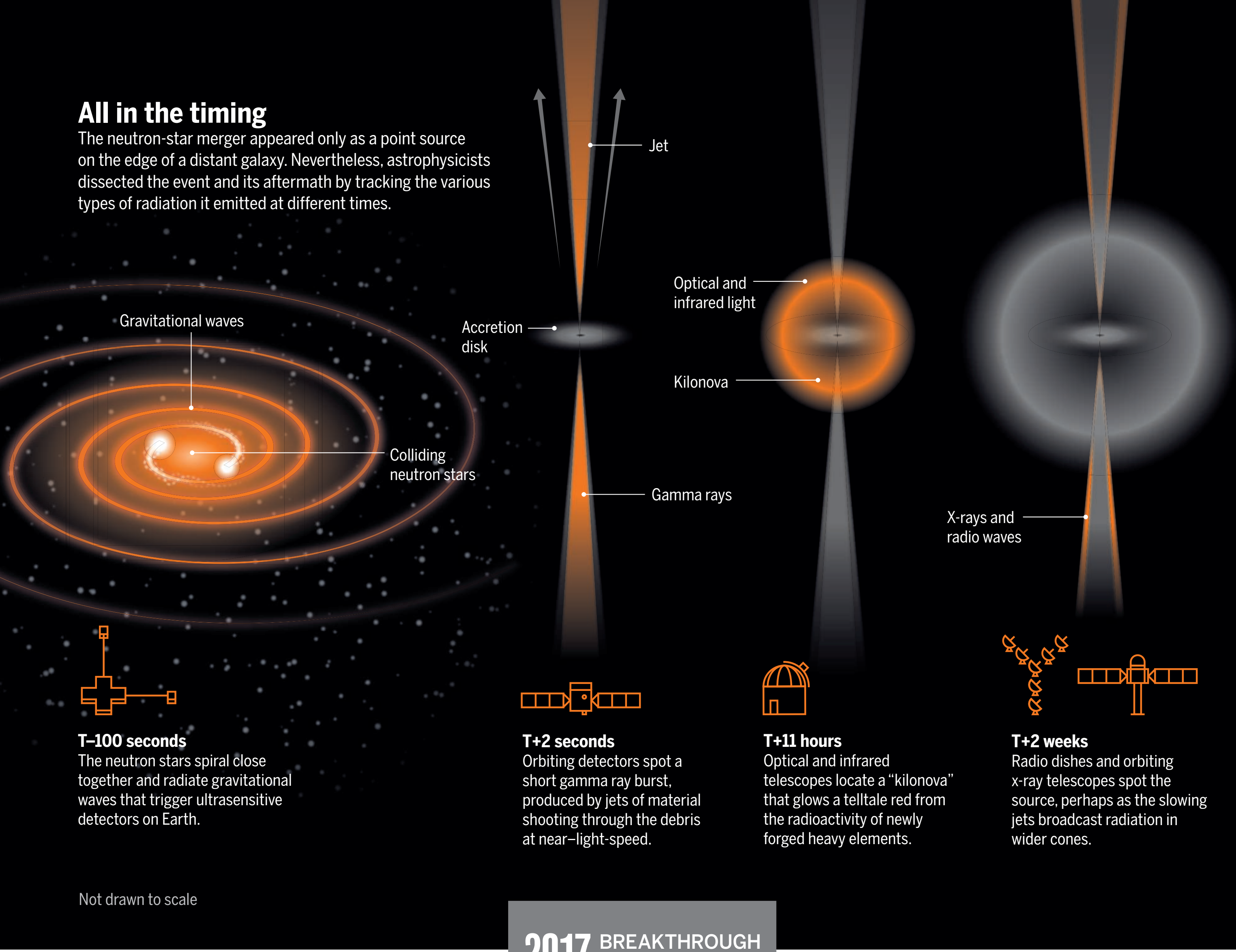

All in the timing

The neutron-star merger appeared only as a point source on the edge of a distant galaxy. Nevertheless, astrophysicists dissected the event and its aftermath by tracking the various types of radiation it emitted at different times.

T–100 seconds
The neutron stars spiral close together and radiate gravitational waves that trigger ultrasensitive detectors on Earth.

T+2 seconds
Orbiting detectors spot a short gamma ray burst, produced by jets of material shooting through the debris at near–light-speed.

T+11 hours
Optical and infrared telescopes locate a "kilonova" that glows a telltale red from the radioactivity of newly forged heavy elements.

T+2 weeks
Radio dishes and orbiting x-ray telescopes spot the source, perhaps as the slowing jets broadcast radiation in wider cones.

Not drawn to scale

GRAPHIC: C. BICKEL/SCIENCE

2017 BREAKTHROUGH *of the* YEAR

COSMIC CONVERGENCE

The merger of two neutron stars captivated thousands of observers and fulfilled multiple astrophysical predictions

By **Adrian Cho**

On 17 August, scientists around the world witnessed something never seen before: One hundred and thirty million light-years away, two neutron stars spiraled into each other in a spectacular explosion that was studied by observatories ranging from gamma ray detectors to radio telescopes. The blast confirmed several key astrophysical models, revealed a birthplace of many heavy elements, and tested the general theory of relativity as never before (*Science*, 20 October, p. 282). That first observation of a neutron-star merger, and the scientific bounty it revealed, is *Science*'s 2017 Breakthrough of the Year.

Especially remarkable was the way the event was spotted: by detecting the infinitesimal ripples in space itself, called gravitational waves, that the spiraling neutron stars radiated before they merged. Scientists first detected such waves just 27 months ago, when the Laser Interferometer Gravitational-Wave Observatory (LIGO) sensed a space tremor from two massive black holes spiraling together in an invisible cataclysm. The discovery of gravitational waves was *Science*'s 2016 Breakthrough of the Year.

If that observation sounded the clarion of discovery, this year's produced a scientific symphony. The difference comes down to matter. A black hole, the ghostly gravitational field that remains when a huge star collapses to a point, contains no matter to heat up and radiate. A neutron star, in contrast, is a ball of nearly pure neutrons, the densest stuff there is. Whereas the colliding black holes emitted nothing but gravitational energy, the neutron-star smashup put on a light show that was studied by more than 70 observatories. "The amount of information we have been able to extract with one event blows my mind," says Laura Cadonati, a physicist at the Georgia Institute of Technology in Atlanta and deputy spokesperson for the LIGO team.

The gravitational waves from the twirling neutron stars tickled not only the enormous LIGO detectors in Hanford, Washington, and Livingston, Louisiana, but also the French-Italian Virgo detector near Pisa, Italy, which, after a 5-year upgrade, had started recording data just 17 days earlier. Researchers immediately knew they were witnessing the death spiral of two neutron stars. Unlike black-hole mergers, which produce secondslong pulses of low-frequency gravitational waves, the lighter neutron stars produced a telltale higher frequency hum that increased in frequency and strength over 100 seconds.

ON OUR WEBSITE

For more on the Breakthrough of the Year, including a video and a podcast, go to: http://scim.ag/2017breakthru.

That crescendo cued the fireworks. Two seconds later, NASA's orbiting Fermi Gamma-ray Space Telescope detected a pulse of gamma rays called a short gamma ray burst. Then, other telescopes took aim. Because the gravitational waves were spotted by three widely spaced detectors, researchers could triangulate the neutron star pair's location in the sky. Within 11 hours, several teams of optical and infrared astronomers had found a new beacon on the edge of the galaxy NGC 4993. Over several days, the source faded from bright blue to dimmer red. Then, after 11 days, it began to glow in x-rays and radio waves. The explosion was easily the most studied event in the history of astronomy, with 3674 researchers from 953 institutions collaborating on a single paper summarizing the merger and its aftermath.

The observations bolstered the 25-year-old hypothesis that neutron-star mergers produce short gamma ray bursts. And the reddish afterglow fit the model of a so-called kilonova, in which neutron-rich matter flung into space by colliding neutron stars hosts a chain of nuclear interactions known as the r-process. The process is thought to produce half the elements heavier than iron, and the heaviest ones would soak up blue light, tinting the glowing radioactive cloud red. "It's been super-exciting to see something that was just an idea come to life," says Daniel Kasen of the University of California, Berkeley, who has modeled kilonovas. "All this stuff was done basically with eyes-closed theory." The observation even bolstered Albert Einstein's general theory of relativity by confirming that gravitational waves travel at the same speed as light and not more slowly, as some alternative theories had predicted.

But the merger also poses puzzles that have whetted astrophysicists' appetites for more data. For example, the gamma ray burst was surprisingly feeble, says Vicky Kalogera, an astrophysicist and LIGO team member at Northwestern University in Evanston, Illinois. Such bursts are thought to originate when narrow jets of material shoot out of a neutron-star merger at near–light-speed, like search beams. The simplest explanation is that the jet may not have pointed straight at Earth. However, it's possible that astrophysicists' model isn't quite right and that neutron-star mergers produce only muted gamma ray bursts, Kalogera says. To resolve the issue, astrophysicists need to see more mergers.

They would also like to see the gravitational waves right up to the point at which the neutron stars spiral into each other. In this first observation, the LIGO and Virgo detectors tracked the stars whirling around each other at an accelerating pace, sending out higher and higher frequency gravitational waves. But at about 500 cycles per second, the waves' frequency climbed out of LIGO's sensitivity range, and the detectors couldn't observe the final few revolutions leading up to the merger.

Those final revolutions could provide insights into the nature of neutron stars, orbs of pure nuclear matter slightly more massive than the sun but just 20 to 30 kilometers wide. Astrophysicists want to know how stiff or squishy neutron star matter is—a property encapsulated in the so-called equation of state. In principle, the gravitational waves can reveal that information: The stiffer the matter is, the larger the neutron stars will be, and the earlier they will tear each other apart as they spiral together, altering the signal. "If we want to determine the equation of state, we need to see the whole event," says James Lattimer, a nuclear astrophysicist at the State University of New York in Stony Brook. Researchers plan to increase LIGO's sensitivity at high frequencies—for instance, by manipulating the laser light circulating in the massive detectors—but doing so may take a few years.

PEOPLE'S CHOICE

Our readers weigh in with their picks for the top breakthrough of 2017.

Visitors to *Science*'s website were offered the chance to vote on a list of candidates for Breakthrough of the Year while *Science* editors and writers were finalizing their choices. A first round of voting narrowed the top candidates to four, and a second round, in which more than 12,000 votes were cast, determined the top People's Choice.

Biomedical topics were popular, accounting for three of the four finalists. In the end, a remarkable success in gene therapy emerged as the winner. The first observation of coherent neutrino scattering, using a portable detector—the only physical science breakthrough to make the top four—took second place.

Science's Breakthrough of the Year did not make the final four, but all the People's Choice finalists are among our runners-up. The full results:

1	Gene therapy success **47%**
2	Compact neutrino detector **24%**
3	Fixing pinpoint mutations **15%**
4	A drug for many cancers **14%**

Scientists also hope to see new types of events, such as mergers of a neutron star and a black hole, which theory suggests are rare. Supernova explosions of individual stars in our Milky Way galaxy should also produce detectable gravitational waves, which could help astrophysicists figure out exactly how the stars blow up. Spinning neutron stars called pulsars might broadcast a steady warble of gravitational waves. In coming decades, scientists hope to launch a space-based gravitational-wave detector that could spot lower frequency waves, such as those from the mergers of supermassive black holes in the centers of galaxies.

Most thrilling would be a signal that astrophysicists haven't predicted at all, says Roger Blandford, a theorist at Stanford University in Palo Alto, California. "I'd love to see something that doesn't fit the expectations." ■

Science

Cosmic convergence

Adrian Cho

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