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JUNE 2022

WHEN BLACK HOLES COLLIDE

Insights from Gravitational Waves

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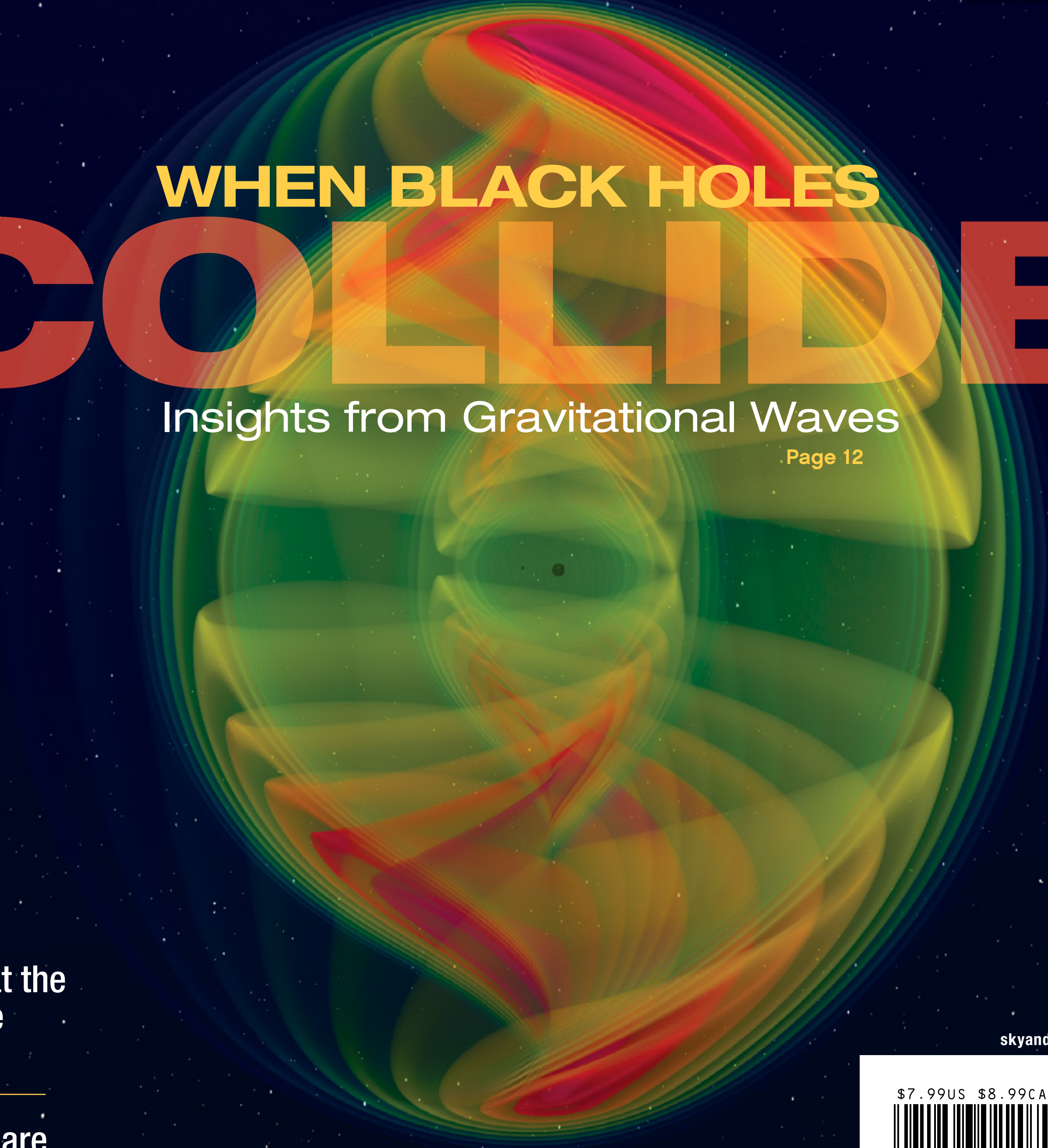

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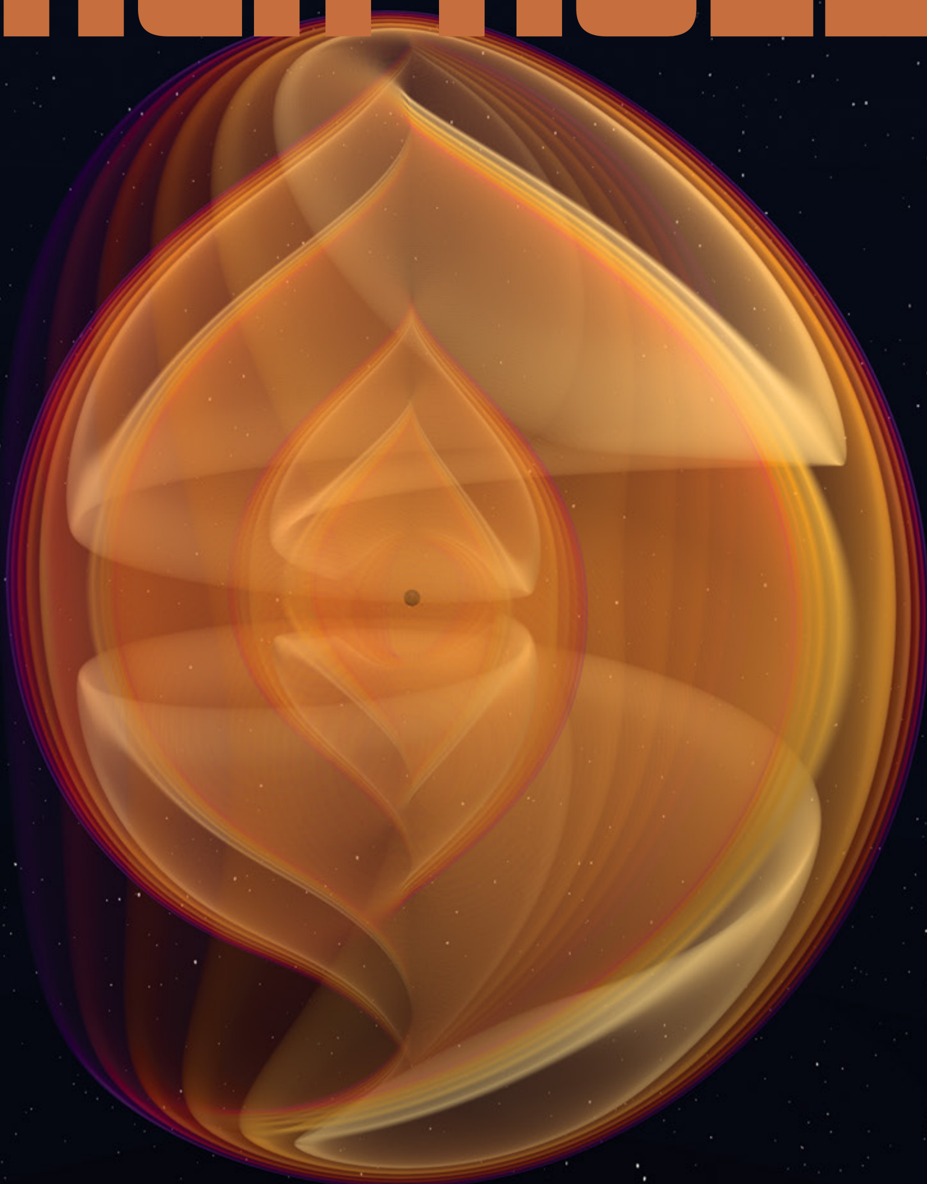
What Gravitational Waves Have Taught Us About BLACK HOLES



MAKING WAVES This visualization is from just before the merger of the two objects involved in GW190814. Yellower colors mark stronger gravitational radiation, and the binary's orbit is from left to right.

N. FISCHER, S. OSSOKINE, H. PFEIFFER, A. BUONANNO (MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS), SIMULATING EXTREME SPACETIMES COLLABORATION

With dozens of detections in hand, scientists are building a compelling picture of these mysterious spacetime objects.

A tsunami has hit astrophysics. Before 2015, we knew of a smattering of star-size black holes, usually thanks to the glow from the gas they're slurping off companion stars. We also had indirect evidence that the fabric of spacetime can undulate, and that these ripples — called gravitational waves — can emanate from tight binary systems and rob them of orbital energy, ultimately sending the two objects crashing into each other.

But we'd never actually detected gravitational waves. Nor did we know of any binaries made solely of black holes. Many astronomers were skeptical that black holes would pair up and merge, or that gravitational-wave detectors would sense them — if the detectors saw anything at all, that is. Well-intended friends fretted about the futures of young scientists going into the field, advising them to turn elsewhere.

Then GW150914 happened. The crash of two distant black holes, each with about 30 times the Sun's mass, sent swells through the cosmos. More than a billion light-years from their point of origin, these waves infinitesimally stretched and squeezed our planet and the twin Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors in the U.S.

Within a few months, "[I] changed from basically the most useless astrophysicist in the world to somebody everybody really wanted to discuss with," says black hole researcher Michela Mapelli (University of Padova, Italy), a member of LIGO's European counterpart, Virgo.

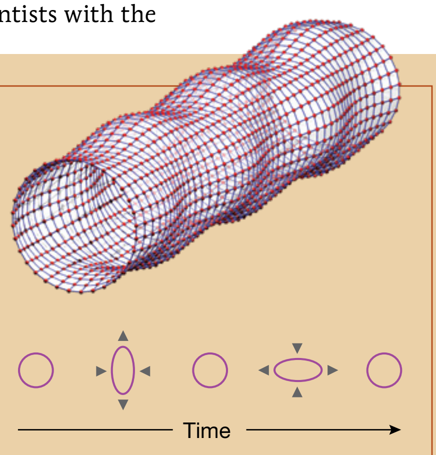
Since that first, watershed detection, scientists with the LIGO and Virgo collaborations have tallied 90 spacetime-shaking events. Each was the merger of two *compact objects*, a catchall term for the skeletons of dead stars that includes both neutron stars and black holes. Almost all of the gravitational-wave events have involved only black holes, though, and the discoveries have multiplied the number of star-size black holes for which we have good mass measurements by a factor of 10. We now estimate that a pair of black holes merges in the local universe every 15 days.

Researchers call the flood of discoveries "dreamlike" and "shocking." "I don't appreciate it enough," says leading LIGO astrophysicist Vicky Kalogera (Northwestern University), laughing. In the first few years, wonder would overwhelm her at the reality she was dealing with — that we can not only detect gravitational waves but also use them to study real objects in the universe. "It would send shivers down my spine," she says.

The typical waves washing over LIGO and Virgo change the detectors' lengths by a factor of 10^{-21}, which is like changing the size of Earth's orbit by the diameter of a hydrogen atom.

But with the latest catalog of detections, released in November 2021, she realized the revolution has become run-of-the-mill. "I was thinking, 'Shame on you, Vicky! You know, you should be more appreciative of what you got to experience in life, because that is dumb luck!'"

The detections have brought key insights into black holes, from their fundamental nature — incredibly simple, just as predicted — to their sizes and origins. But the discoveries are also about more than black holes. They're about writing the story of stars, particularly the massive ones that blaze in brilliant but brief lives and seed the galaxy with heavy elements like the iron in our blood. And on that front, spacetime isn't the only thing that's been shaken up.



PROPAGATION OF A WAVE A gravitational wave stretches and squeezes the spatial dimensions that are perpendicular to its direction of motion. Here, the red dots represent particles floating in space; the blue grid is just to show how the particles are positioned relative to one another. The ellipses are cross sections.

Catching Waves

Gravity is the warping of spacetime by mass. If a massive object accelerates, then the warp itself becomes dynamic, propagating away as a gravitational wave. The ripples are tiny: The typical waves washing over LIGO and Virgo change the detectors' lengths by a factor of 10^{-21}, which is like changing the size of Earth's orbit by the diameter of a hydrogen atom.

But don't be fooled into thinking the waves are weak. Spacetime is stiff, so it resists flexure. If you could convert the energy of a binary black hole merger into light, it would be brighter than all the stars in the observable universe.

Two compact objects whirling around each other create gravitational waves that carry energy away, which in turn causes the objects to spiral closer together. The orbital

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL / SHUTTERSTOCK.COM; 3D WAVE: MARKUS PÖSSEL / HAUS DER ASTRONOMIE / MPI FOR ASTRONOMY; CROSS SECTIONS: LEAH TISCIONE / *S&T*

period sets the waves' frequency, so as the objects inspiral, the waves' frequency rises, sweeping up until the objects suddenly plunge toward each other and collide, creating a "chirp" in the signal. The resulting remnant rings like a bell as it settles down. This *ringdown*, as well as the objects' masses, spins, and distance from Earth, is encoded in the gravitational waves.

LIGO and Virgo can detect waves from roughly 10 hertz to a few kilohertz. Although two black holes might spend a billion years inching closer to each other, the detectors won't "hear" them until the last few seconds or so.

When something hits the detectors that looks like a gravitational-wave event, it triggers an automated public alert. Dozens of team members get calls — usually in the middle of the night for the U.S., when noise from human activity is low and detectors are therefore more sensitive, says LIGO's Chad Hanna (Penn State). The scientists jump to vet the signal. Events that make the cut prompt a more detailed alert to the astronomical community.

The LIGO and Virgo collaborations issued 39 public alerts — about one per week — during the second half of the latest observing run, which lasted from November 2019 to March 2020. Speed is key, because if the event involves a neutron star, then observers must rally to search the skies for a flash of light (*S&T:* Dec. 2021, p. 36).

"We've totally baffled a lot of the theorists, because our mass distribution looks nothing like any mass distribution drawn before."
—MAYA FISHBACH

After the observing run, collaborators do a much deeper analysis, spending months assessing thousands of data streams that record things like the detectors' physical environments and laser power. "People invest a lot of time in really trying to get the right answers," Hanna says — especially early-career scientists, he emphasizes, who are often the ones "banging their heads against the supercomputers."

The final tally can fluctuate a lot: Only 18 of the 39 alerts survived. Scientists also found another 17 that the automated system hadn't spotted. The less-than-optimal success rate stems in part from the fact that every observing run involves new hardware, as researchers try to squeeze every improvement they can out of the instruments. As a consequence, each time they must relearn the system's vagaries.

Down in the Valley

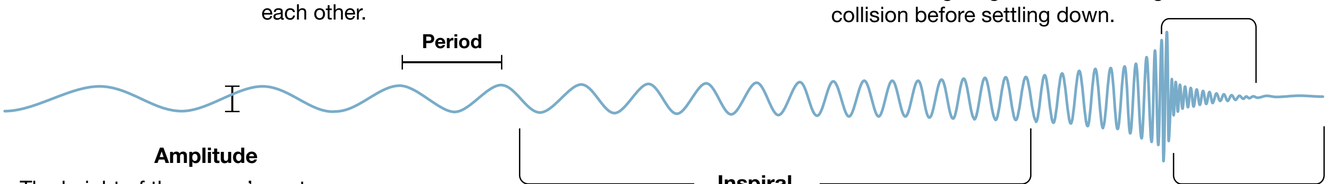
The black holes LIGO and Virgo caught colliding generally had masses from 7 to 50 times that of the Sun. They were usually paired up pretty equally, mass-wise, which is unsurprising because most ways to build a black hole binary tend to join objects of near-equal masses. Independent teams have also trawled the gravitational-wave data and found events beyond the 90 in the collaborations' catalog, and these follow the same trends.

BREAKDOWN OF A GRAVITATIONAL-WAVE EVENT

Time →

Period (Frequency)
The time from crest to crest depends on the size of the black holes' orbit around each other.

Merger and Ringdown
The black holes plummet toward each other and merge. The resulting, larger black hole rings like a bell from the collision before settling down.



Amplitude
The height of the waves' crests encodes information about the black holes' masses, spins, and distance from Earth:

- Gravitational waves fade as they travel, so smaller amplitudes (a.k.a. quieter signals) come from more distant sources.
- More massive black holes create stronger waves.
- If the black holes spin and lean at an angle as they orbit each other, then the orbit will wobble around and the amplitude will vary.

Inspiral
As the black holes spiral in toward each other, their orbit shrinks. This causes the waves' frequency to increase.

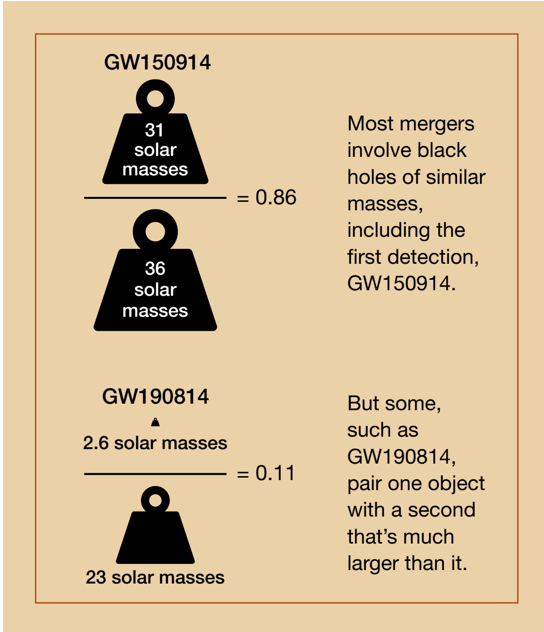
- Smaller black holes come closer together before they collide, so their waves reach a higher frequency.
- The black holes' spins will affect how close the objects approach before merger.
- The black holes' masses determine how quickly the inspiral proceeds.

The exact shape and behavior of the ringdown depend on the black holes' spins when they collide, as well as the remnant's mass and spin.

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL; GRAVITATIONAL-WAVE EVENT: GREGG DINDERMAN / *S&T*

Researchers use advanced statistical techniques to take a step back from these individual finds and study the big picture. This *population analysis* tells astrophysicists what they would detect if their instruments were perfect, explains LIGO's Zoheyr Doctor (Northwestern). "What we're after is what's going on out in the universe, not just what our detector is seeing," he says.

This extrapolation has turned up something unexpected: Black holes tend to cluster at 10 and 35 solar masses. "We've totally baffled a lot of the theorists, because our mass distribution looks nothing like any mass distribution drawn before," says LIGO's Maya Fishbach (also Northwestern).

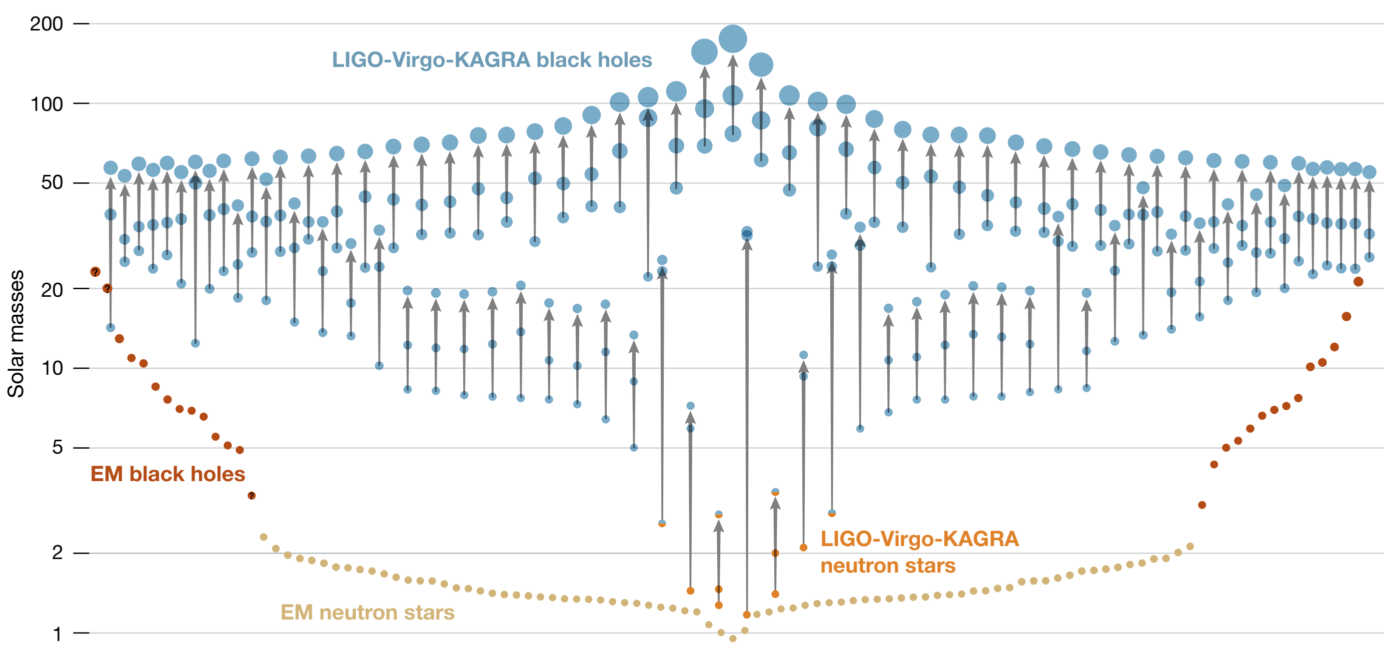


"There were no theoretical reasons," says Feryal Özel (University of Arizona), who helped bring the paucity to astronomers' attention. Small stars are more common than big ones, she explains, "and if the evolution does nothing special and the explosion mechanism does nothing special, then there should have been far more low-mass black holes in the 2- to 5-solar-mass range than, for example, the 5- to 10-solar-mass range."

Gravitational waves have turned up a few objects in the valley, notably the smaller member of GW190814. This event involved a 23-solar-mass black hole swallowing a mystery object of 2.6 solar masses. Many astrophysicists think the mystery object was a tiny black hole, although a rapidly spinning neutron star might be able to withstand collapse at that mass.

Below roughly 10 solar masses, the number of black holes plummets, creating a valley in the plot. This dearth of small black holes has puzzled astronomers long before the advent of gravitational-wave science. Neutron stars can only survive up to maybe 2½ solar masses before they collapse under their own weight; black holes should appear just above that limit. Yet observations of compact objects in stellar binaries have found almost no black holes between 2 and 5 solar masses.

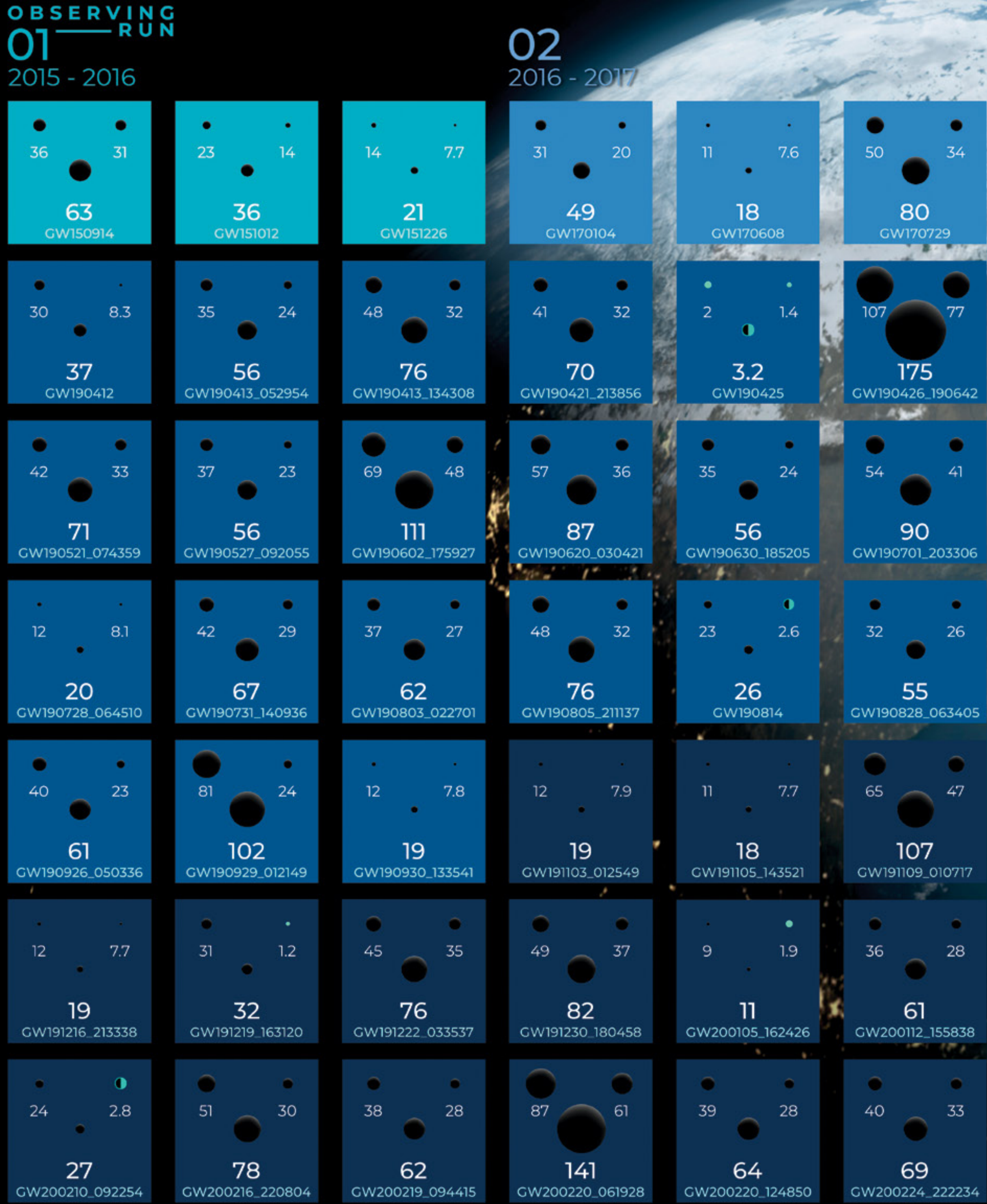
Other observations also suggest the low-mass valley isn't empty. Careful monitoring of tiny flashes created as unseen objects pass between us and our galaxy's stars, bending and magnifying the stars' light, have turned up eight objects that might lie in the valley, Łukasz Wyrzykowski (Warsaw *(continued on page 18)*



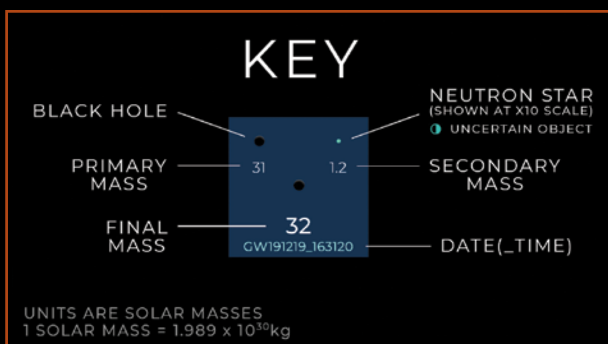
▲ **THE TALLY SO FAR** Scientists have now detected 90 gravitational-wave events (blue and orange), expanding considerably on the compact objects detected at various wavelengths of light (electromagnetic, or "EM"). The dots indicate the two masses of the objects that merged and of the object they created. Almost all of the new discoveries appear to be black holes. Objects that lie just above 2 solar masses are of uncertain nature.

MASS COMPARISONS: GREGG DINDERMAN / *S&T*, SOURCE: LIGO-G2000963; TALLY: LIGO-VIRGO / AARON GELLER / NORTHWESTERN UNIVERSITY

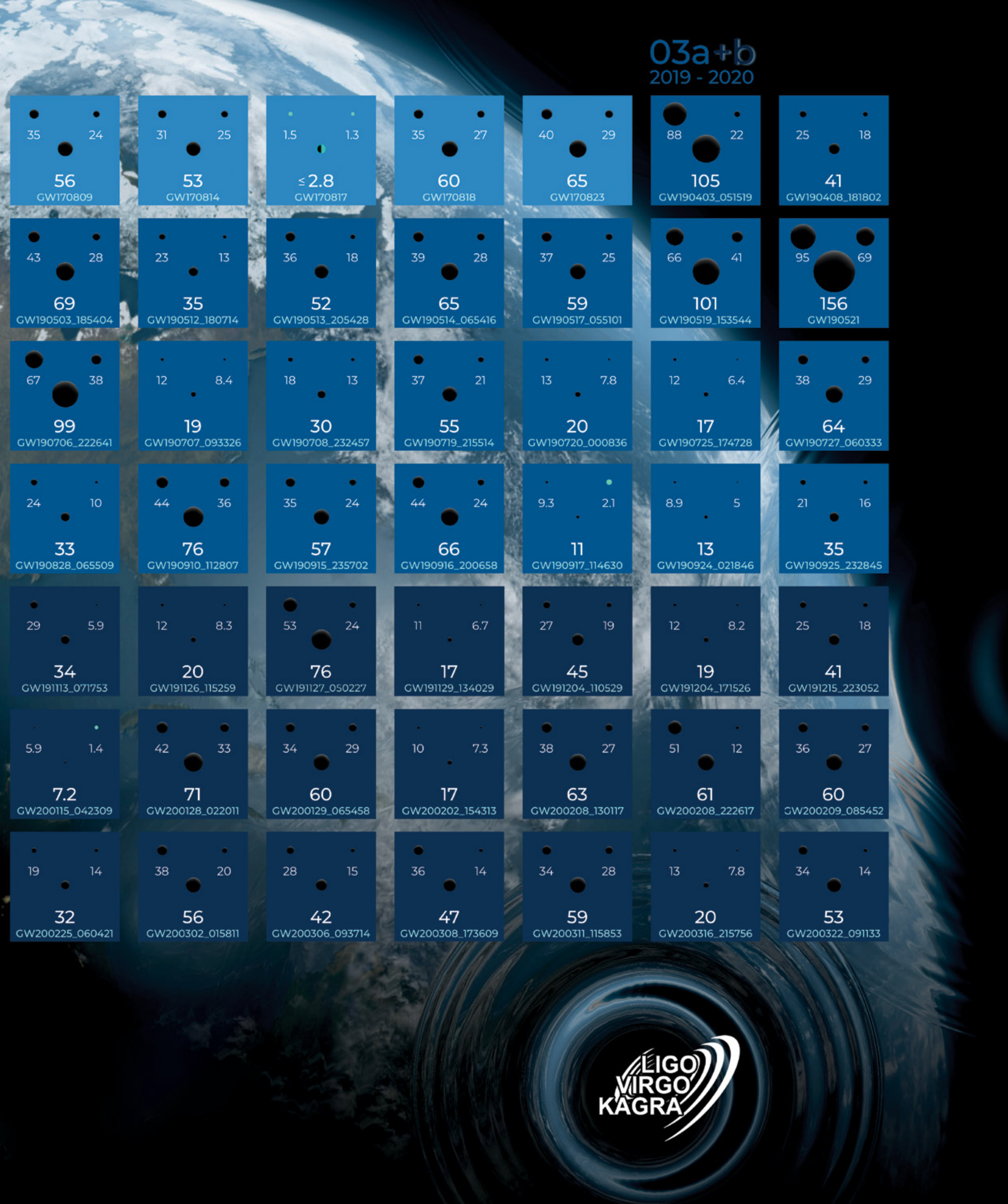
MERGERS DETECTED SINCE 2015



LIGO's first and second observing runs (O1 and O2) bagged 11 gravitational-wave events, including the now-famous double-neutron-star merger GW170817. The third observing run, split into two periods spanning April to October 2019 and November 2019 to March 2020, brought another 79 discoveries. The mass estimates shown here don't include uncertainty ranges, which is why the numbers don't always add up. (In fact, the final mass is always smaller than the sum of the two objects, because some mass is lost as energy in the gravitational waves.)



CARL KNOX / OZGRAV, SWINBURNE UNIVERSITY OF TECHNOLOGY


O3a+b
2019 - 2020
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
LIGO
VIRGO
KAGRA

(continued from page 15)
University Astronomical Observatory, Poland) and others have reported.

Such discoveries don't settle the problem, though. "They should have been *most* numerous," Özel says. "Why aren't these low-mass objects forming at the high numbers that we expected before?"

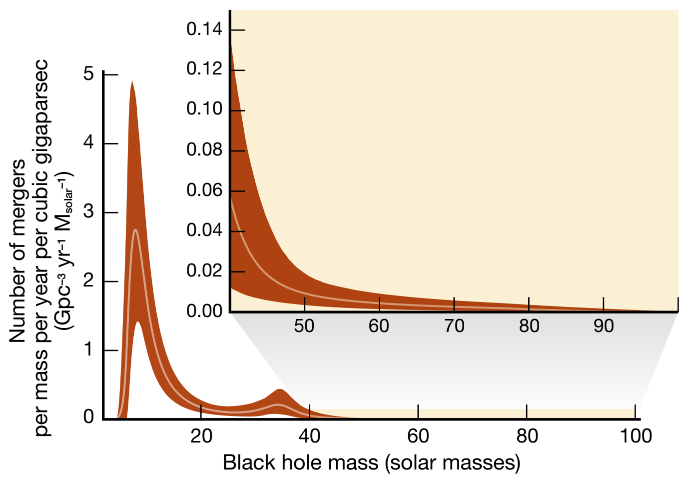
One possibility, she says, is the way stars die. Massive stars have a dense core swaddled in layers and sheathed in a fluffy outer envelope of hydrogen. When a star explodes, it can easily doff the hydrogen envelope, but the layers just above the core tend to implode with the core, as a unit. "And that tends to be five solar masses or more," she says. "Is this the right explanation? I'm not sure."

When Stars Fail

At the other extreme of the mass range, the heftiest objects present their own mystery.

The radiation shining from a star's heart creates an outward pressure that prevents the star from collapsing under its own weight. As massive stars age and fusion runs rampant in their cores, the cores heat up. If the core becomes hot and dense enough, photons can spontaneously transform into pairs of electrons and their antimatter partners, positrons.

But when the photons go poof, so too does the star's defense against implosion. The star's core will suddenly collapse and reignite in an explosion that either throws off vast amounts of material or destroys the star entirely, leaving no remnant. This untimely demise is thought to afflict stars of a certain mass range, preventing the creation of black holes with masses of roughly 50 to 120 Suns.



▲ **HOW BIG ARE BLACK HOLES?** Based on detections so far, researchers can calculate the number of black holes of a given mass that are merging each year in a given volume of space. Doing so reveals that black holes tend to come in two masses: roughly 10 and 35 Suns. Zooming in on the highest masses (inset) also reveals that, contrary to expectations, there are some black holes above 50 solar masses. These plots are for the larger member of the black hole binary, but since black holes tend to pair up equally, the pattern holds for merging black holes overall. Red shading marks the uncertainty range for this model.

Astrophysicists went looking for this theoretical *pair-instability gap* in their gravitational-wave data. Initially, they thought they had found it: An earlier catalog showed hints of a drop in the number of black holes above 45 solar masses. But the latest data complicate matters. The number of black holes falls off at high masses, yes, but it doesn't go to zero. Furthermore, LIGO and Virgo haven't yet detected any merging black holes above the predicted gap, so researchers can't see if there's an upper edge.

It's possible that the uptick in black holes of about 35 solar masses is related to the pair instability. Stars should naturally pile up near the mass gap, because instabilities will cause stars of a range of initial masses to lose enough material to edge themselves down into the safe zone, where they'll ultimately create similar-size black holes. But we shouldn't see the pileup peak right at the mass gap's edge, explains Mapelli, because stars that form black holes of 35 solar masses are far more common than those that form 50-solar-mass ones. When you take that into account, the peak should be around 35 Suns.

Peak aside, there are still about 15 mergers that involved at least one black hole in the upper mass gap. It's entirely possible that the gap doesn't lie quite where astronomers predicted — changes in rotation, composition, nuclear-reaction rates, the way material mixes in the star, and how much mass the star throws off late in life (or loses to a companion) can all shift the mass gap, even 10 to 15 solar masses higher, Mapelli says. Massive stars are messy, especially those born in binaries, and astronomers still have only a patchy picture of what happens as they age and die.

But shifting stellar physics can't solve everything, she and others avow. Take GW190521. The merger of a 95-solar-mass black hole with a 69-solar-mass one, GW190521 was the proverbial canary in the coal mine. No fiddling with stellar evolution can explain that 95-solar-mass object.

There's more than one way to make a black hole, however. Researchers have two broad categories of formation scenarios for black hole binaries. In the *isolated binary scenario*, stars are born together and die together, their remnants merge, and the story ends. In *dynamical scenarios*, however, black holes form, then pair up and merge . . . and maybe merge again with something else.

Dynamical pair-ups can happen in the hearts of stellar clusters, where stars are packed 10,000 to 100,000 times tighter than in the solar neighborhood. They can also occur near galaxies' central supermassive black holes, around which stars and their remnants swarm. The small objects become caught inside the leviathan's huge skirt of hot gas. "The gas will tend to 'organize' the orbits of the black holes so they pair up nicely, like dancers in a formal minuet, rather than the gas-free version, which looks more like a mosh pit," says Saavik Ford (CUNY Borough of Manhattan Community College).

Black holes easily swap partners in dense environs, often multiple times. The compact object their collision creates — called a *second-generation* black hole — can then nab another

GREGG DINDERMAN / S&T, SOURCE: ZOHEYR DOCTOR / CIERA / LVK partner and merge again. Repeat mergers might be rare in star clusters, though: The merger process can come with a recoil that sends the remnant rocketing away at speeds exceeding the cluster's escape velocity. On the other hand, half of the mergers that occur in the gas swirling around a supermassive black hole — known as an *active galactic nucleus (AGN) disk* — may be second-gen events.

"I suspect that many of the highest-mass black-hole mergers we've seen with LIGO and Virgo originate in AGN disks," says Ford. So, too, may events that pair two unequally matched masses, she adds, of which there are a handful in the latest catalog. Unlike starbirth and clusters, AGN disks tend to unite black holes of different sizes, due to the way the gas pushes and traps objects.

Black holes easily swap partners in dense environs, often multiple times. The compact object their collision creates can then nab another partner and merge again.

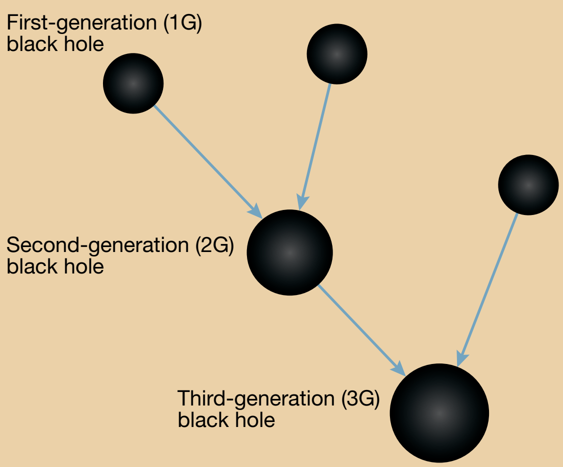
Black hole mergers are normally invisible — except in AGN disks, where the rocketing remnant rams through the surrounding gas, heating it up. In a tantalizing result, Ford, Matthew Graham (Caltech), and their colleagues spotted a flare from an actively accreting supermassive black hole in the same region of sky that GW190521 came from. Based on the flare's appearance, and assuming it's not the AGN playing tricks, the astronomers think that the collision kicked the remnant up out of the disk but that it will come whizzing back through, hopefully sometime in the next few years. They're actively watching for a second flare.

Give It a Whirl

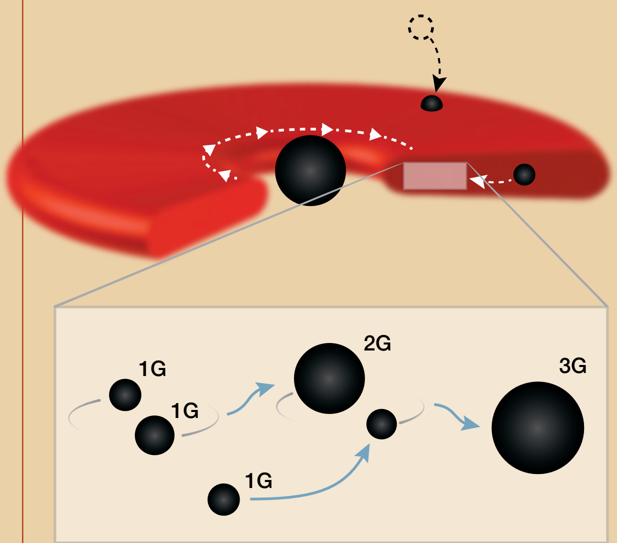
Mass is not enough to distinguish how a black hole was made, though. The hole's spin actually tells you more. As a star ages it puffs up and, like a figure skater throwing out his arms, puts the brakes on its whirl. Assuming the star's core also slows, when the core later collapses into a black hole, the black hole won't spin much. A second-gen black hole, on the other hand, will usually have a spin of 70% of its maximum twirl rate, due to the way it reappropriates the inspiral energy of its forebears.

The tilt of an object's spin axis matters, too. Black holes born from stellar binaries tend to spin upright as they circle each other, because of the stars' interactions before they died. Black holes that partnered up dynamically, however, have no reason to align — they're "bouncing off each other and getting all of their spin directions all jumbled up," Doctor says.

Unfortunately, spin leaves a subtler imprint on gravitational waves than mass does, making it hard to measure



MULTIPLE MERGERS A black hole made from a star's death is called a *first-generation* (1G) black hole. When two 1G black holes merge, they create a *second-generation* (2G) black hole. If a 2G black hole merges with yet another black hole, the result is a 3G black hole. Such chains of mergers are only possible in extremely dense environments, where black holes can easily catch each other.



IN AN AGN DISK Star-size black holes orbiting a supermassive black hole will interact with the leviathan's gas disk and gradually shift their trajectories until their orbits lie within the disk. Once they're inside, the gas forces the small black holes to migrate inward, where they're trapped together and can easily merge multiple times.

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL; MERGER CHAIN: GREGG DINDERMAN / *S&T*, SOURCE: LIGO-G2001426; BH MERGERS IN AN AGN DISK: GREGG DINDERMAN / *S&T*, SOURCE: V. GAYATHRI ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2020 for the merging objects except in special cases. (The remnant's spin is pretty clear.) The 23-solar-mass black hole in GW190814, for example, was so much larger than its companion that its properties dominated the encounter and the resulting waves, like a booming voice overwhelming the other object's whisper. The waves show that the big black hole essentially wasn't spinning, indicating it's likely a stellar skeleton.

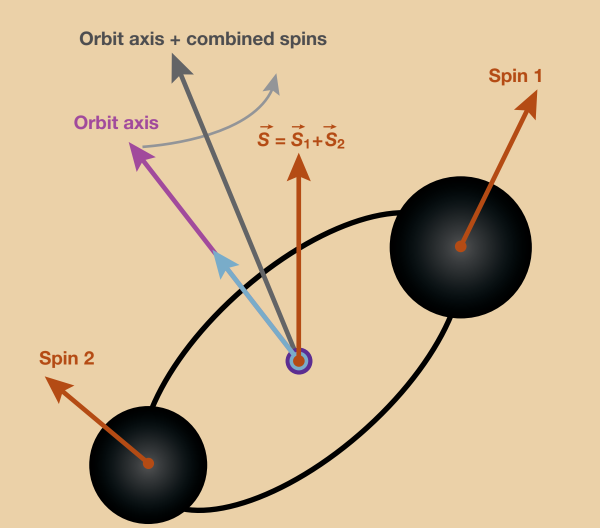
But most of the spin information we have comes from the population analysis, because hints in the cohort add up to reveal trends that a single system can't. The results are intriguing. Statistically speaking, the black holes that collided show a small preference for aligned spins, but roughly 30% were likely askew, telling us that we're indeed seeing binaries made multiple ways. The merging objects also spun slowly, if at all, which sets them apart from the fast-spinning black holes astronomers have seen paired up with stars in the Milky Way. (No one knows why.) Notably, the range of spins widens above 30 solar masses, which might also confirm that the biggest black holes have diverse origins.

One of the biggest surprises is a connection between spins and mass ratio, says LIGO astrophysicist Salvatore Vitale (MIT). The black holes in binaries fall into two camps: either equal mass and no spin, or mismatched in size with notable aligned spins. "None of the traditional formation channels can easily explain this, which is why it's so interesting and beautiful," he says.

"None of the traditional formation channels can easily explain this, which is why it's so interesting and beautiful."
—SALVATORE VITALE

There's a chance that AGN disks *could* explain it, he adds. Mismatched systems can form there, and the gas could override the usual pell-mell nature of dynamical hookups and force the black holes to spin the same way as the disk does. "The usual joke in Bayesian analysis is, 'Would you bet a coffee, a dinner, or your house on this?'" he says, referring to the statistical method used in this work. "I would bet between a coffee and a dinner."

Scientists likely won't have an answer until we've found closer to 1,000 events, says Fishbach. Most collisions so far involve pairs of roughly 30-solar-mass black holes, the detectors' sweet spot. "The things we're really confused about are, what is happening at 60 solar masses and what's happening at 3 solar masses? We only have a handful of detections there now. So even going from a sample size of one or two to, like, five or 10 will be huge."



SPIN Two black holes that orbit each other sometimes also spin. Their spin axes can point parallel to the axis of their orbital motion (as shown for object 2, a setup called *aligned*), or they can be tilted (as with object 1) or even upside-down (in which case the spin axis would be parallel to the orbit's axis but the object would spin, say, clockwise while orbiting counterclockwise). If the spins are misaligned, the orbital plane will wobble (gray arrow).

Rising Tide

During the latest run, LIGO and Virgo saw gravitational waves that had traveled up to 8 billion years to reach us. That covers the last half of cosmic history, revealing how the rate of mergers has changed with time. "Black holes were merging more often in the past than they are now," Doctor says. "Now is the first time when we can confidently say that."

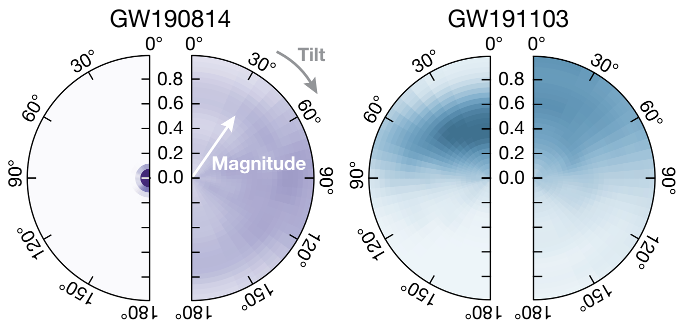
The rate changes in step with star formation across the universe, which peaked about 10 billion years ago. That suggests that the vast majority of the black holes detected either came from stars or were second-generation remnants instead of being *primordial black holes*, hypothetical objects formed in special conditions in the early universe. If such objects exist, then they should merge at a roughly constant rate over time.

Primordial black holes are one of many suggestions to explain dark matter. "This is one of these things that comes in and out of fashion," Hanna says. "It's a polarizing thing. People are like, 'Oh, yeah, of course,' or 'No, you're nuts. Why don't you go join the crackpots?'"

It's unlikely that observations will reach back to the peak of cosmic starbirth in the next run, scheduled to begin at the end of 2022. But the detections could still enable researchers to determine how long a delay there is between star formation and black hole mergers and if the merger rate changes for different mass ranges, Kalogera says. "That is definitely where we want to go next."

This information could help scientists tease apart how the binaries formed, down to the details of the original stel-

BLACK HOLE BACKGROUND: SUDAKARN VIVATVANICHKUL; SPIN: GREGG DINDERMAN / S&T, SOURCE: BHDYNAMICS.COM



◀ **SPINS** Each black hole involved in a merger might be spinning, but scientists can usually only calculate a range of possibilities in terms of how fast and in what direction. Spins are measured from 0 to 1, where 1 is the maximum possible for a given black hole. The coordinates around the circumference indicate the tilt of a black hole's spin axis relative to its orbit: Zero degrees means the black hole was pointing straight up, 90° that it was rolling on its side, and 180° that it was upside-down. Darker colors indicate more likely spin values, and the larger object is the left-hand hemisphere of each pair. For GW190814 *(far left)*, the 23-solar-mass black hole overwhelmed the signal, giving clear signs that it essentially wasn't spinning while also masking any information about its companion's spin. For GW191103, which involved black holes of about 12 and 8 solar masses, it's hard to tell how much the black holes spun or leaned.

lar systems. For example, stars with lower levels of heavy elements grow larger than ones with higher levels, and they make bigger back holes as a result. Galaxies' star-forming gas was more pristine earlier in cosmic history, so bigger black holes might thus be commoner at early cosmic times.

But even if they're made early, that doesn't mean they'll merge early. Recent calculations by Lieke van Son (Center for Astrophysics, Harvard & Smithsonian) suggest that stars able to form black holes above 30 solar masses will also end up in wider binaries than other stellar pairs. Wider binaries take longer to merge, so we should see more high-mass black holes merging *later* in cosmic history, she predicts.

Open the Floodgates

"If, for some reason, we never turned the detectors on again — we're like, 'We're done, and we don't want to detect any gravitational waves anymore — this would be a very unfulfilling end to the story," says Fishbach. "It really feels like we're just at the beginning."

Thanks to upgrades and the addition of a fourth detector (Japan's mine-dwelling KAGRA), the next observing run will have heightened sensitivity. Alerts will come every few days. The rapid-response team will need a new strategy, perhaps limiting wake-up calls to events that the automated system flags as oddballs or involving neutron stars. "It's just a matter of survival," Hanna says. "My graduate students are unwilling to not sleep. I've asked them, they've said no."

But even with the brilliant upgrades that instrumentalists devise, LIGO, Virgo, and KAGRA will ultimately be limited by every astronomer's problem: size. "As scientists, we always think about what comes next," Vitale says. "We never live in the moment."

That next thing could be Cosmic Explorer, a proposed pair of gigantic, ground-based detectors that would be 10 times more sensitive than LIGO. "That simple factor of 10 brings you from seeing one black hole every few days to seeing all of the black holes in the universe, no matter where they are," he says. First light could come in the mid-2030s, around the same time that astronomers will launch the Laser Interferometer Space Antenna (LISA). LISA's sensitivity to lower-frequency gravitational waves will enable it to sense not only smashing supermassive black holes but also stellar-mass black holes years before they merge, giving ground-based detectors a head's up.

In 15 years, astronomers may have seen more than 100,000 black hole collisions. The flood of discoveries will answer questions about the objects' spins, formation, and behavior across cosmic time, as well as what's happening at the smallest and largest masses.

And hopefully, something unexpected will come, too. "It's why I love what we are doing," says Vitale. "Very often, when we see something, it's the first time that humans have seen it."

■ Science Editor **CAMILLE CARLISLE** adores black holes of all sizes. Follow discoveries in her blog, The Black Hole Files: **https://is.gd/bhfiles**.

GROUNDSHAKING

If the first gravitational-wave event had occurred 1 a.u. away, it would have stretched and squeezed Earth on a meter-level scale, causing planet-wide earthquakes. (Fortunately, it was 90 trillion times farther away than that.)