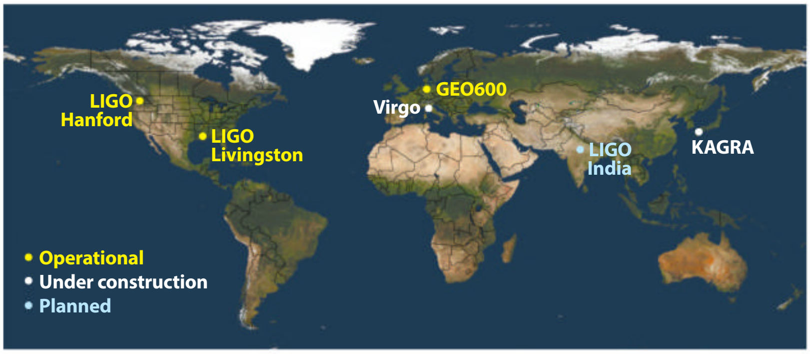
The 90-day experiment began March 1, and if it goes well, the findings will pave the way for eLISA, which will consist of a "mother" and two "daughter" spacecraft in an equilateral triangle connected by laser arms. The detector will pick up gravitational waves generated by binary supermassive black holes, ultra-compact binaries, and small black holes falling into supermassive black holes. That will allow astronomers to study currently mysterious aspects of everything from galaxy formation to how supernovae explode. And eLISA is also likely to find entirely new cosmic phenomena.

"Usually when a new branch of astronomy was born, new sources were discovered," says Benjamin Knispel, a physicist and spokesman for the Albert Einstein Institute in Hanover, Germany. "It is likely that the same thing happens when we detect gravitational waves on a regular basis."

With the fleet of current detectors, and detectors that are still to come, a new era in astronomy has begun. Equipped with an entirely new sense, we may solve age-old mysteries of the cosmos, and even cast light into its unknown unknowns. And LIGO itself has only just begun. The signal announced in February was detected September 14, four days before the official start of the first science run. One can only imagine what they have yet to deliver.

"This is the birth of gravitational wave astronomy. We can now focus on routine observations in space," says Hewitson. "We've only been looking at the universe with our eyes, but we've never heard the universe before. It looks impressive, but imagine when you start listening."

The telescopes of the future



In addition to the two current LIGO sites in the United States, GEO600 is also in operation in Germany, though it is not sensitive to the event observed by LIGO last September. Advanced Virgo in Italy and KAGRA in Japan will soon join the team, and a third LIGO site in India is already in the works. More detectors will help astronomers pinpoint sources' locations and pick out more signals from the noise. LIGO

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