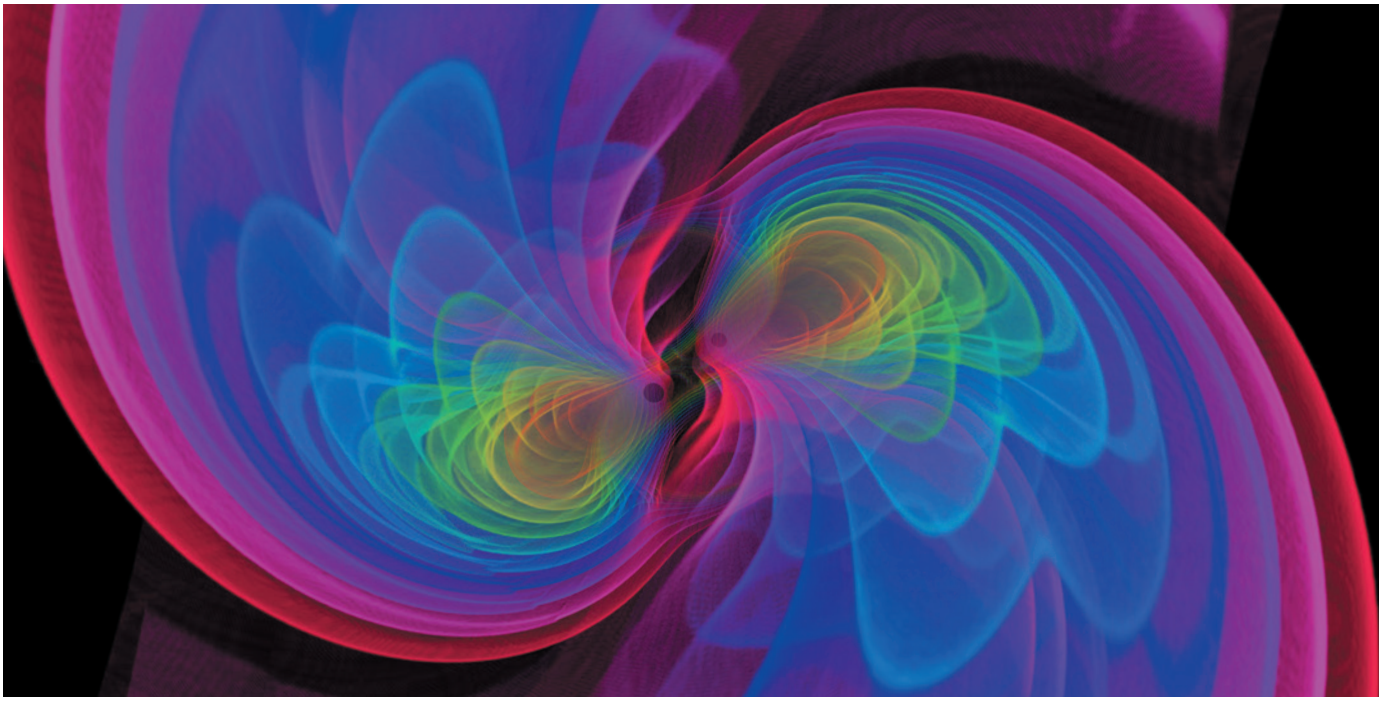
S. OSSOKINE, A. BUONANNO (MAX PLANCK INST. GRAVITATIONAL PHYS.), SCIENTIFIC VISUALIZATION: W. BENGER (AIRBORNE HYDRO MAPPING)



The pair of merging black holes that LIGO detected using gravitational waves — as produced by a computer simulation.

GRAVITATIONAL WAVES

LIGO's path to victory

Historic discovery of ripples in space–time meant ruling out the possibility of a fake signal.

BY DAVIDE CASTELVECCHI

At 11:53 a.m. local time on 14 September 2015, an automated e-mail appeared in the inbox of Marco Drago, a physicist at the Max Planck Institute for Gravitational Physics in Hannover, Germany. It contained links to two plots, each showing a wave shaped like a bird's chirp that emerged suddenly from a noisy background and ended in a crash.

It was a signal that Drago had been trained to spot and that the US-led Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) that he works on was built to detect: the signature ripples in space-time produced when two black holes collide to form a single gravitational sink. No one had ever directly detected gravitational waves before, nor a black-hole merger. The plots, one from each of LIGO's twin detectors in Washington state and Louisiana, would go on to make history.

On 11 February, the LIGO collaboration announced that it had made the first detection of gravitational waves from a black-hole merger that occurred about 400 million parsecs (1.3 billion light years) from Earth. It was just over 100 years after Albert Einstein predicted such waves as part of his general theory of relativity. "We did it!" David Reitze, the executive director of the LIGO Laboratory, said at a press conference in Washington DC.

As well as being expected to lead to a Nobel prize, LIGO's discovery launches the field of gravitational-wave astronomy, in which scientists will 'listen' to the waves to learn more about the Universe (see page 263).

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For more on gravitational waves and LIGO see:
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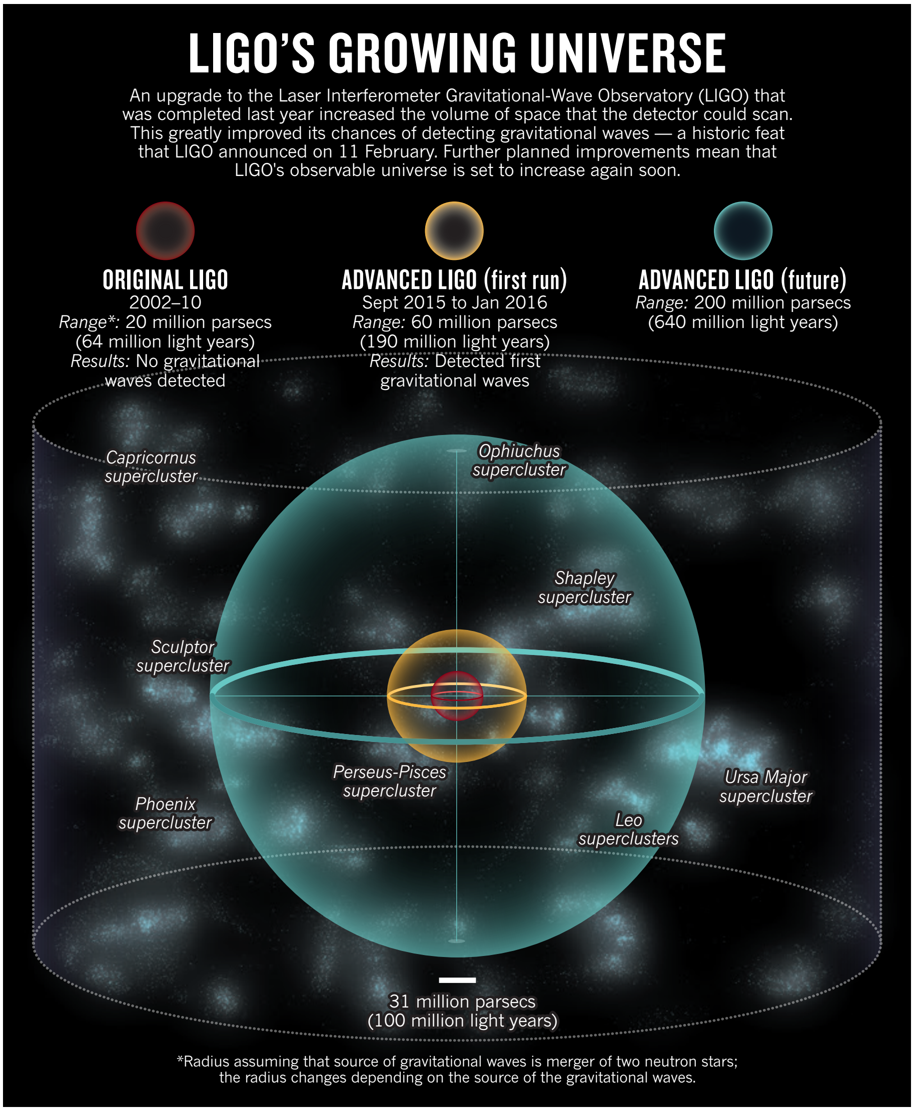
On that September morning, Drago could not take it for granted that he was looking at the chirp of a black-hole merger. "It was clear that it was something extraordinary," he says. But the plots were also something that the LIGO researchers had expected to see injected artificially by their colleagues to test the detectors. "I went down to the office of my colleague Andrew Lundgren to ask him if he was aware of an injection," says Drago.

Lundgren quickly checked the data logs and found no traces of a drill. Next, Drago sent an e-mail to the entire LIGO collaboration — 1,000 researchers spread around the world — to see what they thought.

"When I first saw it, I said 'Oh, it's an injection, obviously'," says physicist Bruce Allen, Drago and Lundgren's boss. Allen, who was ▶



LIGO'S GROWING UNIVERSE

An upgrade to the Laser Interferometer Gravitational-Wave Observatory (LIGO) that was completed last year increased the volume of space that the detector could scan. This greatly improved its chances of detecting gravitational waves — a historic feat that LIGO announced on 11 February. Further planned improvements mean that LIGO's observable universe is set to increase again soon.

*Radius assuming that source of gravitational waves is merger of two neutron stars; the radius changes depending on the source of the gravitational waves.

CLUSTER MAP ADAPTED FROM ANDREW Z. COLVIN/CC-BY-SA

in a meeting at the time, did not bother to enquire until after his lunch break.

Within a few hours, collaborators on the other side of the Atlantic woke up to Drago's e-mail — including experimental physicist Rainer Weiss at the Massachusetts Institute of Technology (MIT) in Cambridge, who is credited as the chief inventor of LIGO. "When I started looking at these waveforms, they were something spectacular," he says.

To many, the timing of the signal seemed too good to be true: the collaboration had completed a five-year upgrade to its instruments (see 'LIGO's growing universe'). Moreover, the LIGO collaboration had also given a small number of its members the power to inject fake signals and to hide whether they were real or simulated in order to test the team's responses. But even such a 'blind injection' ought to have left some traces in the data, says LIGO spokeswoman Gabriela González, a physicist at Louisiana State University in Baton Rouge.

After a long day of calls and e-mails, she determined that no blind injection had occurred and told the entire collaboration.

Only then did Kip Thorne, a theoretical physicist at the California Institute of Technology (Caltech) in Pasadena who co-founded LIGO with Weiss and Caltech colleague Ronald Drever, realize that a 40-year-old dream had come true. But it was not yet time to pop the champagne. The collaboration needed to do more before announcing a discovery to the world. "That night at home, I celebrated by just smiling to myself, because I could not tell my wife yet," Thorne says.

> ***"I celebrated by just smiling to myself, because I could not tell my wife yet."***

González and her team decided to take data for another month before beginning a full analysis: the researchers needed to record the natural noise present in their detectors to have something to compare with the chirp. They concluded that the odds of noise producing that loud pattern — and the very same pattern in both Louisiana and Washington at about the same time — were so low that it should only occur by chance less than once every 203,000 years.

To extract as much information as possible, the researchers then performed lengthy supercomputer simulations, Allen says. These confirmed that the data beautifully matched the predictions of Einstein's general theory of relativity in 1915, and the theoretical work that in the past few decades has led physicists to understand the theory's implications in fine detail.

From the waveforms, the researchers were able to deduce that one black hole was about 36 times the mass of the Sun, and the other was about 29 solar masses. As the two objects orbited each other, they warped the fabric of space and time around them in a fluctuating pattern. Those fluctuations then travelled across the Universe as gravitational waves for an estimated 1.3 billion years, stretching and squeezing space as they moved.

LIGO's twin interferometers bounce laser beams between mirrors at the opposite ends of perpendicular, 4-kilometre-long vacuum pipes. A gravitational wave passing through will alter the length of the pipes in different ways, causing the laser beams to shift slightly out of sync. By the time the waves from the black-hole merger arrived on 14 September, they had become tiny ripples, changing the length of the pipes on the order of just 1 part in 1 billion trillion (10^{21}).

Although the two black holes had probably been orbiting each other for millions of years, LIGO began to pick up their waves only when they reached a frequency of 35 cycles per second (hertz). The frequency rapidly increased to 250 hertz. The signal became chaotic and then rapidly died down; the whole thing was over within a quarter of a second. Crucially, both detectors saw it at roughly the same time — Livingston, in Louisiana, first and Hanford, in Washington, 7 milliseconds later. The delay is an indication of how the waves swept through Earth.

Then came writing the paper. This involved getting 1,000 researchers to agree on every detail, and took some 5,000 e-mails, says LIGO's chief detector scientist Peter Fritschel at MIT. On 21 January, the team submitted the paper, which *Physical Review Letters* published on 11 February (B. P. Abbott *et al. Phys. Rev. Lett.* **116,** 061102; 2016), the same day that LIGO held multiple press conferences around the world.

"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 at the University of Cambridge, UK.

LIGO's triumph is a fitting end to the tale that Einstein began. He never believed that black holes existed. But although astronomers had accumulated compelling evidence for black holes by observing their surroundings, notes Thibault Damour, a theoretical physicist at the Institute of Advanced Scientific Studies near Paris, the LIGO signal is "the first real direct proof of their existence". ■