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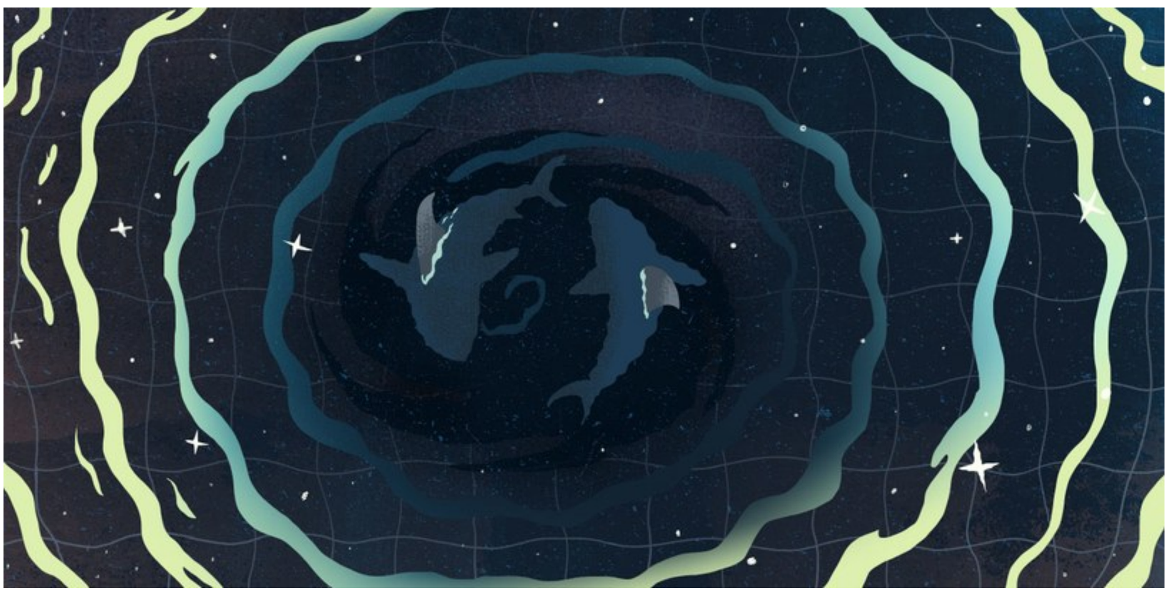
HOW THE FIRST GRAVITATIONAL WAVES WERE FOUND

After decades of speculation and searching, a signal came through. It promises to change our understanding of the universe.

By Nicola Twilley February 11, 2016



A hundred years ago, Albert Einstein predicted the existence of moving ripples in space and time.
Illustration by Aleks Sennwald

Note: On October 3, 2017, the Royal Swedish Academy of Sciences announced that the Nobel Prize in Physics would be awarded to Rainer Weiss, Kip Thorne, and Barry Barish, three pioneers in the study of gravitational waves.

Just over a billion years ago, many millions of galaxies from here, a pair of black holes collided. They had been circling each other for aeons in a sort of mating dance, gathering pace with each orbit, hurtling closer and closer. By the time they were a few hundred miles apart, they were whipping around at nearly the speed of light, releasing great shudders of gravitational energy. Space and time became distorted, like water at a rolling boil. In the fraction of a second that it took for the black holes to finally merge, they radiated a hundred times more energy than all the stars in the universe combined. They formed a new black hole, sixty-two times as heavy as our sun and almost as wide across as the state of Maine. As it smoothed itself out, assuming the shape of a slightly flattened sphere, a few last quivers of energy escaped. Then space and time became silent again.

The waves rippled outward in every direction, weakening as they went. On Earth, dinosaurs arose, evolved, and went extinct. The waves kept going. About fifty thousand years ago, they entered our own Milky Way galaxy, just as *Homo sapiens* were beginning to replace our Neanderthal cousins as the planet's dominant species of ape. A hundred years ago, Albert Einstein, one of the more advanced members of the species, predicted the waves' existence, inspiring decades of speculation and fruitless searching. Twenty-two years ago, construction began on an enormous detector, the Laser Interferometer Gravitational-Wave Observatory (LIGO). Then, on September 14, 2015, at just before eleven in the morning, Central European Time, the waves reached Earth. Marco Drago, a thirty-two-year-old Italian postdoctoral student and a member of the LIGO Scientific Collaboration, was the first person to notice them. He was sitting in front of his computer at the Albert Einstein Institute, in Hannover, Germany, viewing the LIGO data remotely. The waves appeared on his screen as a compressed squiggle, but the most exquisite ears in the universe, attuned to vibrations of less than a trillionth of an inch, would have heard what astronomers call a chirp—a faint whooping from low to high. This morning, in a press conference in Washington, D.C., the LIGO team announced that the signal constitutes the first direct observation of gravitational waves.

When Drago saw the signal, he was stunned. "It was difficult to understand what to do," he told me. He informed a colleague, who had the presence of mind to call the LIGO operations room, in Livingston, Louisiana. Word began to circulate among the thousand or so scientists involved in the project. In California, David Reitze, the executive director of the LIGO Laboratory, saw his daughter off to school and went to his office, at Caltech, where he was greeted by a barrage of messages. "I don't remember exactly what I said," he told me. "It was along these lines: 'Holy shit, what is this?' " Vicky Kalogera, a professor of physics and astronomy at Northwestern University, was in meetings all day, and didn't hear the news until dinnertime. "My husband asked me to set the table," didn't hear the news until dinnertime. "My husband asked me to set the table," she said. "I was completely ignoring him, skimming through all these weird e-mails and thinking, What is going on?" Rainer Weiss, the eighty-three-year-old physicist who first suggested building LIGO, in 1972, was on vacation in Maine. He logged on, saw the signal, and yelled "My God!" loudly enough that his wife and adult son came running.

The collaborators began the arduous process of double-, triple-, and quadruple-checking their data. "We're saying that we made a measurement that is about a thousandth the diameter of a proton, that tells us about two black holes that merged over a billion years ago," Reitze said. "That is a pretty extraordinary claim and it needs extraordinary evidence." In the meantime, the LIGO scientists were sworn to absolute secrecy. As rumors of the finding spread, from late September through this week, media excitement spiked; there were rumblings about a Nobel Prize. But the collaborators gave anyone who asked about it an abbreviated version of the truth—that they were still analyzing data and had nothing to announce. Kalogera hadn't even told her husband.

LIGO consists of two facilities, separated by nearly nineteen hundred miles—about a three-and-a-half-hour flight on a passenger jet, but a journey of less than ten thousandths of a second for a gravitational wave. The detector in Livingston, Louisiana, sits on swampland east of Baton Rouge, surrounded by a commercial pine forest; the one in Hanford, Washington, is on the southwestern edge of the most contaminated nuclear site in the United States, amid desert sagebrush, tumbleweed, and decommissioned reactors. At both locations, a pair of concrete pipes some twelve feet tall stretch at right angles into the distance, so that from high above the facilities resemble carpenter's squares. The pipes are so long—nearly two and a half miles—that they have to be raised from the ground by a yard at each end, to keep them lying flat as Earth curves beneath them.

LIGO is part of a larger effort to explore one of the more elusive implications of Einstein's general theory of relativity. The theory, put simply, states that space and time curve in the presence of mass, and that this curvature produces the effect known as gravity. When two black holes orbit each other, they stretch and squeeze space-time like children running in circles on a trampoline, creating vibrations that travel to the very edge; these vibrations are gravitational waves. They pass through us all the time, from sources across the universe, but because gravity is so much weaker than the other fundamental forces of nature—electromagnetism, for instance, or the interactions that bind an atom together—we never sense them. Einstein thought it highly unlikely that they would ever be we never sense them. Einstein thought it highly unlikely that they would ever be detected. He twice declared them nonexistent, reversing and then re-reversing his own prediction. A skeptical contemporary noted that the waves seemed to "propagate at the speed of thought."

Nearly five decades passed before someone set about building an instrument to detect gravitational waves. The first person to try was an engineering professor at the University of Maryland, College Park, named Joe Weber. He called his

device the resonant bar antenna. Weber believed that an aluminum cylinder could be made to work like a bell, amplifying the feeble strike of a gravitational wave. When a wave hit the cylinder, it would vibrate very slightly, and sensors around its circumference would translate the ringing into an electrical signal. To make sure he wasn't detecting the vibrations of passing trucks or minor earthquakes, Weber developed several safeguards: he suspended his bars in a vacuum, and he ran two of them at a time, in separate locations—one on the campus of the University of Maryland, and one at Argonne National Laboratory, near Chicago. If both bars rang in the same way within a fraction of a second of each other, he concluded, the cause might be a gravitational wave.

In June of 1969, Weber announced that his bars had registered something. Physicists and the media were thrilled; the *Times* reported that "a new chapter in man's observation of the universe has been opened." Soon, Weber started reporting signals on a daily basis. But doubt spread as other laboratories built bars that failed to match his results. By 1974, many had concluded that Weber was mistaken. (He continued to claim new detections until his death, in 2000.)

Weber's legacy shaped the field that he established. It created a poisonous perception that gravitational-wave hunters, as Weiss put it, are "all liars and not careful, and God knows what." That perception was reinforced in 2014, when scientists at BICEP2, a telescope near the South Pole, detected what seemed to be gravitational radiation left over from the Big Bang; the signal was real, but it turned out to be a product of cosmic dust. Weber also left behind a group of researchers who were motivated by their inability to reproduce his results. Weiss, frustrated by the difficulty of teaching Weber's work to his undergraduates at the Massachusetts Institute of Technology, began designing what would become LIGO. "I couldn't understand what Weber was up to," he said in an oral history conducted by Caltech in 2000. "I didn't think it was right. So I decided I would go at it myself."

In the search for gravitational waves, "most of the action takes place on the phone," Fred Raab, the head of LIGO's Hanford site, told me. There are weekly meetings to discuss data and fortnightly meetings to discuss coördination between the two detectors, with collaborators in Australia, India, Germany, the United Kingdom, and elsewhere. "When these people wake up in the middle of the night dreaming, they're dreaming about the detector," Raab said. "That's how intimate they have to be with it," he explained, to be able to make the fantastically complex instrument that Weiss conceived actually work.

Weiss's detection method was altogether different from Weber's. His first insight was to make the observatory "L"-shaped. Picture two people lying on the floor, their heads touching, their bodies forming a right angle. When a gravitational wave passes through them, one person will grow taller while the other shrinks; a moment later, the opposite will happen. As the wave expands space-time in one direction, it necessarily compresses it in the other. Weiss's instrument would gauge the difference between these two fluctuating lengths, and it would do so on a gigantic scale, using miles of steel tubing. "I wasn't going to be detecting anything on my tabletop," he said.

To achieve the necessary precision of measurement, Weiss suggested using light as a ruler. He imagined putting a laser in the crook of the "L." It would send a beam down the length of each tube, which a mirror at the other end would reflect back. The speed of light in a vacuum is constant, so as long as the tubes were cleared of air and other particles the beams would recombine at the crook in synchrony—unless a gravitational wave happened to pass through. In that case, the distance between the mirrors and the laser would change slightly. Since one beam would now be covering a shorter distance than its twin, they would no longer be in lockstep by the time they got back. The greater the mismatch, the stronger the wave. Such an instrument would need to be thousands of times more sensitive than any previous device, and it would require delicate tuning in order to extract a signal of vanishing weakness from the planet's omnipresent din.

Weiss wrote up his design in the spring of 1972, as part of his laboratory's quarterly progress report. The article never appeared in a scientific journal—it was an idea, not an experiment—but according to Kip Thorne, an emeritus professor at Caltech who is perhaps best known for his work on the movie "Interstellar," "it is one of the greatest papers ever written." Thorne doesn't recall reading Weiss's report until later. "If I had read it, I had certainly not understood it," he said. Indeed, Thorne's landmark textbook on gravitational theory, co-authored with Charles Misner and John Wheeler and first published in 1973, contained a student exercise designed to demonstrate the impracticability of measuring gravitational waves with lasers. "I turned around on that pretty quickly," he told me.

Thorne's conversion occurred in a hotel room in Washington, D.C., in 1975. Weiss had invited him to speak to a panel of NASA scientists. The evening before the meeting, the two men got to talking. "I don't remember how it happened, but we shared the hotel room that night," Weiss said. They sat at a tiny table, filling sheet after sheet of paper with sketches and equations. Thorne, who was raised Mormon, drank Dr Pepper; Weiss smoked a corncob pipe stuffed with Three Nuns tobacco. "There are not that many people in the world that you can talk to like that, where both of you have been thinking about the same thing for years," Weiss said. By the time Thorne got back to his own room, the sky was turning pink.

At M.I.T., Weiss had begun assembling a small prototype detector with five-foot arms. But he had trouble getting support from departmental administrators, and many of his colleagues were also skeptical. One of them, an influential astrophysicist and relativity expert named Phillip Morrison, was firmly of the opinion that black holes did not exist—a viewpoint that many of his contemporaries shared, given the paucity of observational data. Since black holes were some of the only cosmic phenomena that could theoretically emit gravitational waves of significant size, Morrison believed that Weiss's instrument had nothing to find. Thorne had more success: by 1981, there was a prototype under way at Caltech, with arms a hundred and thirty-one feet long. A Scottish physicist named Ronald Drever oversaw its construction, improving on Weiss's design in the process.

In 1990, after years of studies, reports, presentations, and committee meetings, Weiss, Thorne, and Drever persuaded the National Science Foundation to fund the construction of LIGO. The project would cost two hundred and seventy-two million dollars, more than any N.S.F.-backed experiment before or since. "That started a huge fight," Weiss said. "The astronomers were dead-set against it, because they thought it was going to be the biggest waste of money that ever happened." Many scientists were concerned that LIGO would sap money from other research. Rich Isaacson, a program officer at the N.S.F. at the time, was instrumental in getting the observatory off the ground. "He and the National instrumental in getting the observatory off the ground. He and the National Science Foundation stuck with us and took this enormous risk," Weiss said.

"It never should have been built," Isaacson told me. "It was a couple of maniacs running around, with no signal ever having been discovered, talking about pushing vacuum technology *and* laser technology *and* materials technology *and* seismic isolation and feedback systems orders of magnitude beyond the current state of the art, using materials that hadn't been invented yet." But Isaacson had written his Ph.D. thesis on gravitational radiation, and he was a firm believer in LIGO's theoretical underpinnings. "I was a mole for the gravitational-wave community inside the N.S.F.," he said.

In their proposal, the LIGO team warned that their initial design was unlikely to detect anything. Nonetheless, they argued, an imperfect observatory had to be built in order to understand how to make a better one. "There was every reason to imagine this was going to fail," Isaacson said. He persuaded the N.S.F. that, even if no signal was registered during the first phase, the advances in precision measurement that came out of it would likely be worth the investment. Ground was broken in early 1994.

It took years to make the most sensitive instrument in history insensitive to everything that is not a gravitational wave. Emptying the tubes of air demanded forty days of pumping. The result was one of the purest vacuums ever created on Earth, a trillionth as dense as the atmosphere at sea level. Still, the sources of interference were almost beyond reckoning—the motion of the wind in Hanford, or of the ocean in Livingston; imperfections in the laser light as a result of fluctuations in the power grid; the jittering of individual atoms within the mirrors; distant lightning storms. All can obscure or be mistaken for a gravitational wave, and each source had to be eliminated or controlled for. One of LIGO's systems responds to minuscule seismic tremors by activating a damping system that pushes on the mirrors with exactly the right counterforce to keep them steady; another monitors for disruptive sounds from passing cars, airplanes, or wolves.

"There are ten thousand other tiny things, and I really mean ten thousand," Weiss said. "And every single one needs to be working correctly so that nothing interferes with the signal." When his colleagues make adjustments to the observatory's interior components, they must set up a portable clean room, sterilize their tools, and don what they call bunny suits—full-body protective gear—lest a skin cell or a particle of dust accidentally settle on the sparkling gear"—lest a skin cell or a particle of dust accidentally settle on the sparkling optical hardware.

The first iteration of the observatory—Initial LIGO, as the team now calls it—was up and running in 2001. During the next nine years, the scientists measured and refined their instruments' performance and improved their data-analysis algorithms. In the meantime, they used the prototype at Caltech and a facility in Germany to develop ever more sensitive mirror, laser, and seismic-isolation technology. In 2010, the detectors were taken offline for a five-year, two-hundred-million-dollar upgrade. They are now so well shielded that when the facilities manager at the Hanford site revs his Harley next to the control room, the scientist monitoring the gravitational-wave channel sees nothing. (A test of this scenario is memorialized in the logbook as "Bubba Roars Off on a Motor Cycle.") The observatory's second iteration, Advanced LIGO, should eventually be capable of surveying a volume of space that is more than a thousand times greater than its predecessor's.

Some of the most painstaking work took place on the mirrors, which, Reitze said, are the best in the world "by far." Each is a little more than a foot wide, weighs nearly ninety pounds, and is polished to within a hundred-millionth of an inch of a perfect sphere. (They cost almost half a million dollars apiece.) At first, the mirrors were suspended from loops of steel wire. For the upgrade, they were attached instead to a system of pendulums, which insulated them even further from seismic tremors. They dangle from fibres of fused silica—glass, basically—which, although strong enough to bear the weight of the mirrors, shatter at the slightest provocation. "We did have one incident where a screw fell and pinged one, and it just went poof," Anamaria Effler, a former operations specialist at the Hanford site, told me. The advantage of the fibres is their purity, according to Jim Hough, of the University of Glasgow. "You know how, when you flick a whiskey glass, it will ring beautifully?" he asked. "Fused silica is even better than a whiskey glass—it is like plucking a string on a violin." The note is so thin that it is possible for LIGO's signal-processing software to screen it out—another source of interference eliminated.

A technician inspects one of LIGO's optics. Courtesy LIGO

Preparing Advanced LIGO took longer than expected, so the new and improved instrument's start date was pushed back a few days, to September 18, 2015. Weiss was called in from Boston a week prior to try to track down the source of some radio-frequency interference. "I get there and I was horrified," he said. "It was everywhere." He recommended a weeklong program of repairs to address the issue, but the project's directors refused to delay the start of the first observing run any longer. "Thank God they didn't let me do it," Weiss said. "I would have had the whole goddamn thing offline when the signal came in."

On Sunday, September 13th, Effler spent the day at the Livingston site with a colleague, finishing a battery of last-minute tests. "We yelled, we vibrated things with shakers, we tapped on things, we introduced magnetic radiation, we did all kinds of things," she said. "And, of course, everything was taking longer than it was supposed to." At four in the morning, with one test still left to do—a simulation of a truck driver hitting his brakes nearby—they decided to pack it in. They drove home, leaving the instrument to gather data in peace. The signal arrived not long after, at 4:50 A.M. local time, passing through the two detectors within seven milliseconds of each other. It was four days before the start of Advanced LIGO's first official run.

The fact that gravitational waves were detected so early prompted confusion and disbelief. "I had told everyone that we wouldn't see anything until 2017 or 2018," Reitze said. Janna Levin, a professor of astrophysics at Barnard College and Columbia University, who is not a member of the LIGO Scientific Collaboration, was equally surprised. "When the rumors started, I was like, Come on!" she said. "They only just got it locked!" The signal, moreover, was almost too perfect. "Most of us thought that, when we ever saw such a thing, it would be something that you would need many, many computers and calculations to drag out of the noise," Weiss said. Many of his colleagues assumed that the signal was some kind of test.

The LIGO team includes a small group of people whose job is to create blind injections—bogus evidence of a gravitational wave—as a way of keeping the scientists on their toes. Although everyone knew who the four people in that group were, "we didn't know what, when, or whether," Gabriela González, the collaboration's spokeswoman, said. During Initial LIGO's final run, in 2010, the detectors picked up what appeared to be a strong signal. The scientists analyzed it intensively for six months, concluding that it was a gravitational wave from somewhere in the constellation of Canis Major. Just before they submitted their results for publication, however, they learned that the signal was a fake.

This time through, the blind-injection group swore that they had nothing to do with the signal. Marco Drago thought that their denials might also be part of the test, but Reitze, himself a member of the quartet, had a different concern. "My worry was—and you can file this under the fact that we are just paranoid cautious about making a false claim—could somebody have done this maliciously?" he said. "Could somebody have somehow faked a signal in our detector that we didn't know about?" Reitze, Weiss, González, and a handful of others considered who, if anyone, was familiar enough with both the apparatus and the algorithms to have spoofed the system and covered his or her tracks. There were only four candidates, and none of them had a plausible motive. "We grilled those guys," Weiss said. "And no, they didn't do it." Ultimately, he said, "We accepted that the most economical explanation was that it really is a black-hole pair."

Subgroups within the LIGO Scientific Collaboration set about validating every aspect of the detection. They reviewed how the instruments had been calibrated, took their software code apart line by line, and compiled a list of possible environmental disturbances, from oscillations in the ionosphere to earthquakes in the Pacific Rim. ("There was a very large lightning strike in Africa at about the same time," Stan Whitcomb, LIGO's chief scientist, told me. "But our magnetometers showed that it didn't create enough of a disturbance to cause this event.") Eventually, they confirmed that the detection met the statistical threshold of five sigma, the gold standard for declaring a discovery in physics. This meant that there was a probability of only one in 3.5 million that the signal was spotted by chance.

The September 14th detection, now officially known as GW150914, has already yielded a handful of significant astrophysical findings. To begin with, it represents the first observational evidence that black-hole pairs exist. Until now, they had existed only in theory, since by definition they swallow all light in their vicinity, rendering themselves invisible to conventional telescopes. Gravitational waves are the only information known to be capable of escaping a black hole's crushing gravity.

The LIGO scientists have extracted an astonishing amount from the signal, including the masses of the black holes that produced it, their orbital speed, and the precise moment at which their surfaces touched. They are substantially heavier than expected, a surprise that, if confirmed by future observations, may help to explain how the mysterious supermassive black holes at the heart of many galaxies are formed. The team has also been able to quantify what is known as the ringdown—the three bursts of energy that the new, larger black hole gave off as it became spherical. "Seeing the ringdown is spectacular," Levin said. It offers confirmation of one of relativity theory's most important predictions about black holes—namely, that they radiate away imperfections in the form of gravitational waves after they coalesce.

The detection also proves that Einstein was right about yet another aspect of the physical universe. Although his theory deals with gravity, it has primarily been tested in our solar system, a place with a notably weak gravitational regime. "You think Earth's gravity is really something when you're climbing the stairs," Weiss said. "But, as far as physics goes, it is a pipsqueak, infinitesimal, tiny little effect." Near a black hole, however, gravity becomes the strongest force in the universe, capable of tearing atoms apart. Einstein predicted as much in 1916, and the LIGO results suggest that his equations align almost perfectly with real-world observation. "How could he have ever known this?" Weiss asked. "I would love to present him with the data that I saw that morning, to see his face."

Since the September 14th detection, LIGO has continued to observe candidate signals, although none are quite as dramatic as the first event. "The reason we are making all this fuss is because of the big guy," Weiss said. "But we're very happy that there are other, smaller ones, because it says this is not some unique, crazy, cuckoo effect."

Virtually everything that is known about the universe has come to scientists by way of the electromagnetic spectrum. Four hundred years ago, Galileo began exploring the realm of visible light with his telescope. Since then, astronomers have pushed their instruments further. They have learned to see in radio waves and microwaves, in infrared and ultraviolet, in X-rays and gamma rays, revealing the birth of stars in the Carina Nebula and the eruption of geysers on Saturn's eighth moon, pinpointing the center of the Milky Way and the locations of Earth-like planets around us. But more than ninety-five per cent of the universe remains imperceptible to traditional astronomy. Gravitational waves may not illuminate the so-called dark energy that is thought to make up the majority of that obscurity, but they will enable us to survey space and time as we never have before. "This is a completely new kind of telescope," Reitze said. "And that means we have an entirely new kind of astronomy to explore." If what we witnessed before was a silent movie, Levin said, gravitational waves turn our universe into a talkie.

As it happens, the particular frequencies of the waves that LIGO can detect fall within the range of human hearing, between about thirty-five and two hundred and fifty hertz. The chirp was much too quiet to hear by the time it reached Earth, and LIGO was capable of capturing only two-tenths of a second of the black holes' multibillion-year merger, but with some minimal audio processing the event sounds like a glissando. "Use the back of your fingers, the nails, and just run them along the piano from the lowest A up to middle C, and you've got the whole signal," Weiss said.

Different celestial sources emit their own sorts of gravitational waves, which means that LIGO and its successors could end up hearing something like a cosmic orchestra. "The binary neutron stars are like the piccolos," Reitze said. Isolated spinning pulsars, he added, might make a monochromatic "ding" like a triangle, and black holes would fill in the string section, running from double bass on up, depending on their mass. LIGO, he said, will only ever be able to detect violins and violas; waves from supermassive black holes, like the one at the center of the Milky Way, will have to await future detectors, with different sensitivities.

Several such detectors are in the planning stages or under construction, including the Einstein Telescope, a European project whose underground arms will be more than twice the length of LIGO's, and a space-based constellation of three instruments called eLISA. (The European Space Agency, with support from NASA, launched a pathfinder mission in December.) Other detectors are already up and running, including the BICEP2 telescope, which, despite its initial false alarm, may still detect the echoes of gravitational waves from even further back in the universe's history. Reitze's hope, he told me, is that the chirp will motivate more investment in the field.

Advanced LIGO's first observing run came to an end on January 12th. Effler and the rest of the commissioning team have since begun another round of improvements. The observatory is inching toward its maximum sensitivity; within two or three years, it may well register events on a daily basis, capturing more data in the process. It will come online again by late summer, listening even more closely to a celestial soundtrack that we have barely imagined. "We are opening up a window on the universe so radically different from all previous windows that we are pretty ignorant about what's going to come through," Thorne said. "There are just bound to be big surprises."

Correction: A previous version of this article misstated the travel time of a gravitational wave by one order of magnitude.

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