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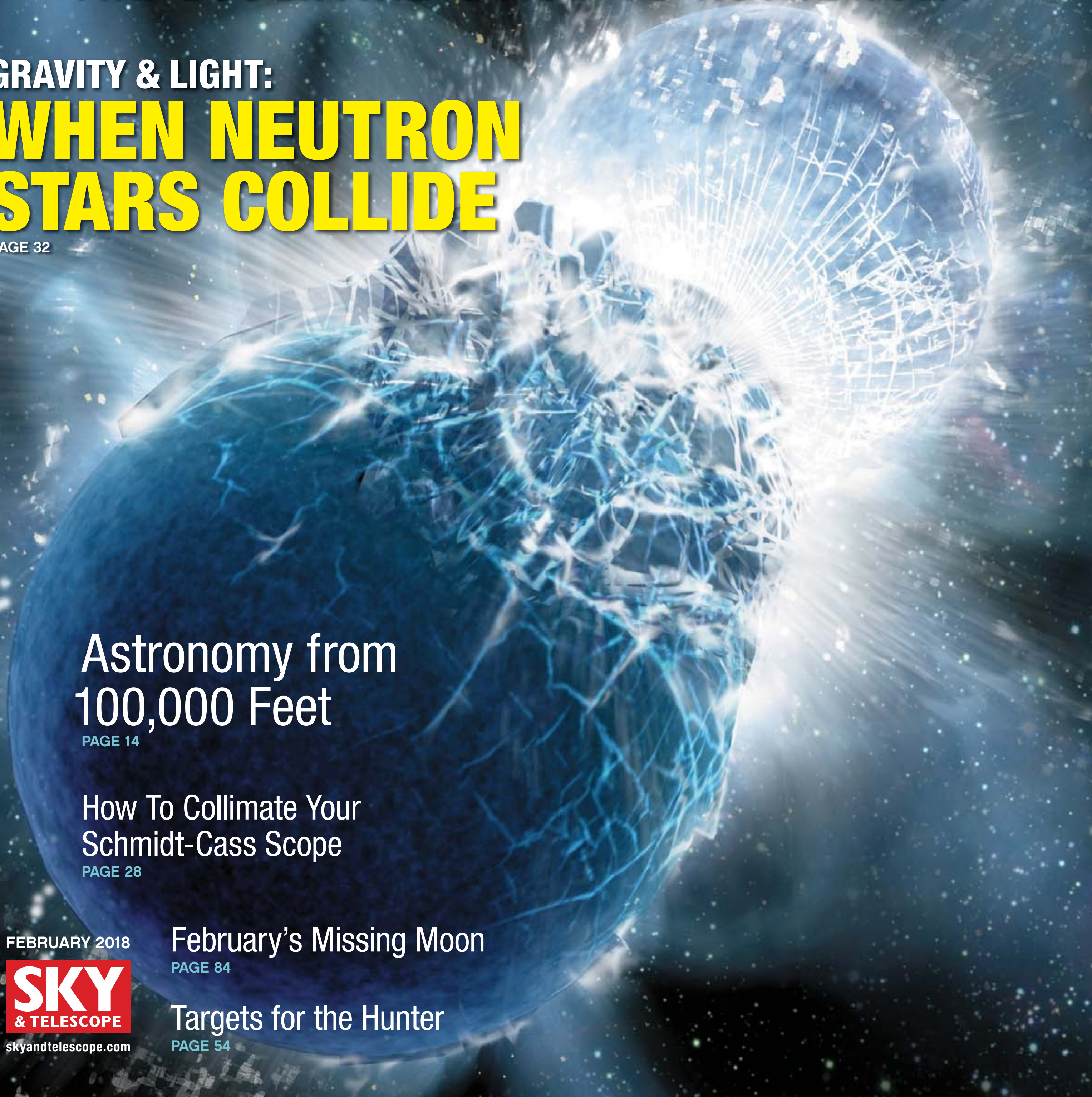

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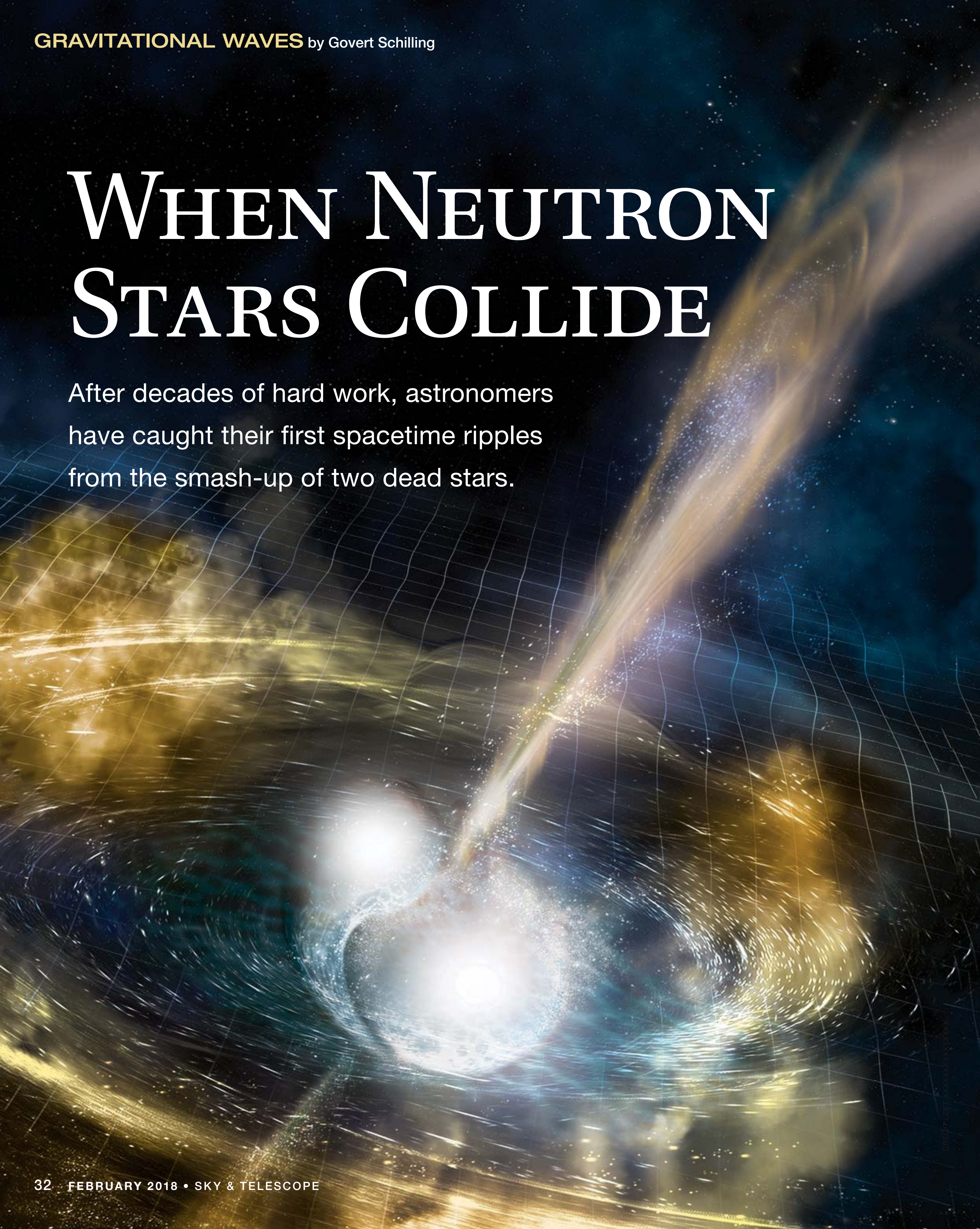
by Govert Schilling

WHEN NEUTRON STARS COLLIDE

After decades of hard work, astronomers have caught their first spacetime ripples from the smash-up of two dead stars.



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On August 17th, a new age of astronomy began. That day, the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) registered tiny ripples in spacetime, produced by a pair of frantically orbiting neutron stars right before they collided. But the reason that they herald a new age is that they didn't come alone: Telescopes on the ground and in space detected the cosmic smash-up and the fading glow of its radioactive fireball all across the electromagnetic spectrum (*S&T:* Jan. 2018, p. 10).

Astronomers have known neutron star binaries exist since 1974, when Russell Hulse and Joseph Taylor (then at the University of Massachusetts, Amherst) discovered the first one, PSR 1913+16. The two objects have an average separation of less than a million kilometers and an orbital period of 7.75 hours. But that separation and period are shrinking with time. In fact, the binary's very slow decrease in orbital period, measured over subsequent years by Taylor, Joel Weisberg (now at Carleton College), and others, perfectly matches Einstein's prediction for energy loss due to the emission of gravitational waves. Some 300 million years from now, the two neutron stars in the Hulse-Taylor binary will collide and merge.

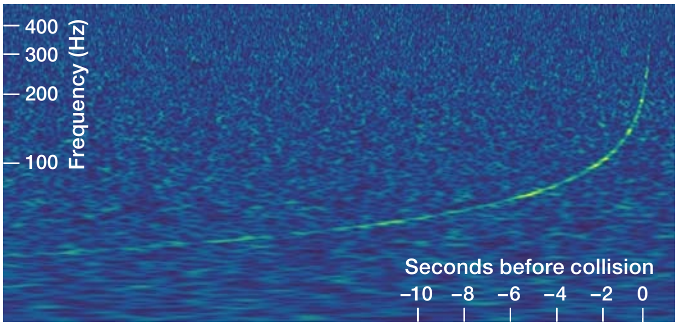
This slow death dance provided the first hard evidence, even if it was indirect, that gravitational waves were real, and the discovery of PSR 1913+16 ultimately earned Hulse and Taylor the 1993 Nobel Prize in Physics. The objects' inexorable inspiral also gave a huge boost of confidence for physicists such as Rainer Weiss (MIT) and Kip Thorne (Caltech), who were designing the first prototypes of LIGO-like laser interferometers. If one binary neutron star would coalesce in 300 million years, others might do so tomorrow — and the energetic burst of gravitational waves the collision produced should be detectable with extremely sensitive instruments here on Earth.

On August 17th, tomorrow arrived. "We've been waiting for this for 40 years," says Ralph Wijers (University of Amsterdam, The Netherlands).

"I couldn't believe my eyes," adds LIGO lead astrophysicist Vicky Kalogera (Northwestern University). Back when LIGO caught its first event in September 2015, many team members didn't believe it was real (*S&T:* Sept. 2017, p. 24). But in the neutron stars' case, it was immediately clear that here was the thing they'd all been waiting for. "It's a lot more exciting than the first gravitational-wave detection."

Astronomers around the world share Kalogera's elation. Observing both gravitational waves and electromagnetic radiation from the catastrophic coalescence of two hyperdense neutron stars provides astronomers with a wealth of new, detailed information. The new buzzword is *multi-messenger astronomy*, the study of objects or phenomena in the universe using fundamentally different types of emission. The detection of neutrinos from supernova 1987A had provided a tantalizing glimpse of this future, but as Edo Berger (Harvard) comments, "2017 August 17 will always be remembered as the singular moment when multi-messenger astronomy was born."

ILLUSTRATION: NSF / LIGO / SONOMA STATE UNIVERSITY / A. SIMONNET; CHIRP: LSC / ALEX NITZ; SKY MAP: DATA SOURCE: IAIR ARCAVI ET AL. / *NATURE* 2017

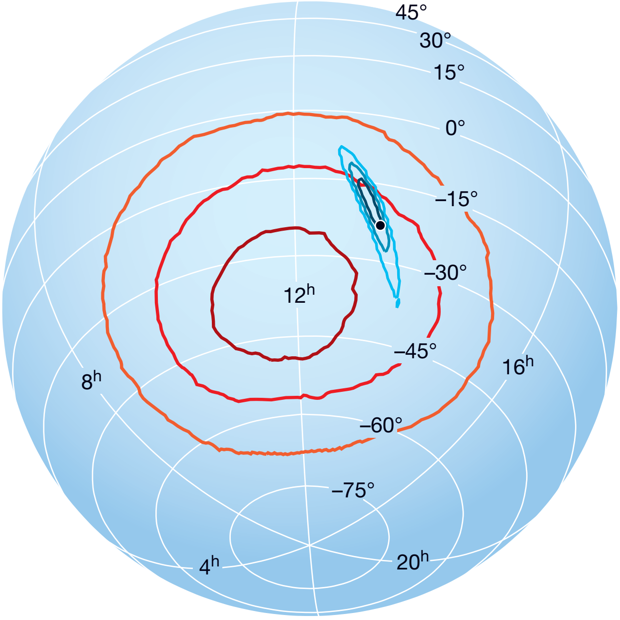


▲ **THE CHIRP** This spectrogram combines the signals from both LIGO detectors to show the characteristic sweeping "chirp" signal of a merger. As the neutron stars came closer to each other, circling faster, they produced higher-frequency gravitational waves, shown by the greenish line sweeping upwards, until eventually they merged (not shown).

How History Was Made

Rumors about the neutron star event had circulated since August 18th, when Craig Wheeler (University of Texas, Austin) tweeted: "New LIGO. Source with optical counterpart. Blow your sox off!" Then, on September 27th, the LIGO and Virgo collaborations announced the detection of GW170814, the gravitational-wave signal of a black hole merger. The discovery led some to assume that the earlier rumors had been just hype: Because these colliding black holes shouldn't give off any light, you wouldn't expect an optical counterpart.

But in a speech October 3rd after his co-reception of the 2017 Nobel Prize in Physics (shared with Thorne and former LIGO director Barry Barish of Caltech), Weiss confirmed another announcement was coming — and wouldn't say



▲ **FINDING GW170817** Gravitational-wave data homed in on a banana-shaped region in the Southern Hemisphere (blue lines), more specific than the region specified by gamma-ray data (red lines). The black dot marks the location of the kilonova, in the galaxy NGC 4993.

what. Thirteen days later on October 16th, at a large press conference at the National Press Club in Washington, D.C., astronomers and physicists finally revealed their secret.

Here's what happened. On Thursday, August 17th, at 12:41:04 UT, LIGO bagged its fifth confirmed gravitational-wave signal, now designated GW170817. But this signal had a much longer duration than the first four: Instead of a second or less, like the earlier detections, the spacetime ripples were seen for roughly 100 seconds, increasing in frequency from a few tens of hertz to above 600 Hz before disappearing into the detectors' noise.

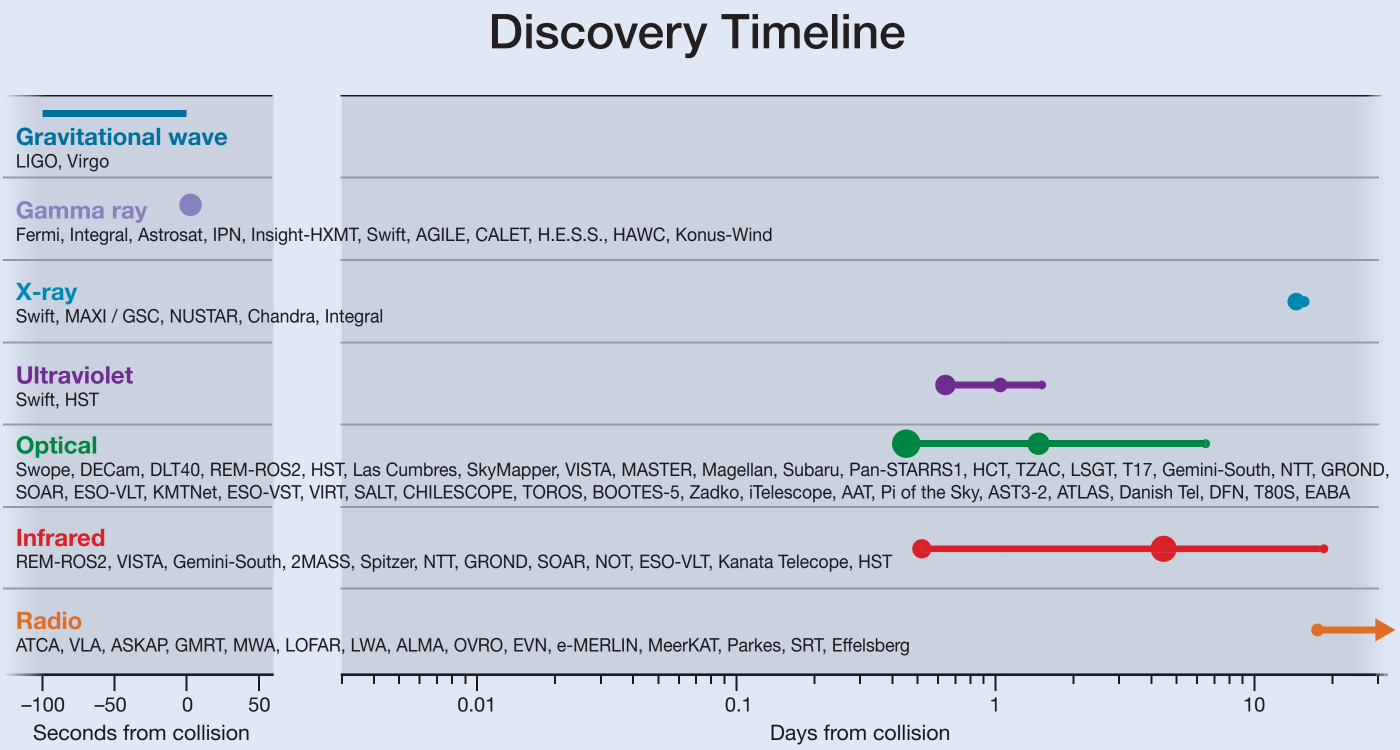
This is the gravitational-wave signal expected from closely orbiting neutron stars, with masses of about 1.2 and 1.6 times the mass of the Sun. Eventually, they whirled around each other many hundreds of times per second (faster than your kitchen blender), a fair fraction of the speed of light. As the "Einstein waves" emitted by the accelerating masses drained the system of orbital energy, the neutron stars drew closer together. Ultimately, the two merged. (This finale went undetected by LIGO: The waves' frequency was too high.) From the LIGO data, astronomers determined that the collision took place roughly 130 million light-years from Earth.

A mere 1.7 seconds after the gravitational-wave event, at 12:41:06 UT, NASA's Fermi Gamma-ray Space Telescope detected a 2-second gamma-ray burst — a brief, powerful flash of the most energetic electromagnetic radiation in nature. The European Space Agency's Integral gamma-ray observatory confirmed the outburst.

Short gamma-ray bursts were already thought to be produced by colliding neutron stars. The merger would blast two narrow, energetic jets of particles and radiation into space (probably perpendicular to the neutron stars' orbital plane). If one of the jets were directed toward Earth, we would see a gamma-ray burst lasting less than two seconds or so. The natural question was, could GRB 170817A possibly be related to the LIGO event that was observed just 1.7 seconds before?

Initially, astronomers had doubts. Gamma-ray bursts usually occur at distances of billions of light-years. GRB 170817A looked about as bright to Fermi as other GRBs, so if this 2-second burst had indeed occurred at a mere 130 million light-years distance, it must have been unusually wimpy.

In principle, one might think researchers could answer the question by simply looking to see if the two signals came from the same place on the sky. But astronomers unfortunately couldn't precisely pinpoint the source of the gamma-rays. Fermi's "error box" measured a few tens of degrees in diameter (the full Moon is only half a degree wide), and NASA's Swift satellite, which sometimes can catch a Fermi event with its more precise X-ray telescope, didn't see any X-ray emission immediately after the GRB.



SEQUENCE OF DISCOVERIES This timeline breaks down the discovery and follow-up observations of the neutron-star merger, relative to the inferred collision time. After the initial gravitational-wave and gamma-ray detections, the time scale is logarithmic. The colored dots represent observations from each wavelength range, with areas approximately scaled by brightness; the lines indicate when the source was detectable by at least one telescope in that band. The names of the relevant instruments or teams appear in each section.

GREGG DINDERMAN / S&T, SOURCE: B. P. ABBOTT ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2017 (848:L12, DOI 10.3847)

However, once the LIGO team dug the gravitational-wave signal out of the data from both detectors — it took a while before the Livingston signal was retrieved from the data stream because of a technical glitch — the researchers used the 3-millisecond difference in arrival time to trace the origin of the waves back to somewhere within two thin, banana-shaped strips of sky in the southern celestial hemisphere. These "bananas" were extremely narrow in this particular case, thanks to the long duration of the event. And one overlapped with Fermi's error box.

Virgo to the Rescue

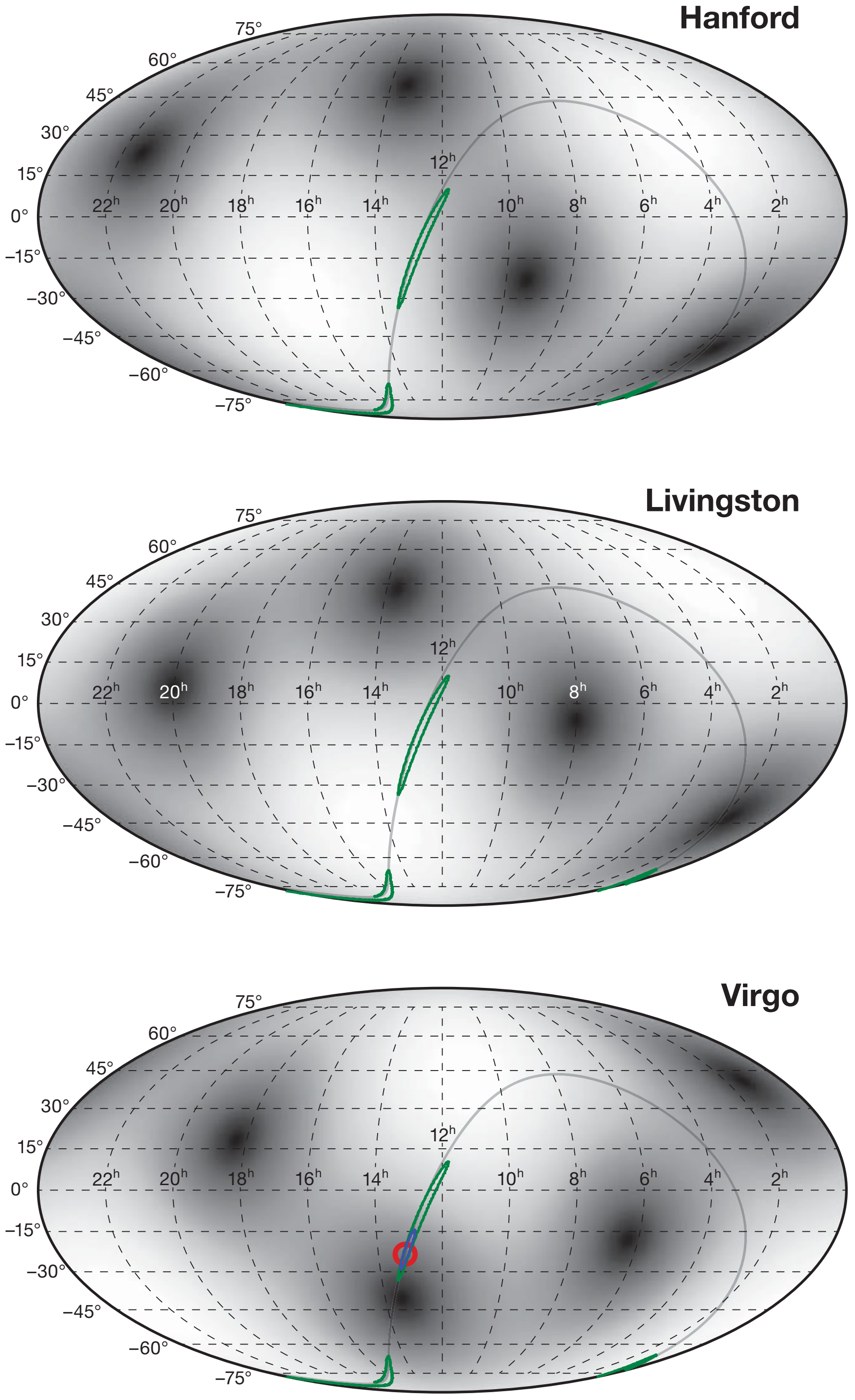
Finding an optical counterpart to the gamma-ray burst would settle the issue, because the debris from colliding neutron stars should glow at other wavelengths. But on the basis of the LIGO and gamma-ray data alone, astronomers could only narrow the search area to some 60 square degrees — still far too much area to search effectively.

Luckily, a third gravitational-wave detector was up and running: Europe's Virgo observatory, in Italy, had been observing in tandem with LIGO since August 1st. Using the differences in a signal's arrival time at three detectors makes it possible for scientists to identify the source's location much more precisely than with just two. In fact, they had used this technique three days before, to trace the black hole merger GW170814 back to a large region on the border of the southern constellations Horologium and Eridanus (*S&T:* Jan. 2018, p. 10).

Yet surprisingly, Virgo had not "triggered" on GW170817. The Einstein-wave signal of the coalescing neutron stars arrived 22 milliseconds earlier at Virgo than it did at Livingston, but it almost doesn't show up in Virgo's data stream — even though the European instrument shouldn't have had any problem detecting it, given its amplitude.

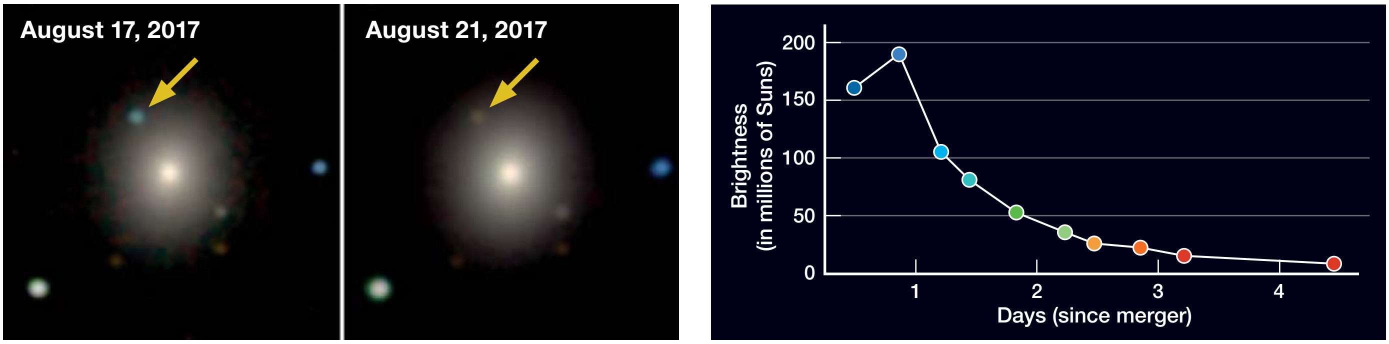
It soon became clear why. Laser interferometers like LIGO and Virgo can detect gravitational waves from nearly every direction. But because of their design, there are four regions of sky on the instrument's local horizon for which the detection sensitivity is much lower than average. At the very center of those regions are blind spots. It turned out that the source of the spacetime ripples nearly coincided with one of Virgo's blind spots.

By combining the LIGO data with the weak Virgo signal, astronomers were able to fence off a much smaller, elongated part of the sky, with an area of just some 28 square degrees. The sector lay in southern Virgo and eastern Hydra and smack in the overlap region between LIGO's thin "banana" and Fermi's error box.



▲ **BLIND LEADING THE BLIND** Each of the gravitational-wave detectors has four blind spots across the sky, but the three patterns do not match. Based on the time delay between the signal's arrival at LIGO's two sites, the source of GW170817 lay somewhere along the large gray circle's edge; the signal's strength narrowed the possibilities to the two green regions. Because the signal was so weak in Virgo's data, researchers realized that the source lay near one of that observatory's blind spots, but not near LIGO's — and one of Virgo's spots abuts the region LIGO's data favored (three-site localization in purple). The red circle is the real location.

REED ESSICK / LIGO



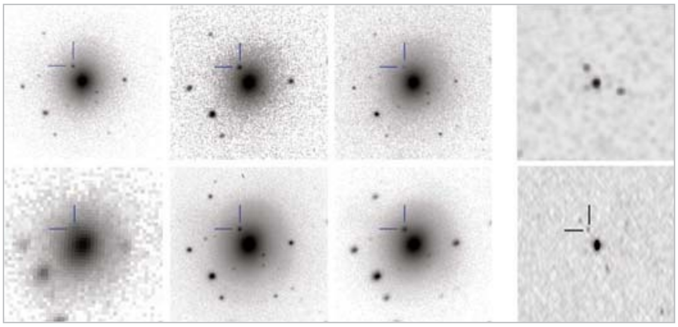
▲ **FIRST LIGHT** *Left:* These composite images of NGC 4993 show the kilonova (marked by yellow arrows) upon discovery on August 17th and four days later, on August 21st, when it had dramatically reddened. Both images use data from the Swope and Magellan telescopes, taken in different filters. The left-hand image contains the first optical photons received from the afterglow, called SSS17a. *Right:* The kilonova reddened and faded by a factor of more than 20 in just a few days, as shown here in data from Las Cumbres Observatory telescopes.

Counterpart Search

Now the hunt was on. Over recent years, the LIGO-Virgo Collaboration had signed a formal agreement with about 100 teams of astronomers all over the world to share this kind of information under strict embargo, meaning they couldn't go public with it before a specified date. The alert system would enable the teams to search for electromagnetic counterparts of any gravitational-wave signals with telescopes on the ground and in space, preferably right after the detection. With the latest coordinates of the search area for GW170817 in hand, some 70 teams trained their instruments at the suspected crime scene.

The 1-meter Henrietta Swope Telescope at the Las Campanas Observatory in northern Chile was the first to strike gold. The team's success depended on a clever strategy. The LIGO data provided them with a rough indication of the source's distance, and within the search area there were only a few dozen galaxies at this distance range. Astronomers with the Swope Supernova Survey rapidly checked the galaxies one by one, in order of probability, to see if they could find an optical transient in any of them.

Around 23:33 UT, they found a 17th-magnitude point of light some 10 arcseconds (7,000 light-years) northeast of the core of the lenticular (S0) galaxy NGC 4993, which lies near the binary star Gamma Hydrae. The source was surprisingly bright, enough for experienced amateur astronomers to have picked it out with large (16-inch) telescopes. The galaxy's redshift puts it at a distance of 130 million light-years, the same distance as inferred from the gravitational waves.



▲ **FIRST IMAGES** These are the first six observations of the kilonova (three left-hand columns), all taken within 12 hours of the gravitational-wave signal. On the right are the first detection in X-rays 9 days later (top) and in radio 16 days later.

Without doubt, here was the optical counterpart of both the neutron star collision that produced the gravitational-wave signal and the short gamma-ray burst.

In the subsequent days and weeks, dozens of ground-based telescopes and space observatories observed that point, including the Hubble Space Telescope, Gemini South, Keck, the European Southern Observatory's Very Large Telescope, ALMA, the Chandra X-ray Observatory (it picked up X-rays some 9 days after the event), and the Very Large Array (radio waves 16 days after the crash). Researchers even searched for high-energy neutrinos in data from the IceCube neutrino detector in Antarctica and the Pierre Auger Observatory in Argentina, but they found no matches.

"I would think this is the most intensely observed astronomical event in history," Kalogera says. The paper describing the follow-up observations (unofficially known as the "multi-messenger paper") is coauthored by some 3,600 physicists and astronomers from more than 900 institutions. According to some estimates, a whopping 15% of the worldwide astronomical community are on the author list. And it's only one of many dozens of papers on GW170817 released on October 16th, in journals including *Physical Review Letters*, *The Astrophysical Journal Letters*, *Science*, and *Nature*.

Striking Gold

Astronomers have now observed the fading aftermath of the neutron star collision at every possible electromagnetic wavelength. The aftermath phenomenon is known as a *kilonova* — a bright, transient event less luminous than a supernova, but about a thousand times as bright as a normal nova and some 100 million times more luminous than the Sun. Only once before, in June 2013, have astronomers found a possible kilonova in conjunction with a short gamma-ray burst, but that one was extremely faint, due to its distance of some 4 billion light-years (*S&T:* Nov. 2013, p. 12).

MULTIWAVELENGTH THUMBNAILS: B. P. ABBOTT ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2017 (848:L12, DOI 10.3847); IMAGES: 1M2H / U.C. SANTA CRUZ AND CARNEGIE OBSERVATORIES / RYAN FOLEY; GRAPH: LEAH TISCIONE / *S&T*; SOURCE: SARAH WILKINSON / LCO

The kilonova — a term coined in 2010 by Vahe Petrosian (Stanford), Brian Metzger (Columbia University), and others — is basically the sizzling fireball from the neutron star smash-up. Chunks of hot, dense nuclear matter are hurled into space, in all possible directions, with velocities easily reaching 20% or 30% the speed of light. Liberated from the neutron stars' extreme gravity, the debris expands, rapidly losing its ultra-high density. This debris is primarily neutrons but has some protons, too. The neutrons and protons in the resulting thermonuclear cauldron quickly combine into heavy atomic nuclei. These nuclei capture more neutrons, making them unstable and, therefore, highly radioactive. The extra neutrons decay more slowly into protons, releasing the energy that makes the ejecta glow. What remains is an incredibly hot expanding shell, loaded with some of the heaviest elements in the periodic table.

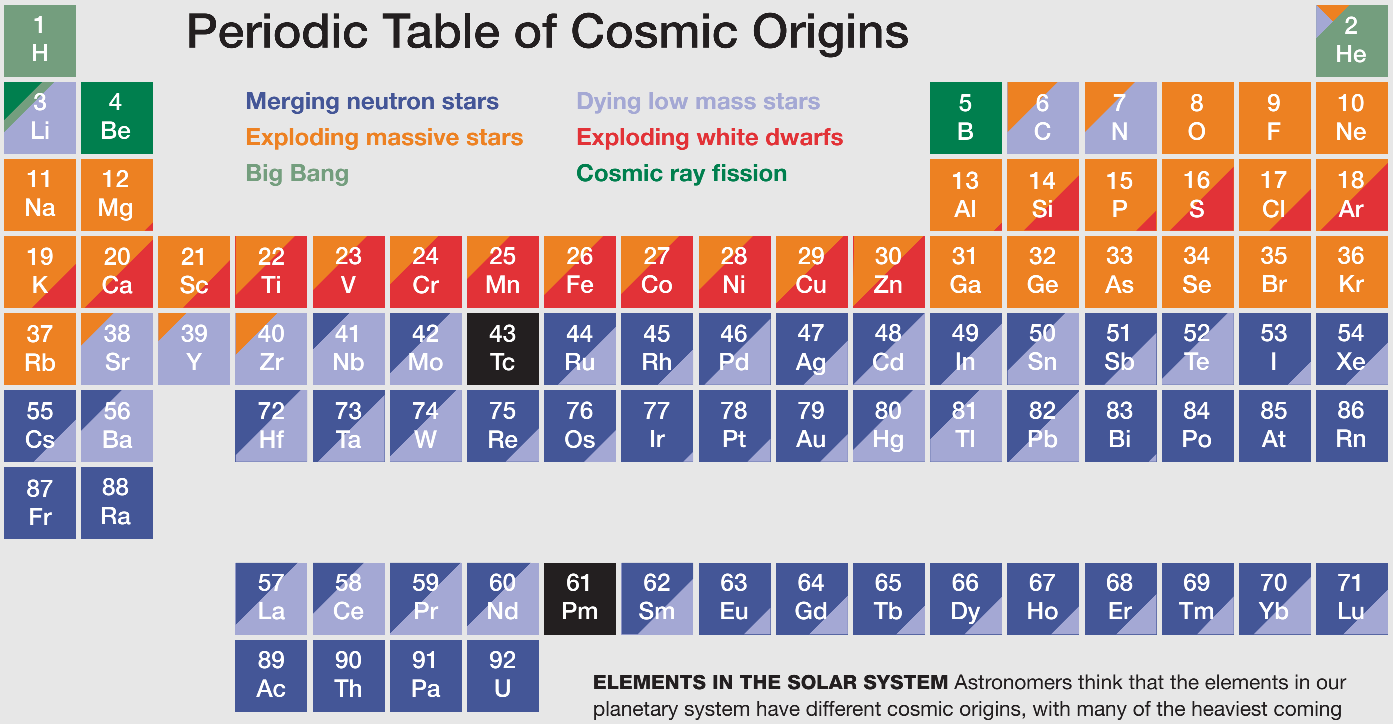
Spectroscopic observations by the X-shooter instrument at the Very Large Telescope and other instruments have indeed indicated the existence of heavy *rare earth elements* (also known as lanthanides) in the fireball that resulted from the neutron star merger. According to Metzger, "It would take improbable fine-tuning to not also produce much heavier elements." The observations thus appear to confirm the theory that the majority of elements more massive than iron are produced by the decay of nuclear matter in the aftermath of neutron star collisions, rather than in supernova explosions — a possibility first suggested way back in 1974 by the late David Schramm and his then-PhD student James Lattimer (Stony Brook University).

For example, Harvard's Berger once calculated that a run-of-the-mill neutron star merger might produce some 10 times the mass of the Moon in pure gold. Gijs Nelemans (Radboud University, The Netherlands) thinks it may well be much higher, up to at least a few Earth masses. Metzger agrees. "From the optical light curve of the kilonova," he says, "it appears that the collision ejected some 5% of a solar mass of material into space, more than enough for the formation of many Earth masses' worth of gold."

So apparently, with the discovery of the counterpart of GW170817, scientists also literally struck gold. According to Edward van den Heuvel (University of Amsterdam), a retired expert on compact binary star evolution, astronomers have discovered 16 binary neutron stars so far in the Milky Way. "From this number, I estimate that neutron star collisions occur once every 50,000 years or so in our Milky Way Galaxy," he says. "Over the age of the Milky Way, that amounts to a few hundred thousand of these gold-spawning events in just one galaxy. That's a lot of gold."

To Be Determined

A few mysteries remain, though. One is the nature of the gamma-ray signal observed by Fermi. If GRB 170817A was a regular gamma-ray burst, one of its jets must have been aimed at our home planet in order for us to see it. But in that



ELEMENTS IN THE SOLAR SYSTEM Astronomers think that the elements in our planetary system have different cosmic origins, with many of the heaviest coming from neutron-star mergers (dark purple). Those with more than one source are divided according to the approximate proportions from each process. Technetium (Tc), promethium (Pc), and elements heavier than uranium don't have stable isotopes and are therefore blacked out or excluded.

LEAH TISCIONE / S&T; SOURCE: JENNIFER JOHNSON / SDSS / CC BY 2.0

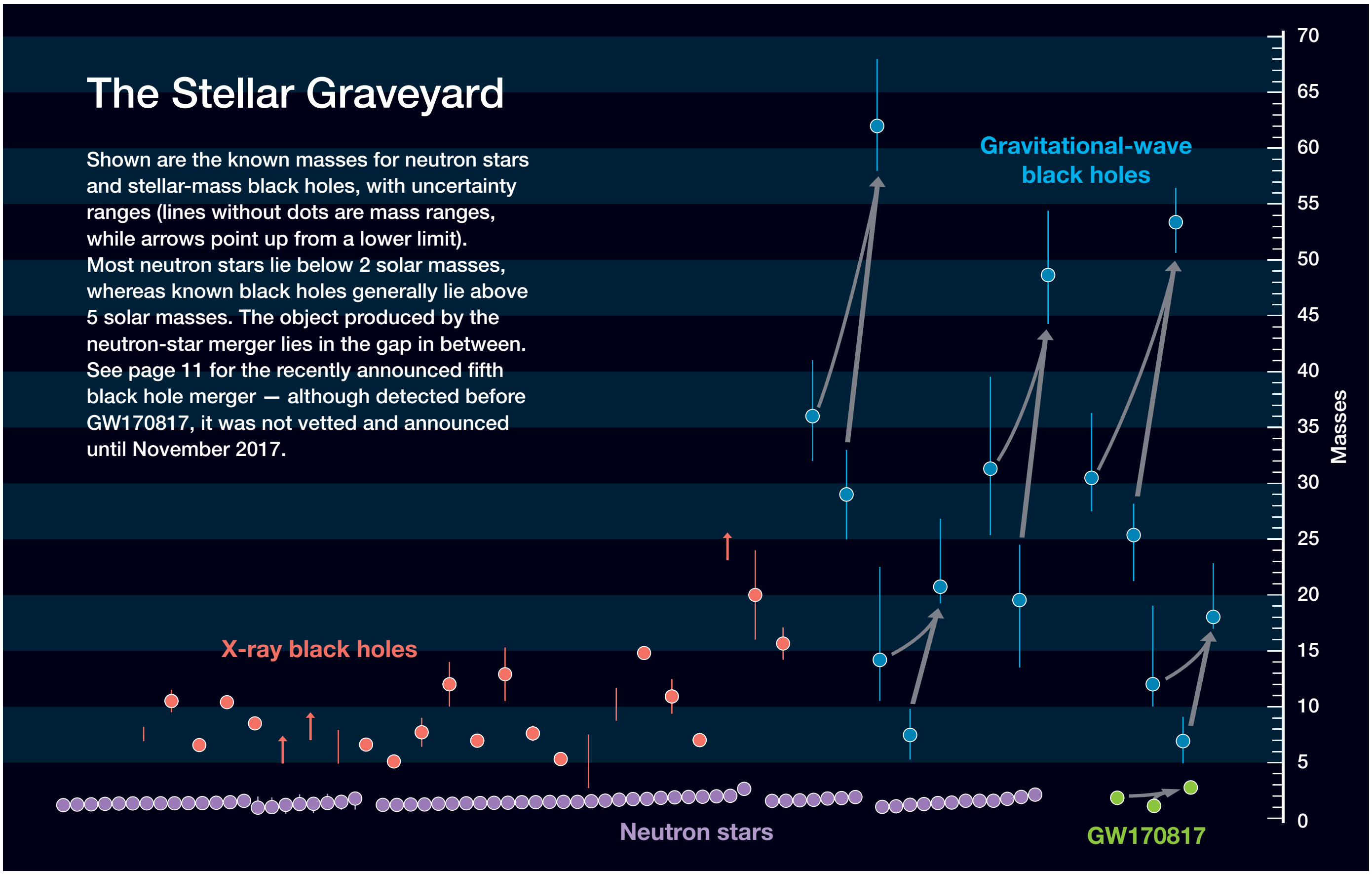
case, astronomers would have expected it to be at least 10,000 times more powerful in gamma rays than they detected, given how close it was. Moreover, the jets should also have produced prompt X-ray emission, which was not detected. So maybe we observed the gamma-ray burst slightly from the side? Many astronomers, including Kalogera and Eleonora Troja (NASA Goddard), who led the X-ray follow-up, think that is the most likely explanation for the weakness of the gamma-ray burst. Troja also says that the delay in X-rays — observed 9 days later — would be natural when looking at the jet from an angle. The same holds for the radio waves from the source, which didn't show up until early September. While the optical and infrared glow of the kilonova is thermal radiation from the radioactive fireball, the X-rays and radio waves are produced by the energetic gamma-ray burst jet after it started to broaden as it slowed down.

Mansi Kasliwal (Caltech) and colleagues suggest a more complex version of this scenario, in which the jets get stuck (either temporarily or permanently) in a thick cocoon of material that the jets inflated as they drilled through the collision ejecta. In this setup, the jet is still off-axis, but the cocoon itself would emit the gamma rays, at a much weaker level than seen from a jet pointed straight at Earth. Wijers and his colleagues had put forward a similar scenario to explain the strange behavior of the long gamma-ray burst GRB 980425, which was also relatively close and surprisingly weak, and coincided with a supernova explosion known as SN 1998bw. Wijers also notes that this model neatly accounts for the transition of the optical counterpart of GRB 170817A from blue to red wavelengths within 48 hours.

A detailed analysis of all existing kilonova observations may eventually solve the issue. And future observations of the site of the cosmic catastrophe could also shed light on another as-yet-unsolved mystery: What was the fate of the two neutron stars? A small fraction of their combined mass was ejected into space, but what happened to the rest? Did the two city-sized stars merge into a hyper-massive neutron star of a few solar masses, or did they collapse into a stellar-mass black hole? Astronomers have only detected a few neutron stars that weigh in just above 2 solar masses — an upper limit that might have implications for the physics of these stars. The merger remnant might be extremely informative.

Unfortunately, the LIGO data can't provide a definitive answer: The final stages of the merger event weren't observed. With the earlier black hole crashes, LIGO could detect hints of the collision's "ring-down phase," a brief period in which the amplitude of the gravitational waves rapidly dwindles to zero. From the characteristics of this ring-down, astronomers were able to estimate the final mass of the merged black hole.

But in the case of GW170817, the rising wave frequency moved out of LIGO's detection range before the two neutron



The Stellar Graveyard

Shown are the known masses for neutron stars and stellar-mass black holes, with uncertainty ranges (lines without dots are mass ranges, while arrows point up from a lower limit). Most neutron stars lie below 2 solar masses, whereas known black holes generally lie above 5 solar masses. The object produced by the neutron-star merger lies in the gap in between. See page 11 for the recently announced fifth black hole merger — although detected before GW170817, it was not vetted and announced until November 2017.

LEAH TISCIONE / *S&T*, LIGO SOURCES: LIGO AND VIRGO COLLABORATIONS
NEUTRON STARS: F. ÖZEL AND P. FREIRE / *ANNUAL REVIEWS OF ASTRONOMY AND ASTROPHYSICS* 2016
BLACK HOLES: GRZEGORZ WIKTOROWICZ AND CHRIS BELCZYNSKI / STELLARCOLLAPSE.ORG

stars actually collided, and the signal was lost, says Kalogera. So astronomers do not have strong observational data to constrain the properties of the merged object, even though the LIGO observations indicate a total system mass on the order of 2.7 to 2.8 solar masses (the individual masses of the two neutron stars are not known very precisely).

Nelemans is confident enough to claim that the collision must have produced a new black hole. "If there was a hyper-massive neutron star there right now, it would be extremely hot, and we would have detected it in X-rays," he says.

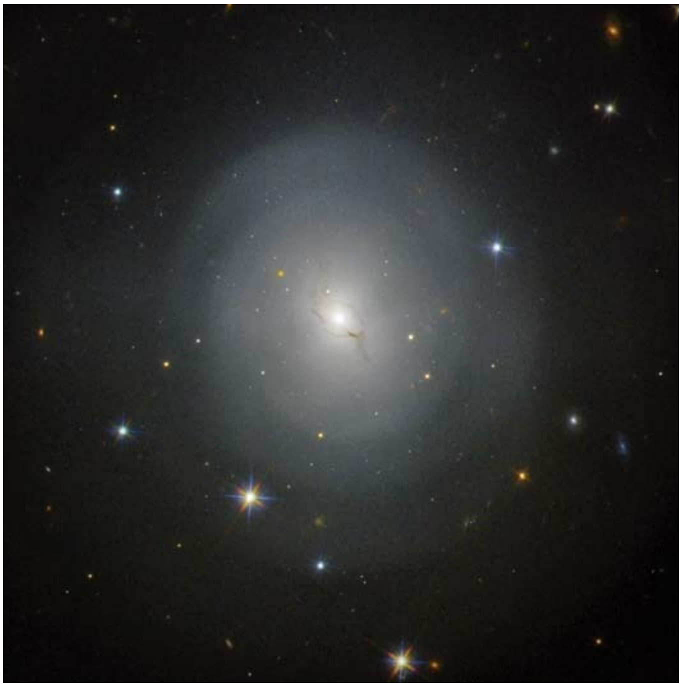
Metzger agrees. "But," he adds, "if there had been an immediate collapse into a black hole, you wouldn't expect so much ejecta." Instead, the two neutron stars may first have coalesced into a hyper-massive object of some 2.8 solar masses, held up by its incredibly fast rotation, before further collapsing into a black hole after a fraction of a second.

Making History

The GW170817 observations, spectacular as they are, may turn out to be the proverbial tip of the iceberg of future revelations on gamma-ray bursts, binary star evolution, heavy element synthesis, general relativity, the behavior of matter in extreme environments, and the properties of neutron stars. Physicists are particularly interested in the material properties of these hyper-dense stellar remnants, which easily pack a hundred thousand tons of matter into a volume of one cubic millimeter. We can't yet recreate such extreme conditions in a laboratory on Earth.

In principle, a detailed study of gravitational-wave signals such as GW170817 should provide more information on neutron-star structure, especially when the high-frequency waves from the final stages of the merger can also be observed in detail. As the two neutron stars draw closer and closer, they will be stretched and squeezed by mutual tidal forces. The magnitude of the resulting deformations tells physicists something about the interior structure of the star, the way its density changes with depth, the material's stiffness, and so forth. This so-called *equation of state* has not yet been determined on the basis of the current GW170817 observations, says Lattimer. But so far, everything appears to be consistent with constraints from nuclear experiments in laboratories on Earth.

Moreover, he adds, the fact that the merger produced such a massive, relativistically expanding fireball puts some constraints on the tidal deformations of the two neutron stars. "More compact stars can get closer together before they coalesce," he says. "As a result, they collide more powerfully and eject more mass." From the estimated ejecta mass, it follows that the neutron stars are at most 27 kilometers in diameter; another line of evidence indicates that they cannot be smaller than 22 kilometers across. The smaller neutron stars are, the more likely it is that they may contain extreme forms of matter deep within their cores, although theoretical details are still pretty sketchy (*S&T:* July 2017, p. 16). "It's remarkable that one single event can yield so much information," Lattimer says.



▲ **NGC 4993** This Hubble image shows the lenticular galaxy NGC 4993, which lies near the border of the constellation Hydra, the Sea Serpent. The orange dot upper left of the galaxy's center is the kilonova.

NASA AND ESA

And there's more. From the near-simultaneous arrival time of the gamma rays and the gravitational waves, it follows that spacetime ripples propagate at the speed of light to within a few parts in a quadrillion — confirming predictions of Einstein's theory of relativity. And an independent measure of the host galaxy's distance (based on the observed Einstein-wave amplitude), combined with NGC 4993's recession velocity, yields a Hubble constant between 62 and 82 kilometers per second per megaparsec — nicely in line with existing measurements. With future observations, astronomers expect to significantly crank up the precision in this estimate.

As 2017 Nobel laureate Barry Barish noted when GW170817 was announced, the new discovery establishes gravitational-wave science as an emerging field. And it's emerging fast, too. In the fall of 2018, both LIGO and Virgo will start yet another observing run, at an even higher sensitivity. Van den Heuvel can't wait to see the next spectacular breakthrough. "These measurements are incredibly hard," he says. When the Einstein waves passed, the length of LIGO and Virgo's detector arms changed by less than an atomic nucleus, he explains. "But within 20 years or so, gravitational-wave measurements may be just as routine as X-ray observations have become over the past 40 years. It's really beyond my wildest dreams."

■ *Sky & Telescope* Contributing Editor **GOVERT SCHILLING** lives in the Netherlands but loves to explore his home planet. His latest book is *Ripples in Spacetime: Einstein, Gravitational Waves, and the Future of Astronomy*, published by Harvard University Press in 2017.