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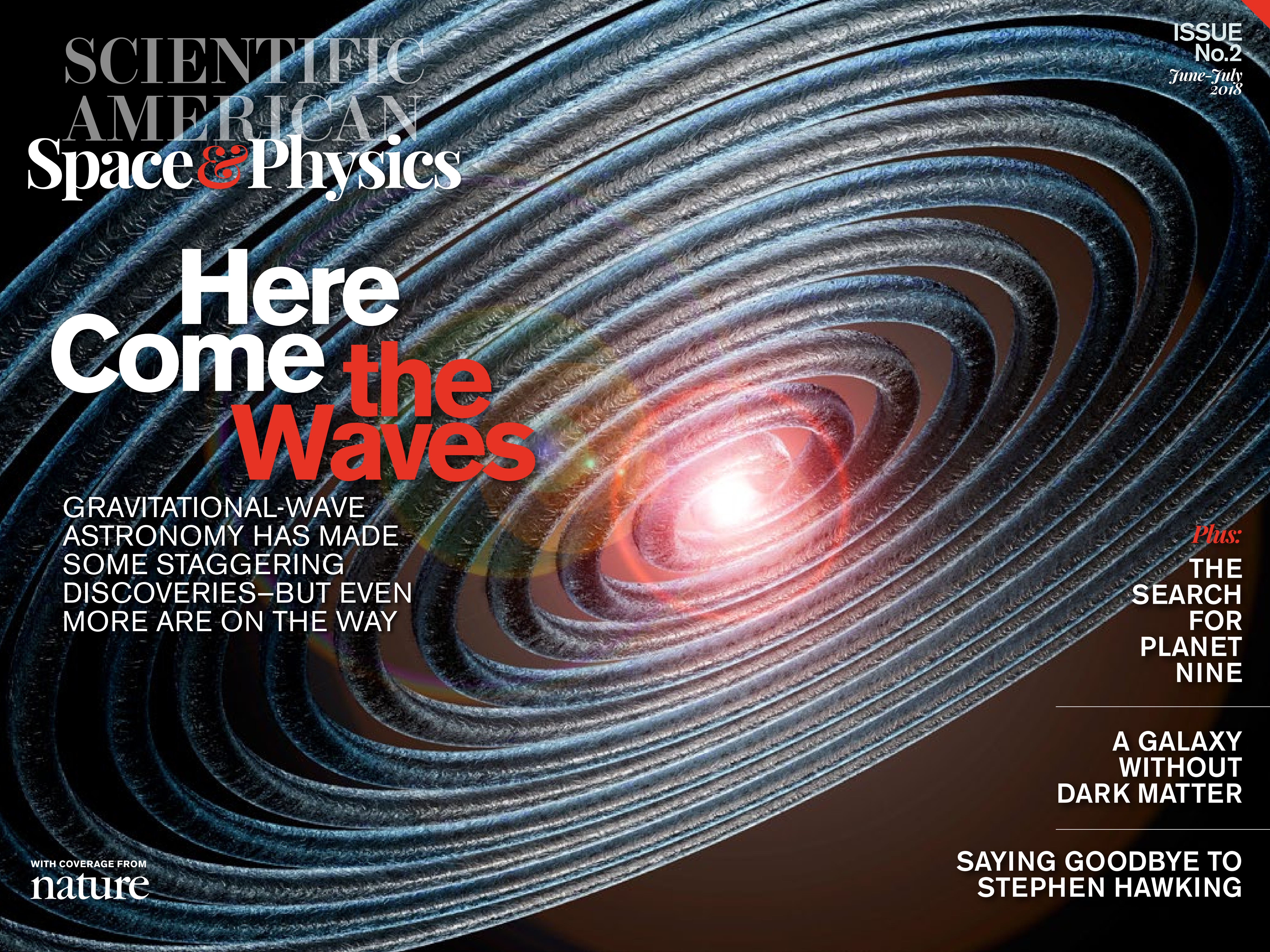

Here Come the Waves

GRAVITATIONAL-WAVE ASTRONOMY HAS MADE SOME STAGGERING DISCOVERIES—BUT EVEN MORE ARE ON THE WAY

Plus:

THE SEARCH FOR PLANET NINE

A GALAXY WITHOUT DARK MATTER

SAYING GOODBYE TO STEPHEN HAWKING

WITH COVERAGE FROM
nature

Your Opinion Matters!

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The Ripple Effect

The February 11, 2016, announcement that scientists had successfully detected gravitational waves was a historic moment for physics. To be sure, the confirmation of Albert Einstein's 100-year-old prediction sent ripples of excitement even beyond the scientific community. But that was just the beginning. Researchers have quickly logged additional records of gravitational waves using the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) and a second wave detector called Virgo in Italy. As Davide Castelvecchi reports for our sister publication *Nature* (see "Here Come the Waves"), these and future observations will start yielding insights into the origins of black holes, the extreme anatomy of neutron stars, the structure and pattern of galaxies, and Einstein's general theory of relativity. "Gravitational waves might even provide a window into what happened in the first few moments after the big bang," Castelvecchi writes. It is indeed an exciting time for physics and cosmology.

Elsewhere in this issue Lee Billings reports on the progress on the great hunt for our solar system's missing planet (see "Looking for Planet Nine, Astronomers Gaze into the Abyss"), and the world says goodbye to one of the greatest minds in physics (see "Stephen Hawking: The Universe Does Not Forget, and Neither Will We").

Andrea Gawrylewski
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On the Cover

An artist's rendition of gravitational waves

ON THE COVER: GETTY IMAGES; THIS PAGE: NASA *UNSPLASH*

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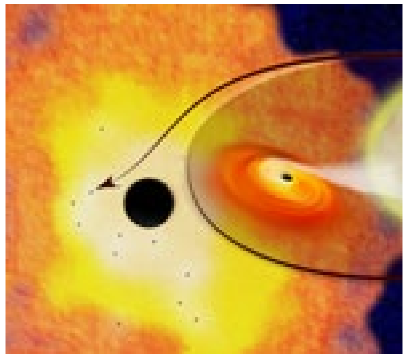
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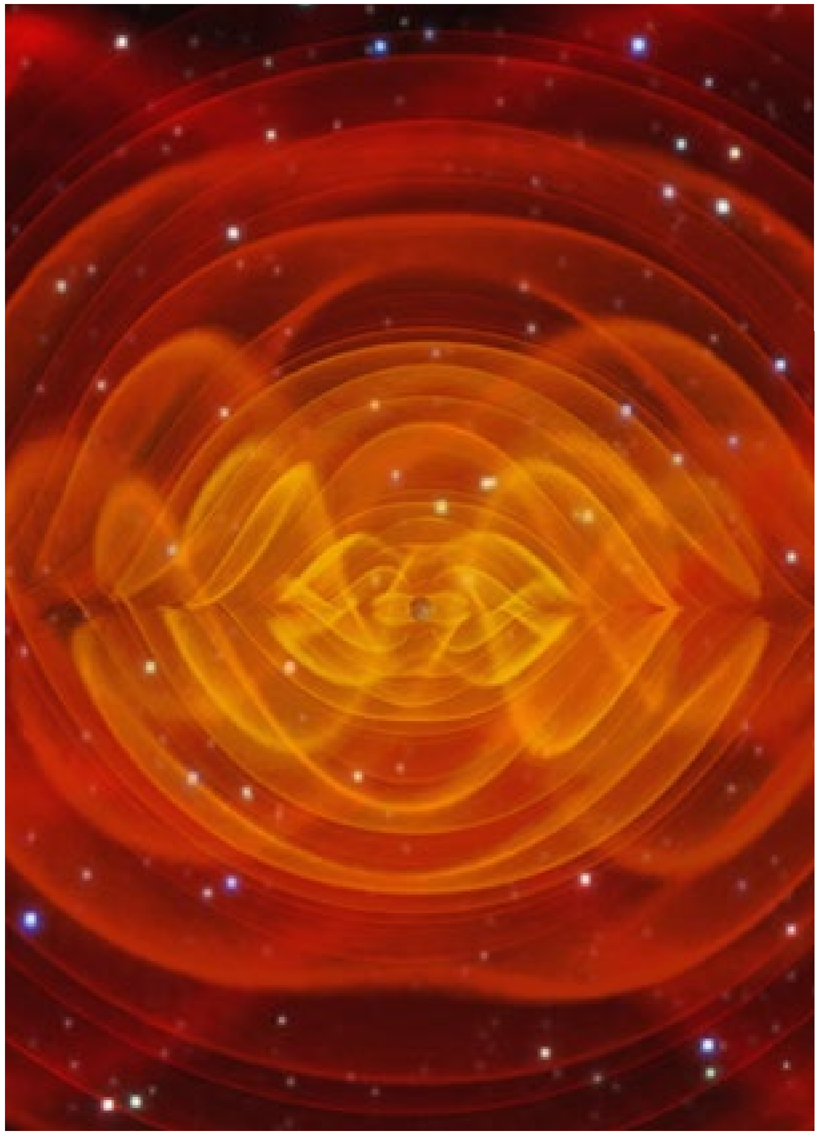
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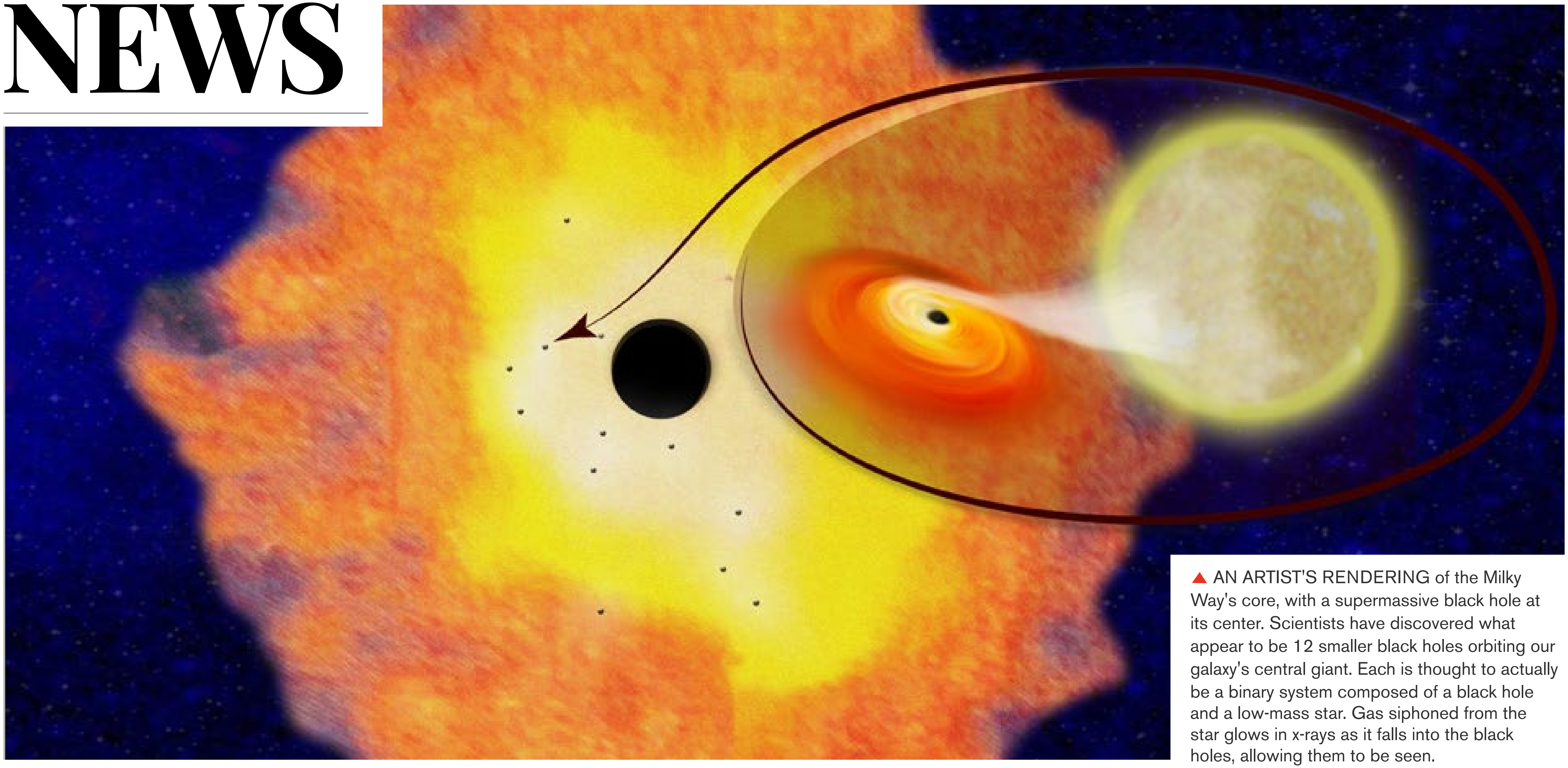


▲ AN ARTIST'S RENDERING of the Milky Way's core, with a supermassive black hole at its center. Scientists have discovered what appear to be 12 smaller black holes orbiting our galaxy's central giant. Each is thought to actually be a binary system composed of a black hole and a low-mass star. Gas siphoned from the star glows in x-rays as it falls into the black holes, allowing them to be seen.

COLUMBIA UNIVERSITY

Astronomers Spy Swarms of Black Holes at Our Galaxy's Core

Anticipated but never before seen, the existence of tens of thousands of these dark objects at the galactic center could have far-reaching implications for astrophysics

For the first time astronomers have glimpsed a long-predicted population of black holes lurking at the heart of the Milky Way.

Scientists already knew that our galaxy's core holds a supermassive black hole weighing millions of times more than our sun, and that this great beast is enveloped by a diverse entourage of lesser companions. Trapped in its gravitational clutches, run-of-the-mill stars whip around this gargantuan black hole like fireflies in a hurricane. So, too, do astrophysical exotica such as neutron stars and white dwarfs—the remnants left by normal stars when they die. Presumably black holes should be there as well, either born on the galactic center's doorstep from the deaths of massive stars or arriving via migration from farther out.

Such black holes should each weigh 10 to 20 times more than our sun. That bulk would make them behave a bit like heavy pebbles outpacing fine silt to the watery bottom of a well, jostling through the lighter surrounding stars to reach stable orbits very close to the Milky Way's core. Since the 1970s theorists studying this process have predicted a galactic center swarming with thousands of black holes bounded by an outer "cusp" beyond which the black holes' numbers should plummet. But despite their predicted prevalence, these black holes are so dark and quiescent that they have been all but undetectable against the galactic center's stellar splendor—at least, until now.

Using 12 years of archival data from NASA's Chandra X-Ray Observatory, a team led by Columbia University astrophysicist Charles J. Hailey has found a dozen potential black holes within a few light-years of the Milky Way's center, well within the gravitational reach of our galaxy's supermassive black hole. The team speculates these must be the first observational signs of the long-theorized cusp. Based on the emissions and spatial distribution of these 12 systems, the team estimates 10,000 to 20,000 of these objects should be swirling around our galaxy's core, mostly unseen. For perspective, apart from these newfound dozen scientists have only identified about 60 black holes in the entire Milky Way, and all but a few are far from the galactic center. The findings appear in a paper published in April in *Nature*.

The study appears to vindicate predictions from theorists such as Mark Morris, an astrophysicist at the University of California, Los Angeles, who in 1993 penned a key paper predicting tens of thousands of stellar-mass black holes would form a disk around the galactic center. Across the decades, other theorists tackling the problem have arrived at similar estimates. "There hasn't ever been much controversy about this idea, because it's just an inevitable consequence of simple Newtonian dynamics," Morris says. "The only thing is, it has been really hard to prove."

"Finding evidence for a large number of black holes at the center of the Milky Way confirms a fundamental and major prediction of galactic dynamics," Hailey says. "These objects also provide a unique laboratory for learning about how big black holes interact with little ones, because we can't readily study these processes in other, more distant galaxies."

Hailey and his team used Chandra data because black holes at the galactic center should be most visible via x-rays, produced when the black holes form a binary system with a low-mass star and feed on their captured companion.

Siphoned off by the black hole's gravitational pull, the star's outer layers will pile up outside the black hole's maw in a spiraling, steadily glowing disk. The intense x-ray emissions from these disks would be exceedingly faint when viewed from the earth's vicinity, sending only one photon apiece into Chandra's optics every five or 10 minutes. These weak emissions would also be intermixed with many other x-ray sources from the galactic center. To pin down the nature of their dozen candidates, Hailey's team plotted their spectral peaks and tracked their activity across time, finding patterns consistent with previous observations of binary black hole emissions elsewhere in the galaxy. The fact that there must then be tens of thousands of black holes at the galactic center stems from the notion that these objects would only very rarely be accompanied by a star to make them glow—most would remain isolated, invisible singletons.

Morris calls the work "exciting" but notes that due to the very low total numbers of photons used in the analysis, of the dozen putative black holes some might actually merely be statistical flukes produced by coincidentally timed emissions from other sources. Hailey, too, admits that of the dozen sources detected he only feels certain half are black holes—the remaining six, he says, display behavior that could also be explained as emissions from rapidly spinning neutron stars called millisecond pulsars.

Despite such uncertainty, Jordi Miralda-Escudé, an astrophysicist at the University of Barcelona unaffiliated with the work, says the results should have profound implications for future research. "A discovery like this will always have consequences that we cannot presently predict," he says. "If confirmed, the existence of these black holes suggests similar concentrations should exist in the centers of most galaxies throughout the universe." Such confirmations could come from perhaps another decade of additional Chandra observations or from studies by Chandra's proposed successor, a space telescope called Lynx that NASA is presently studying for potential development and launch in the 2020s or 2030s.

Scientists studying gravitational waves would likely benefit the most from further studies of black holes hidden at the Milky Way's core. Predicted by Einstein more than a century ago, these elusive ripples in spacetime have only recently been observed, and the majority of detections to date have been traced to merging black holes billions of light-years away. Mysteriously, most of these black holes are inconveniently sized, appearing too large to have readily formed directly from dying massive stars. Alternative explanations posit these anomalously massive black holes grew and merged in throngs of stars called globular clusters, but that process can easily require more time than the current age of the universe. "So how do you get these things?" Morris says. "Hundreds of papers have been written already speculating about this. But if you have clusters of black holes at the centers of galaxies, there are mechanisms by which some could rapidly grow, form binaries and merge with each other."

Regardless of how scientists follow up this discovery, one way or another the result will be "pinning down the number of black holes in the center of a normal galaxy like the Milky Way," Hailey says. "That will be invaluable, especially for researchers trying to calculate the nature and number of gravitational-wave events expected from galaxy cores. All the information astrophysicists need is right there, at the center of our galaxy."

—Lee Billings

Does a Quantum Equation Govern Some of the Universe's Large Structures?

A new paper uses the Schrödinger equation to describe debris disks around stars and black holes—and provides an object lesson about what "quantum" really means

Researchers who want to predict the behavior of systems governed by quantum mechanics—an electron in an atom, say, or a photon of light traveling through space—typically turn to the Schrödinger equation. Devised by Austrian physicist Erwin Schrödinger in 1925, it describes subatomic particles and how they may display wavelike properties such as interference. It contains the essence of all that appears strange and counterintuitive about the quantum world.

But it seems the Schrödinger equation is not confined to that realm. In a paper published in January in *Monthly Notices of the Royal Astronomical Society,* planetary scientist Konstantin Batygin of the California Institute of Technology claims this equation can also be used to understand the emergence and behavior of self-gravitating astrophysical disks. That is, objects such as the rings of the worlds Saturn and Uranus or the halos of dust and gas that surround young stars and supply the raw material for the formation of a planetary system or even the accretion disks of debris spiraling into a black hole.

This artist's concept shows a swirling debris disk of gas and dust surrounding a young protostar.

NASA AND JPL

And yet there's nothing "quantum" about these things at all. They could be anything from tiny dust grains to big chunks of rock the size of asteroids or planets. Nevertheless, Batygin says, the Schrödinger equation supplies a convenient way of calculating what shape such a disk will have, and how stable it will be against buckling or distorting. "This a fascinating approach, synthesizing very old techniques to make a brand-new analysis of a challenging problem," says astrophysicist Duncan Forgan of the University of Saint Andrews in Scotland, who was not part of the research. “The Schrödinger equation has been so well studied for almost a century that this connection is clearly handy.”

FROM CLASSICAL TO QUANTUM

This equation is so often regarded as the distilled essence of “quantumness” that it is easy to forget what it really represents. In some ways Schrödinger pulled it out of a hat when challenged to come up with a mathematical formula for French physicist Louis de Broglie’s hypothesis that quantum particles could behave like waves. Schrödinger drew on his deep knowledge of classical mechanics, and his equation in many ways resembles those used for ordinary waves. One difference is that in quantum mechanics the energies of “particle–waves” are quantized: confined to discrete values that are multiples of the so-called Planck’s constant h, first introduced by German physicist Max Planck in 1900.

This relation of the Schrödinger equation to classical waves is already revealed in the way that a variant called the nonlinear Schrödinger equation is commonly used to describe other classical wave systems—for example in optics and even in ocean waves, where it provides a mathematical picture of unusually large and robust “rogue waves.”

But the normal “quantum” version—the linear Schrödinger equation—has not previously turned up in a classical context. Batygin says it does so here because the way he sets up the problem of self-gravitating disks creates a quantity that sets a particular “scale” in the problem, much as h does in quantum systems.

LOOPY PHYSICS

Whether around a young star or a supermassive black hole, the many mutually interacting objects in a self-gravitating debris disk are too complicated to describe mathematically. But Batygin uses a simplified model in which the disk’s constituents are smeared and stretched into thin “wires” that loop in concentric ellipses right around the disk. Because the wires interact with one another through gravity, they can exchange orbital angular momentum between them, rather like the transfer of movement between the gear bearings and the axle of a bicycle.

> **“The Schrödinger equation has been so well studied for almost a century that this connection is clearly handy.”**
>
> *—Duncan Forgan*

This approach uses ideas developed in the 18th century by the mathematicians Pierre-Simon Laplace and Joseph-Louis Lagrange. Laplace was one of the first to study how a rotating clump of objects can collapse into a disk-like shape. In 1796 he proposed our solar system formed from a great cloud of gas and dust spinning around the young sun.

Batygin and others had used this “wire” approximation before, but he decided to look at the extreme case in which the looped wires are made thinner and thinner until they merge into a continuous disk. In that limit he found the equation describing the system is the same as Schrödinger’s, with the disk itself being described by the analog of the wave function that defines the distribution of possible positions of a quantum particle. In effect, the shape of the disk is like the wave function of a quantum particle bouncing around in a cavity with walls at the disk’s inner and outer edges.

The resulting disk has a series of vibrational “modes,” rather like resonances in a tuning fork, that might be excited by small disturbances—think of a planet-forming stellar disk nudged by a passing star or of a black hole accretion disk in which material is falling into the center unevenly. Batygin deduces the conditions under which a disk will warp in response or, conversely, will behave like a rigid body held fast by its own mutual gravity. This comes down to a matter of timescales, he says. If the angular momentum of the objects orbiting in the disk is transferred from one to another much more rapidly than the perturbation’s duration, the disk will remain rigid. “If, on the other hand, the self-interaction timescale is long compared with the perturbation timescale, the disk will warp,” he says.

IS “QUANTUMNESS” REALLY SO WEIRD?

When he first saw the Schrödinger equation materialize out of his theoretical analysis, Batygin says he was stunned. “But in retrospect it almost seems obvious to me that it must emerge in this problem,” he adds.

What this means, though, is the Schrödinger equation can itself be derived from classical physics known since the 18th century. It doesn’t depend on “quantumness” at all—although it turns out to be applicable to that case.

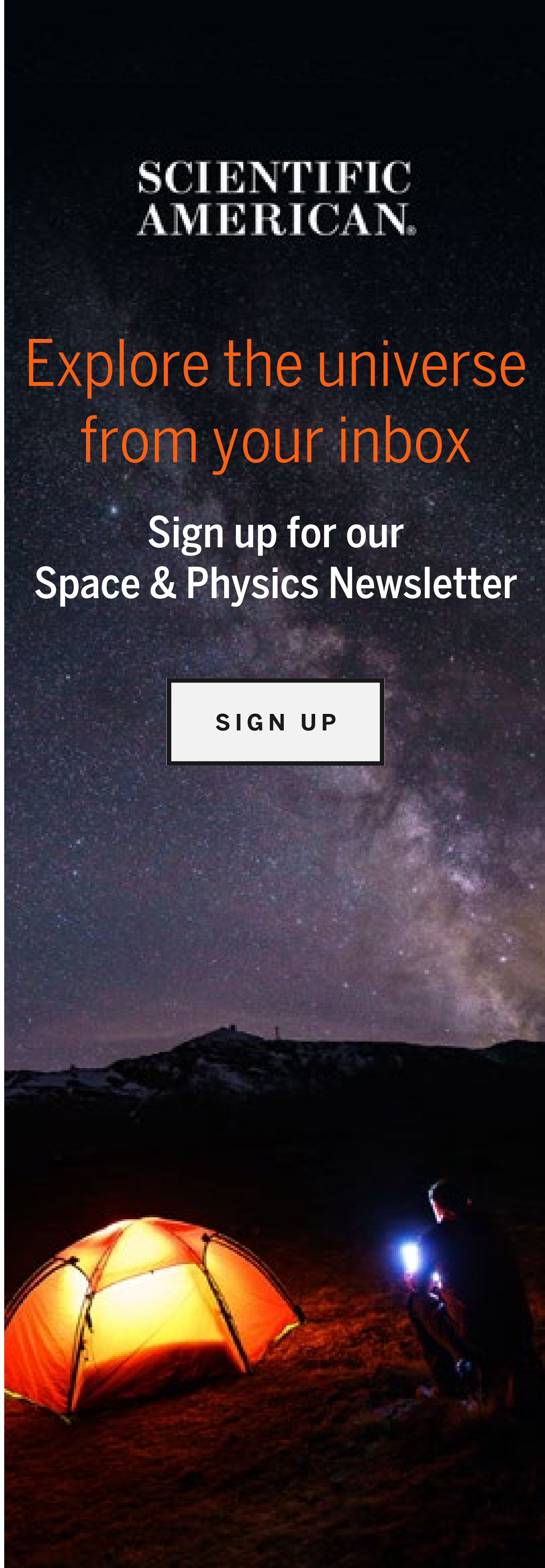
That’s not as strange as it might seem. For one thing, science is full of examples of equations devised for one phenomenon turning out to apply to a totally different one, too. Equations concocted to describe a kind of chemical reaction have been applied to the modeling of crime, for example, and very recently a mathematical description of magnets was shown also to describe the fruiting patterns of trees in pistachio orchards.

But doesn’t quantum physics involve a rather uniquely odd sort of behavior? Not really. The Schrödinger equation does not so much describe what quantum particles are actually “doing,” rather it supplies a way of predicting what might be observed for systems governed by particular wavelike probability laws. In fact, other researchers have already shown the key phenomena of quantum theory emerge from a generalization of probability theory that could, too, have been in principle devised in the 18th century, before there was any inkling that tiny particles behave this way.

The advantage of his approach is its simplicity, Batygin notes. Instead of having to track all the movements of every particle in the disk using complicated computer models (so-called N-body simulations), the disk can be treated as a kind of smooth sheet that evolves over time and oscillates like a drumskin. That makes it, Batygin says, ideal for systems in which the central object is much more massive than the disk, such as protoplanetary disks and the rings of stars orbiting supermassive black holes. It will not work for galactic disks, however, like the spiral that forms our Milky Way.

But Ken Rice of the Royal Observatory in Scotland, who was not involved with the work, says that in the scenario in which the central object is much more massive than the disk, the dominant gravitational influence is the central object. “It’s then not entirely clear how including the disk self-gravity would influence the evolution,” he says. “My simple guess would be that it wouldn’t have much influence, but I might be wrong.” Which suggests the chief application of Batygin’s formalism may not be to model a wide range of systems but rather to make models for a narrow range of systems far less computationally expensive than N-body simulations.

Astrophysicist Scott Tremaine of the Institute for Advanced Study in Princeton, N.J., also not part of the study, agrees these equations might be easier to solve than those that



describe the self-gravitating rings more precisely. But he says this simplification comes at the cost of neglecting the long reach of gravitational forces, because in the Schrödinger version only interactions between adjacent "wire" rings are taken into account. "It's a rather drastic simplification of the system that only works for certain cases," he says, "and won't provide new insights into these disks for experts." But he thinks the approach could have useful pedagogical value, not least in showing that the Schrödinger equation "isn't some magic result just for quantum mechanics, but describes a variety of physical systems."

But Saint Andrews's Forgan thinks Batygin's approach could be particularly useful for modeling black hole accretion disks that are warped by companion stars. "There are a lot of interesting results about binary supermassive black holes with 'torn' disks that this may be applicable to," he says.

—Philip Ball

NASA's Next Exoplanet Hunter Will Seek Worlds Close to Home

The Transiting Exoplanet Survey Satellite is designed to spot planets orbiting nearby bright stars

Filling the shoes of NASA's Kepler spacecraft won't be easy. Since its launch in 2009, Kepler has discovered nearly three quarters of the 3,700-plus known exoplanets. And there are thousands more candidates waiting to be confirmed.

So NASA is taking a different approach with its next planet-hunting mission. On April 18, the agency launched the US$337-million Transiting Exoplanet Survey Satellite (TESS), which will scrutinize 200,000 nearby bright stars for signs of orbiting planets. TESS will probably find fewer worlds than Kepler did, but they will arguably be more important ones.

"It's not so much the numbers of planets that we care about, but the fact that they are orbiting nearby stars," says Sara Seager, an astrophysicist at the Massachusetts Institute of Technology (MIT) in Cambridge and deputy science director for TESS.

TESS is meant to identify planets that are close enough to Earth for astronomers to explore them in detail. Team scientists estimate that the spacecraft will discover more than 500 planets that are no more than twice the size of Earth. These worlds will form the basis for decades of further studies, including searches for signs of life. "We'll see a whole new opening of exoplanet studies," Seager says.

▲The Transiting Exoplanet Survey Satellite will search more than 85 percent of the sky for planets around nearby stars. Here, technicians work on the spacecraft shortly before its April 18 launch.

LEIF HEIMBOLD NASA

MEETING THE NEIGHBOURS

Both Kepler and TESS are designed to scan the sky for planetary transits, the slight dimming that occurs when a planet moves across the face of a star and temporarily blocks some of its glow. For most of its mission, Kepler stared at a deep but narrow slice of the universe—peering out some 920 parsecs (3,000 light years) from Earth but covering only 0.25% of the sky. Its celestial census showed that planets were common throughout the Milky Way. “We found that planets are everywhere,” says Elisa Quintana, an astrophysicist at NASA’s Goddard Space Flight Center in Greenbelt, Maryland.

By contrast, TESS will go shallow and broad—looking at stars within 90 parsecs of Earth but covering more than 85% of the sky. Its four cameras will give the spacecraft a field of view about 20 times the size of Kepler’s. TESS will sweep the southern sky first and then, after a year, turn its attention to northern stars; all told, it will observe at least 30 million celestial objects.

The observing swathes will overlap at the south and north ecliptic poles, which are points perpendicular to the plane of Earth’s orbit. That is by design, because NASA’s James Webb Space Telescope, now planned for a 2020 launch, will also be able to study those regions at any given time. Webb’s 6.5-metre primary mirror will allow detailed spectroscopic studies of the planets’ atmospheres, but it will be in high demand for a range of other astronomical research. “The time on Webb is going to be so precious,” says George R. Ricker, an astrophysicist at MIT and TESS’s principal investigator.

Once TESS spots interesting planetary candidates, a fleet of Earth-based observatories will kick into action. These will include planet-hunting stalwarts such as the HARPS instrument at the European Southern Observatory in La Silla, Chile, and the new Miniature Exoplanet Radial Velocity Array (MINERVA)-Australis, a group of five planned 0.7-metre telescopes near Toowoomba, Australia. “We have the ability to hammer on a target every night if we need to,” says Rob Wittenmyer, an astronomer at the University of Southern Queensland in Toowoomba who helps lead MINERVA-Australis.

These and other ground-based telescopes will be able to deduce the TESS planets’ masses, and from that their composition—whether rocky, icy, gassy or something else.

A WHOLE NEW WORLD

Recent research suggests that TESS may yield a greater bounty than once thought. Earlier this year, MIT astronomer Sarah Ballard recalculated how many planets TESS might find orbiting the cool, plentiful stars known as M dwarfs—and predicted some 990 such planets, 1.5 times more than earlier estimates. The sheer volume of discoveries would allow astronomers to begin comparing broad classes of exoplanets: learning how stellar flares affect planetary atmospheres, for instance, or what sorts of planets surround stars of different ages.

TESS will soon have company. The European Space Agency (ESA) plans to launch its Characterising Exoplanet Satellite late this year. The craft will measure the sizes of known planets—from those a little bigger than Earth to ones that are roughly Neptune-sized—orbiting nearby bright stars. ESA is also planning two missions for the 2020s: PLATO to study Earth-sized exoplanets and ARIEL to study planetary atmospheres.

The next generation of missions will come just in time: Kepler is on its last legs, with only a few months’ worth of fuel left to help it make its final discoveries.

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—Alexandra Witze

Black Hole Pretenders Could Really Be Bizarre Quantum Stars

New research reveals a possible mechanism allowing “black stars” and “gravastars” to exist

When giant stars die, they don’t just fade away. Instead they collapse in on themselves, leaving behind a compressed stellar remnant, usually a city-sized, superdense ball of neutrons appropriately called a neutron star. In extreme cases, however, most theorists believe an expiring giant star will form a black hole—a pointlike “singularity” with effectively infinite density and a gravitational field so powerful that not even light, the fastest thing in the universe, can escape once falling in. Now a new study is reinvigorating an alternative idea that objects with names such as “black stars” or “gravastars” might exist midway between neutron stars and black holes. If real, these exotic stellar corpses should appear nearly identical to black holes save in one key way—they could not irretrievably swallow light.

There are good reasons to seek such alternatives, because black holes raise a host of theoretical problems. For instance, their singularities are supposedly hidden by invisible boundaries known as event horizons. Throw something into a black hole and once it passes the event horizon it should be gone—forever—with no hope whatsoever of return. But such profound annihilation clashes with other long-cherished laws of physics that suggest the destruction of information is impossible, including information encoded within anything falling into black holes.

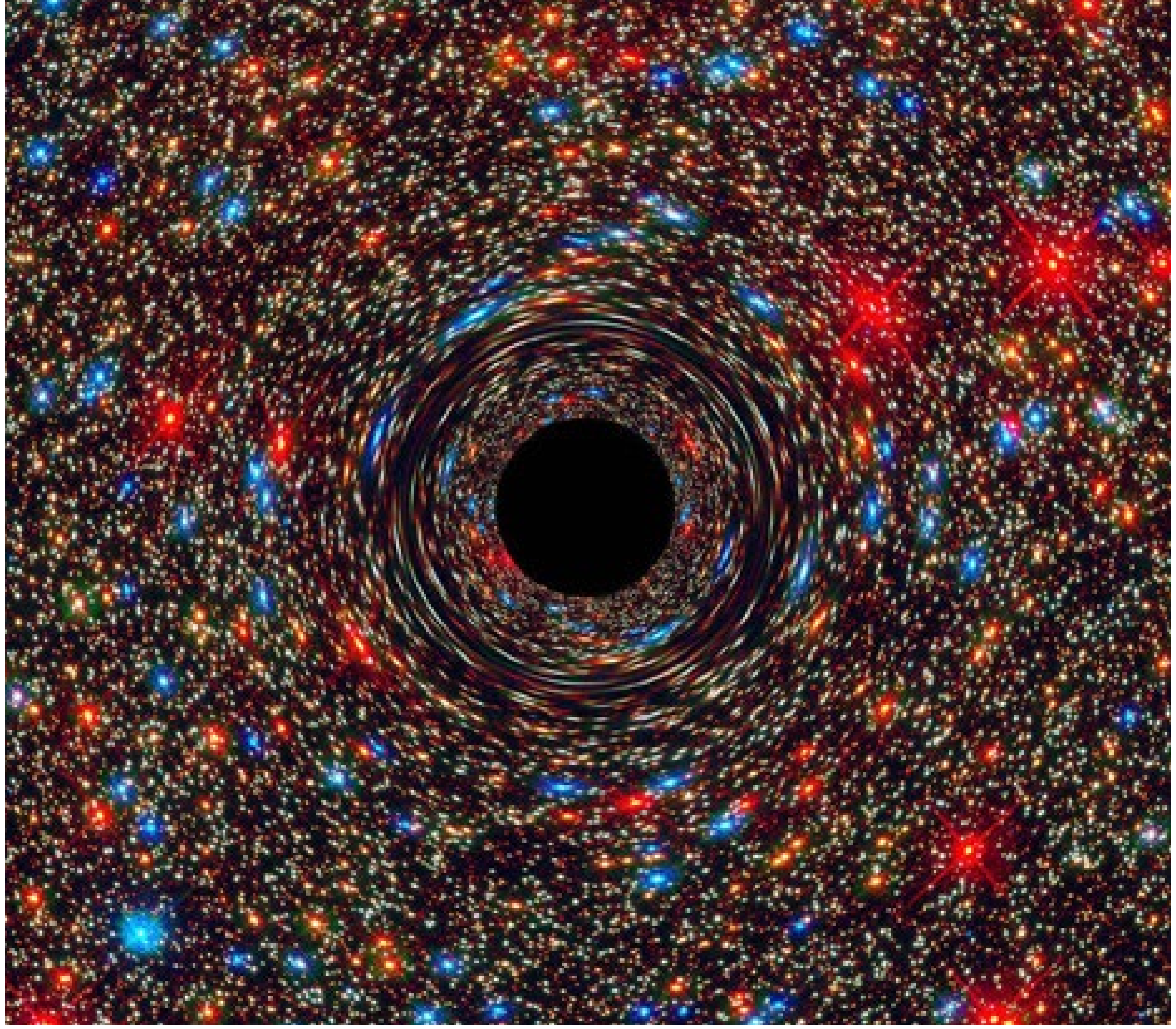
Conceived and developed across the past two decades in part to sidestep such conundrums, models of black stars and gravastars postulate these objects would lack singularities and event horizons. But questions have lingered as to whether such objects could actually form—and remain stable after they did. New research from theoretical physicist Raúl Carballo-Rubio of the International School for Advanced Studies in Italy provides a novel mechanism that might allow black stars and gravastars to exist.

Carballo-Rubio investigated a strange phenomenon known as quantum vacuum polarization. Quantum physics, the best description yet of how all known subatomic particles behave, suggests reality is fuzzy, limiting how precisely one can know the properties of the most basic units of matter—for instance, one can never absolutely know a particle's position and momentum at the same time. One strange consequence of this uncertainty is that a vacuum is never completely empty but instead foams with so-called virtual particles that continuously fluctuate into and out of existence.

In the presence of gigantic amounts of energy of the sort produced by the collapse of a giant star, previous research found these virtual particles can polarize, or arrange themselves depending on their properties, much as magnets are divided into north and south poles. Carballo-Rubio calculated that the polarization of these particles can produce a surprising effect inside the powerful gravitational fields of dying giant stars—a field that repels instead of attracts.

Matter and energy curve the fabric of spacetime, resulting in gravitational fields, according to Einstein's theory of general relativity. Planets and stars have a positive amount of energy on average, and the resulting gravitational fields are attractive in nature. When virtual particles polarize, however, the vacuum they occupy can on average possess negative energy, and "this curves spacetime in a way that the associated gravitational field is repulsive," Carballo-Rubio says—which, of course, could prevent the formation of a black hole. (A similar phenomenon causes relatively light stellar remnants to form neutron stars instead of black holes; their gravitational fields are not strong enough to crush neutrons into a singularity.)

Two prior models suggested repulsive gravity might keep stellar remnants from collapsing to form black holes. One proposed stellar remnants instead formed gravastars, objects filled with quantum vacuum overlaid by a thin shell of matter. The other model suggested the result of these collapses were black stars, where "matter and the quantum vacuum are interlaced throughout the structure in a meticulous balance," Carballo-Rubio says. Both objects still have powerful gravitational fields that profoundly warp



NASA, ESA, AND D. COE, J. ANDERSON, AND R. VAN DER MAREL (STSCI) light, so they look dark, like black holes.

Carballo-Rubio says there was previously great uncertainty regarding the properties of black stars and gravastars. His new work tackled this issue by creating a mathematical framework that incorporated the effects of repulsive gravity into equations describing the expansion and contraction of stars, a problem “that was thought to be tractable only with the help of computers,” he notes. His new model suggests a hybrid of a black star and a gravastar could exist—one where matter and quantum vacuum are spread throughout the structure, but with matter in higher concentrations in the shell than in the core. Carballo-Rubio detailed his study on February 9 in *Physical Review Letters.*

“This work is interesting and worthwhile, showing that new kinds of solutions can exist to Einstein's equations which are not black holes,” says physicist Emil Mottola of Los Alamos National Laboratory, who was not involved in the study.

Some researchers would claim the quantum effects that Carballo-Rubio bases his argument on are negligible, however. As such, they may be too weak to support the existence of black stars and gravastars, says theoretical physicist Paolo Pani of Sapienza University of Rome, who did not participate in this work.

> **“This work is interesting and worthwhile, showing that new kinds of solutions can exist to Einstein's equations which are not black holes.”**
>
> *—Emil Mottola*

In addition, whereas Carballo-Rubio’s work argues black stars and gravastars are mathematically possible, that “does not imply that they exist in nature,” says physicist Cecilia Chirenti of the Federal University of ABC in Brazil, who did not take part in the research. For example, Pani notes it is still unclear whether stellar remnants can naturally evolve to form these structures. Furthermore, Mottola says, “Caballo-Rubio does not explain why his solution is stable and what keeps it from collapsing to a black hole.”

One way to find out whether black stars, gravastars or black holes actually exist is by analyzing gravitational waves unleashed by what scientists currently interpret as merging black holes. When any mass moves, it generates gravitational waves that travel at the speed of light, stretching and squeezing spacetime along the way.

As black holes spiral toward each other, they should each give off gravitational waves, but their event horizons should absorb those directly falling onto them. Because black stars and gravastars lack event horizons, however, they can reflect gravitational waves, and the LIGO and Virgo observatories could detect these “echoes,” Pani says. If such signals are discovered, they could yield insights into both general relativity and quantum physics that could help lead to a model of “quantum gravity,” marrying both long-disparate theories.

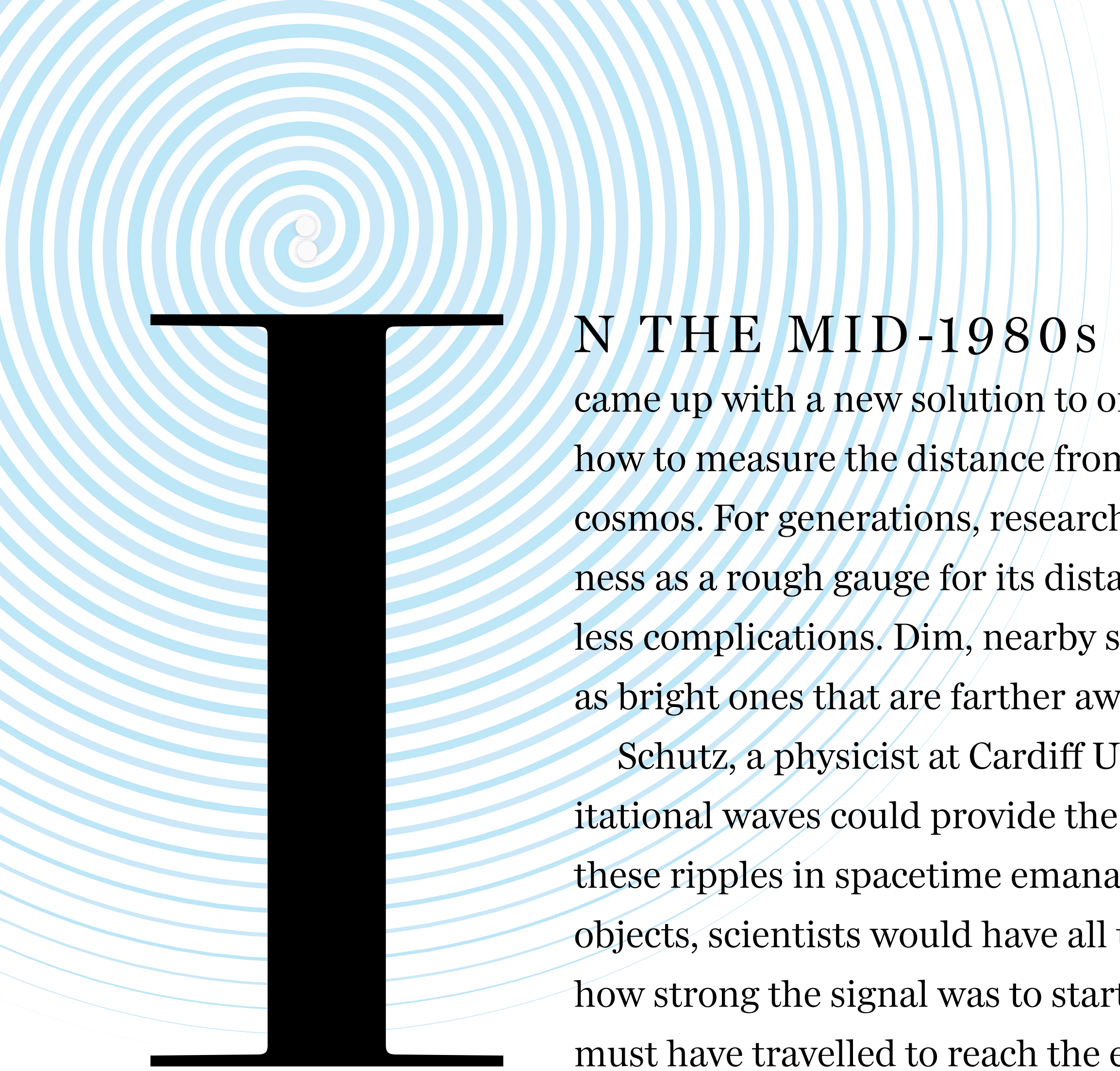
–Charles Q. Choi

GETTY IMAGE; AN ARTIST'S RENDITION OF GRAVITATIONAL-WAVES

After a clutch of historic detections, gravitational-wave researchers have set their sights on some ambitious scientific quarry

Here Come the Waves

Davide Castelvecchi is a senior reporter at *Nature* in London covering physics, astronomy, mathematics and computer science.



IN THE MID-1980s BERNARD SCHUTZ came up with a new solution to one of astronomy's oldest problems: how to measure the distance from the earth to other objects in the cosmos. For generations, researchers have relied on an object's brightness as a rough gauge for its distance. But this approach carries endless complications. Dim, nearby stars, for example, can masquerade as bright ones that are farther away.

Schutz, a physicist at Cardiff University in Wales, realized that gravitational waves could provide the answer. If detectors could measure these ripples in spacetime emanating from interacting pairs of distant objects, scientists would have all the information needed to calculate how strong the signal was to start with—and so how far the waves must have travelled to reach the earth. Thus, he predicted, gravitational waves could be unambiguous markers of how quickly the universe is expanding.

His idea was elegant but impractical: nobody at the time could detect gravitational waves. But last August Schutz finally got the opportunity to test this concept when the reverberations of a 130-million-year-old merger between two neutron stars passed through gravitational-wave detectors on the earth. As luck would have it, the event occurred in a relatively nearby galaxy, producing a much cleaner first measure than Schutz had dreamed. With that one data point, Schutz was able to show that his technique could become one of the most reliable for measuring distance. "It was hard to believe," Schutz says. "But there it was."

More mergers like that one could help researchers to resolve an ongoing debate over how fast the universe currently is expanding. But cosmology is just one discipline that could make big gains through detections of gravitational waves in the coming years. With a handful of discoveries already under their belts, gravitational-wave scientists have a long list of what they expect more data to bring, including insight into the origins of the universe's black holes; clues about the extreme conditions inside neutron stars; a chronicle of how the universe structured itself into galaxies; and the most stringent tests yet of Albert Einstein's general theory of relativity. Gravitational waves might even provide a window into what happened in the first few moments after the big bang.

Researchers will soon start working down this list with the help of the U.S.-based Laser Interferometer Gravitational-Wave Observatory (LIGO), the Virgo observatory near Pisa, Italy, and a similar detector in Japan that could begin making observations next year. They will get an extra boost from space-based interferometers and from terrestrial ones that are still on the drawing board—as well as from other methods that could soon start producing their own first detections of gravitational waves.

Like many scientists, Schutz hopes that the best discoveries will be ones that no theorist has even dreamed of. "Any time you start observing something so radically new, there's always the possibility of seeing things you didn't expect."

SPINNING CLUES

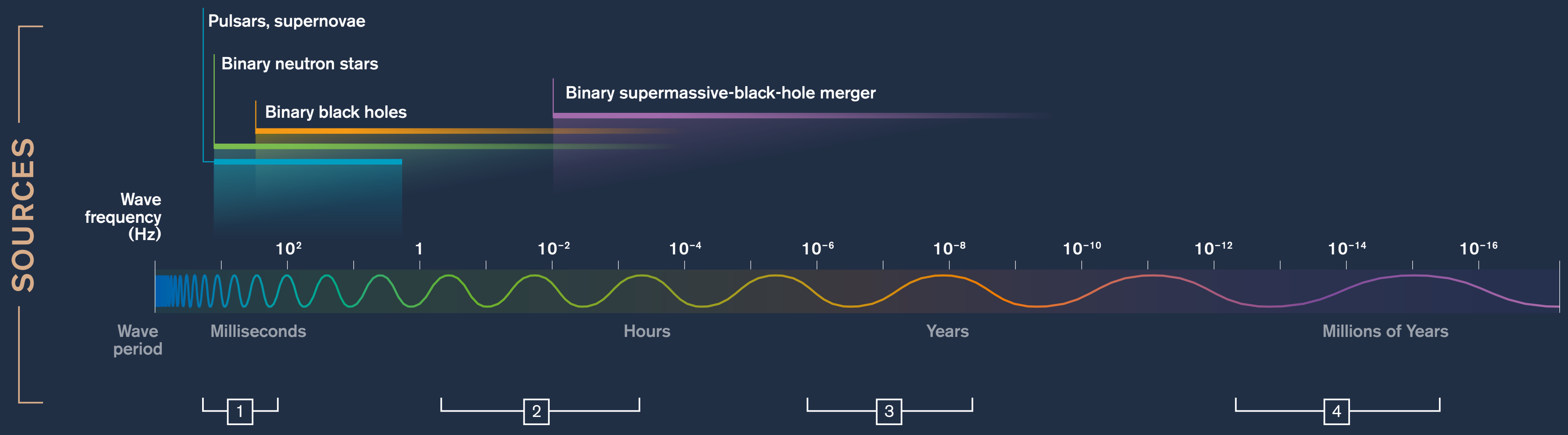
FOR A FIELD OF RESEARCH that is not yet three years old, gravitational-wave astronomy has delivered discoveries at a staggering rate, outpacing even the rosiest expectations. In addition to the discovery in August of the neutron-star merger, LIGO has recorded five pairs of black holes coalescing into larger ones since 2015 (see 'Making Waves'). The discoveries are the most direct proof yet that black holes truly exist and have the properties predicted by general relativity. They have also revealed, for the first time, pairs of black holes orbiting each other.

Researchers now hope to find out how such pairings came to be. The individual black holes in each pair should form when massive stars run out of fuel in their cores and collapse, unleashing a supernova explosion and leaving behind a black hole with a mass ranging from a few to a few dozen suns.

There are two leading scenarios for how such black

THE GRAVITATIONAL-WAVE SPECTRUM

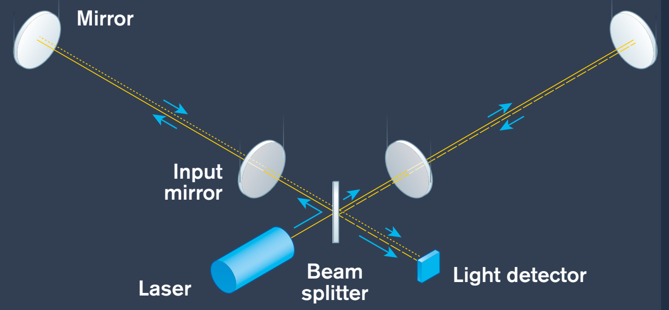
Much like electromagnetic waves, gravitational waves are emitted by many different objects over a wide range of frequencies. Terrestrial interferometers such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo are sensitive to only a subset of those frequencies, which limits their ability to “see” certain cosmic phenomena. They won’t detect collisions of supermassive black holes found in the hearts of galaxies, for example. But space-based interferometers and other approaches for picking up gravitational waves could extend physicists’ reach.



DETECTORS

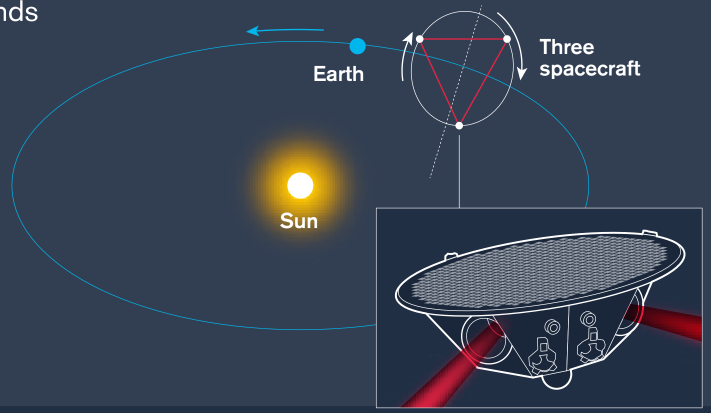
1 GROUND-BASED INTERFEROMETER 400 Hz – 30 Hz

Current observatories such as LIGO can detect waves that are longer than the detectors’ lengths (3–4 kilometres), corresponding to periods of a few hundredths to a few thousandths of a second.



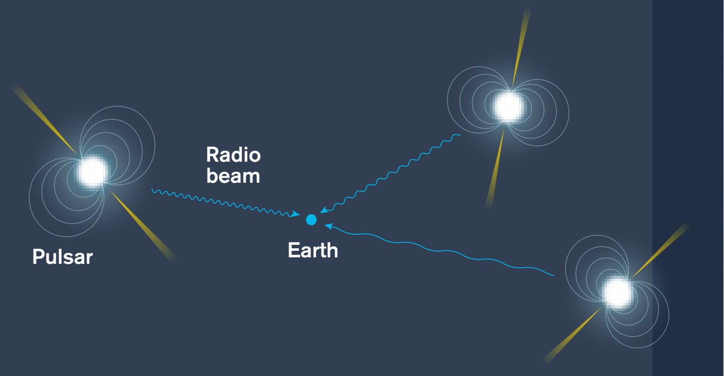
2 SPACE-BASED INTERFEROMETER 100 milliHz – 0.1 milliHz

LISA, the trio of probes slated to fly in the 2030s, will have virtual arms millions of kilometres long, which will make it sensitive to waves with periods of tens of seconds to a few hours.



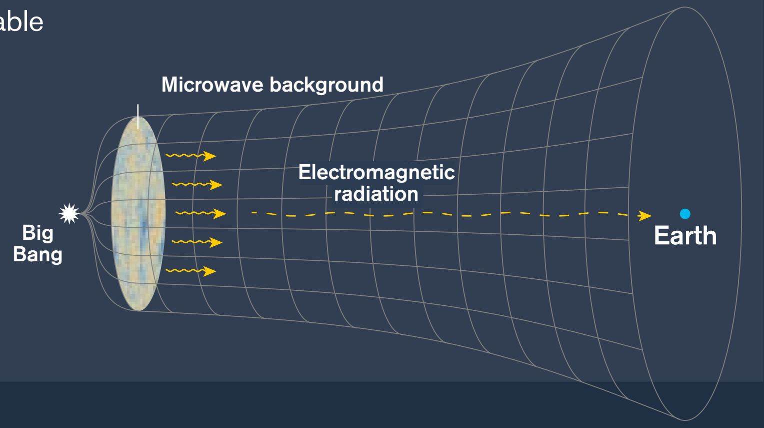
3 PULSAR TIMING 320 nanoHz – 1 nanoHz

Gravitational waves from distant galaxies perturb the distance between the earth and stars in the Milky Way. Researchers hope to detect waves of periods lasting years, by examining delays in the radio signals from spinning neutron stars known as pulsars.



4 CMB MEASUREMENT ~10^{-13} – 10^{-16} Hz

The universe’s oldest measurable radiation (the cosmic microwave background, or CMB) could carry evidence of gravitational waves from the big bang. Those waves would not be detectable more directly; by now, they would stretch across a significant fraction of the observable universe.



JASIEK KRZYSZTOFIAK NATURE; SOURCE: NASA

holes could come to circle each other. They might start as massive stars in each other's orbit and stay together even after each goes supernova. Alternatively, the black holes might form independently but be driven together later by frequent gravitational interactions with other objects—something that could happen in the centres of dense star clusters.

Either way, the objects' energy gradually disperses in the form of gravitational waves, a process that pulls the pair into an ever tighter and faster spiral, eventually fusing into one more massive black hole. Ilya Mandel, a LIGO theorist at the University of Birmingham in England, says that for LIGO and Virgo to see such pairs merge, typical black holes need to have started their mutual orbit separated by a distance of less than one quarter that between the earth and the sun. "If you start out with the two black holes any farther apart, it will take longer than the age of the universe" for them to merge, Mandel says.

The five black-hole mergers discovered so far are not sufficient to determine which formation scenario dominates. But in an August analysis of the first three detections, a group including Mandel and Will M. Farr, a theoretical astrophysicist and LIGO member at the University of Birmingham, suggested that just 10 more observations could provide substantial evidence in favour of one scenario or the other. This would involve scrutinizing the gravitational waves for clues about how black holes rotate: those that pair up after forming independently should have randomly oriented spins, whereas those with a common origin should have spin axes that are parallel to each other and roughly perpendicular to the plane in which they orbit.

Further observations could also provide insight into some of the fundamental questions about black-hole formation and stellar evolution. Collecting many measurements of masses should reveal gaps—ranges in which few or no black holes exist, says Vicky Kalogera, a LIGO astrophysicist at Northwestern University in Evanston, Illinois. In particular, "there should be a paucity of black holes at the low-mass end," she says, because relatively small supernovae tend to leave behind neutron stars, not black holes, as remnants. And at the high end—around 50 times the mass of the sun—researchers expect to see another cutoff. In very large stars, pressures at the core are thought eventually to produce antimatter, causing an explosion so violent that the star simply disintegrates without leaving any remnants at all. These events, called pair-instability supernovae, have been theorized, but so far there has been scant observational evidence to back them up.

Eventually, the black-hole detections will delineate a map of the universe in the way galaxy surveys currently do, says Rainer Weiss, a physicist at the Massachusetts Institute of Technology in Cambridge who was the principal designer of LIGO. Once the numbers pile up, "we can actually begin to see the whole universe in black holes," he says. "Every piece of astrophysics will get something out of that."

TO RAMP UP THESE OBSERVATIONS, LIGO and Virgo have plans to improve their sensitivity, which will reveal not only more events but also more details about each merger. Among other things, physicists are eager to see the detailed "ringdown" waves that a post-merger black hole emanates as it settles into a spherical shape—an observation that could potentially reveal cracks in the general theory of relativity.

Having more observatories spread around the globe will also be crucial. KAGRA, a detector under construction deep underground in Japan, might start gathering data by late 2019. Its location—and in particular its orientation with respect to incoming waves—will complement LIGO's and Virgo's, and enable researchers to nail down the polarization of the gravitational waves, which encodes information about the orientation of the orbital plane and the spin of the spiralling objects. And India is planning to build another observatory in the next decade, made in part with spare components from LIGO.

An even bigger trove of discoveries could come from observing neutron-star mergers. So far, researchers have announced only one such detection, called GW170817. That signal, seen last August, was almost certainly the most intensely studied event in astronomy's history. And it solved a number of long-standing mysteries in one stroke, including the origin of gold and other heavy elements in the universe, as well as the cause of some gamma-ray bursts.

Further observations could allow scientists to explore the interiors of these objects. Neutron stars are thought to be as dense as matter can possibly be without collapsing into a black hole, but exactly how dense is anybody's guess. No laboratory experiment can study those conditions, and there are dozens of proposals for what happens there. Some theories predict that quarks—the subatomic components that make up protons and neutrons—should break free from each other and roam about, perhaps in superconducting, superfluid states. Others posit that heavier "strange" quarks form and become part of exotic cousins of the neutron.

Pinning down the radii of neutron stars might allow physicists to evaluate the theories, because they predict different "equations of state"—formulae that link pressure, temperature and density of matter. Such equations determine to what extent matter can be compressed, and so how wide or narrow a neutron star will be for a given mass and how massive such stars can get.

The 100-second-long signal in August eventually became too high in pitch for LIGO and Virgo to detect, which prevented the observatories from seeing the two neutron stars' final moments, when they should have deformed each other in ways that would have revealed their size and hardness, or resistance to compression. Still, says Bangalore S. Sathyaprakash, a LIGO theoretical physicist at the Pennsylvania State University in University Park, from that one event, "we can rule out equations of state that allow neutron-star sizes larger than 15 kilometres in radius"—a figure that is consistent with other measurements and favours "softer" matter.

Future detections—and detectors—will give much more detail. Sathyaprakash says that the Einstein Telescope, a possible next-generation observatory dreamed up by a team in Europe, could take physicists far beyond an upper limit. "We want to be able to pin down the radius to the level of 100 metres," he says—a precision that would be astounding, given that these objects are millions of light years away.

SIREN CALLS

SIGNALS SIMILAR TO GW170817, which was observed through both gravitational waves and light, could have dramatic implications for cosmology. Schutz calculated in 1985 that the frequency, or pitch, of waves from spiralling objects, together with the rate at which that pitch increases, reveals information about the objects' collective mass. That determines how strong their waves should be at the source. By measuring the strength of the waves that reach the earth—the amplitude of the signal actually picked up by interferometers—one can then estimate the distance that the waves have travelled from the source. All other things being equal, a source that is twice as far, for example, will produce a signal half as strong. This type of signal has been dubbed a standard siren, in a nod to a common method of gauging distances in cosmology: stars called standard candles have a well-known brightness, which allows researchers to work out their distance from the earth.

By coupling the distance measurement of GW170817 with an estimate of how fast the galaxies in that region are receding from the earth, Schutz and his collaborators made a new and completely independent estimate of the Hubble constant—the universe's current rate of expansion. The result, part of a crop of papers released by LIGO, Virgo and some 70 other astronomy teams on 16 October, "ushers in a new era for both cosmology and astrophysics," says Wendy L. Freedman, an astronomer at the University of Chicago in Illinois who has made highly precise measurements of the Hubble constant using time honoured but less-direct techniques.

As a direct and independent measure of this constant, standard sirens could help to resolve a disagreement among cosmologists. State-of-the-art techniques, refined over nearly a century of work that started with Edwin Hubble himself, now give estimates that differ by a few per cent. This first standard-siren measurement does not resolve the tension: the expansion rate it predicts falls somewhere in the middle of the range and, because it is based on just one merger event, has a large error bar. But in the future, researchers expect standard sirens to nail down the Hubble constant with an error of less than 1 percent. So far, standard candles have done it with precisions of 2–3 percent.

Standard sirens could become even more powerful tools with space-based interferometers such as the Laser Interferometer Space Antenna (LISA), a trio of probes that the European Space Agency, which is leading the mission, plans to launch in the 2030s. LISA is designed to be sensitive to low-frequency waves that ground-based observatories cannot detect. This would give it access to more massive systems, which radiate stronger gravitational waves. In principle, LISA could pick up sirens from across the universe and, with the help of conventional telescopes, measure not just the current rate of cosmic expansion but also how that rate has evolved through the aeons. Thus, LISA could help to address cosmology's biggest puzzle: the nature of dark energy, the as-yet-unidentified cosmic component that is driving the universe's expansion to accelerate.

Whereas ground-based interferometers detect events that are brief and far between, LISA is expected to hear a cacophony of signals as soon as it turns on, including a constant chorus of tight binary white dwarfs—the ubiquitous remnants of sun-sized stars—in our own galaxy. "It's as if we lived in a noisy forest and we had to single out the sounds of individual birds," says astrophysicist Monica Colpi of the University of Milan–Bicocca in Italy, who is part of a committee setting the mission's science goals.

> **"It's as if we lived in a noisy forest and we had to single out the sounds of individual birds."** *—Monica Colpi*

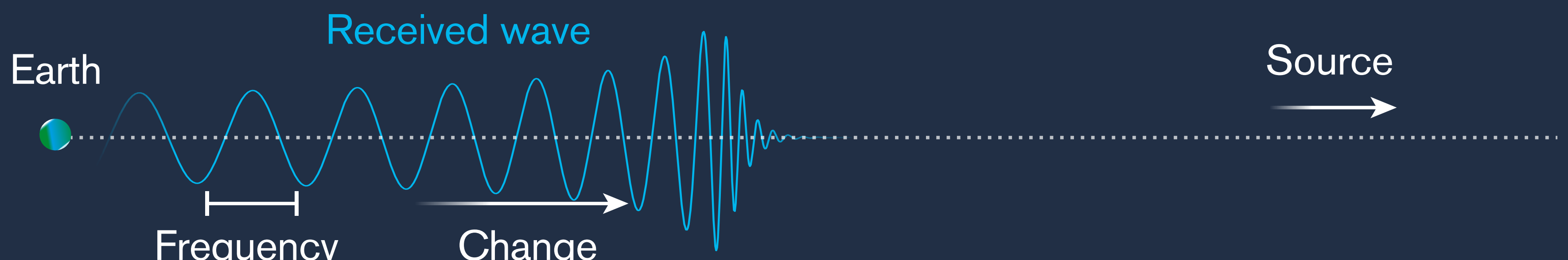
Occasionally, LISA should see black-hole mergers such as the ones LIGO does, but on a much grander scale. Most galaxies are thought to harbour a central supermassive black hole that weighs millions or even billions of solar masses. Over a scale of billions of years, galaxies might merge several times; eventually their central black holes might merge, too. These events are not frequent for individual galaxies, but because there are trillions of galaxies in the observable universe, a detectable

MAKING WAVES

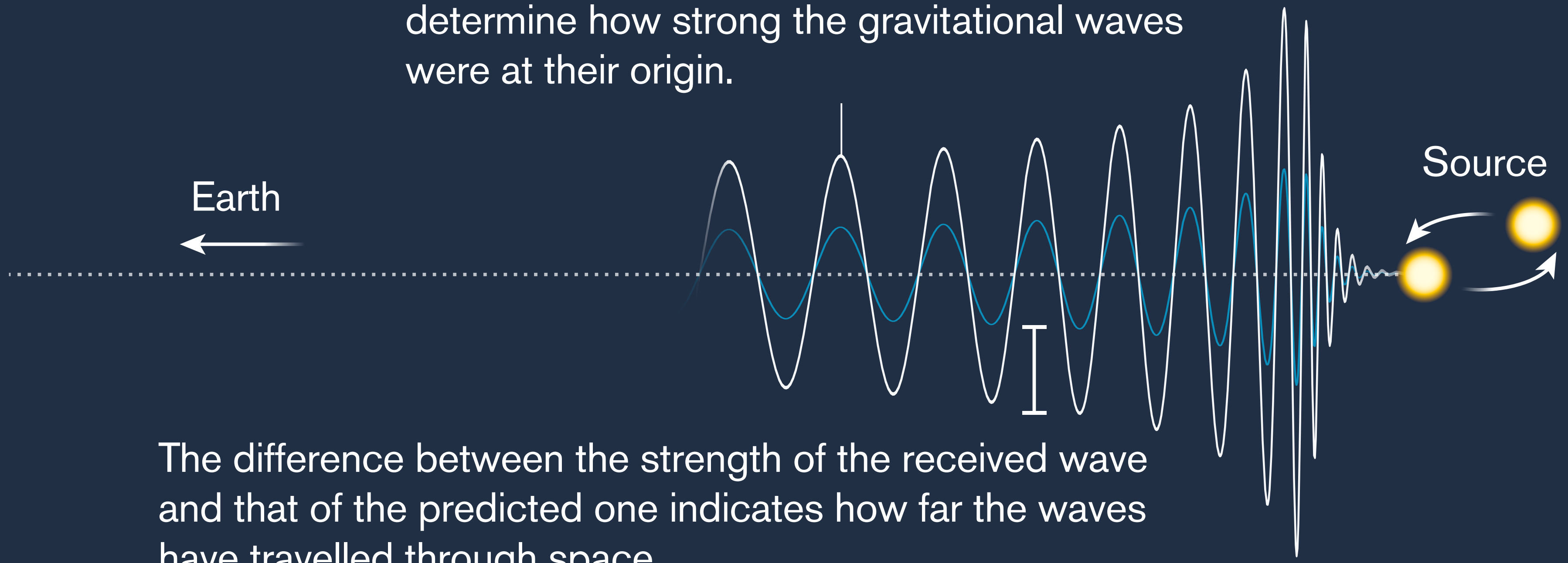
When two black holes or neutron stars spiral into each other, they produce distinctive ripples in spacetime called gravitational waves. Teams with LIGO's two detectors in the U.S. and with Virgo, the observatory's counterpart in Italy, have announced the detection of six events so far.

DECIPHERING A WAVE

When a signal is received, the frequency and rate of frequency change provide information about the masses of the objects in the binary source.



With this information, physicists can then determine how strong the gravitational waves were at their origin.

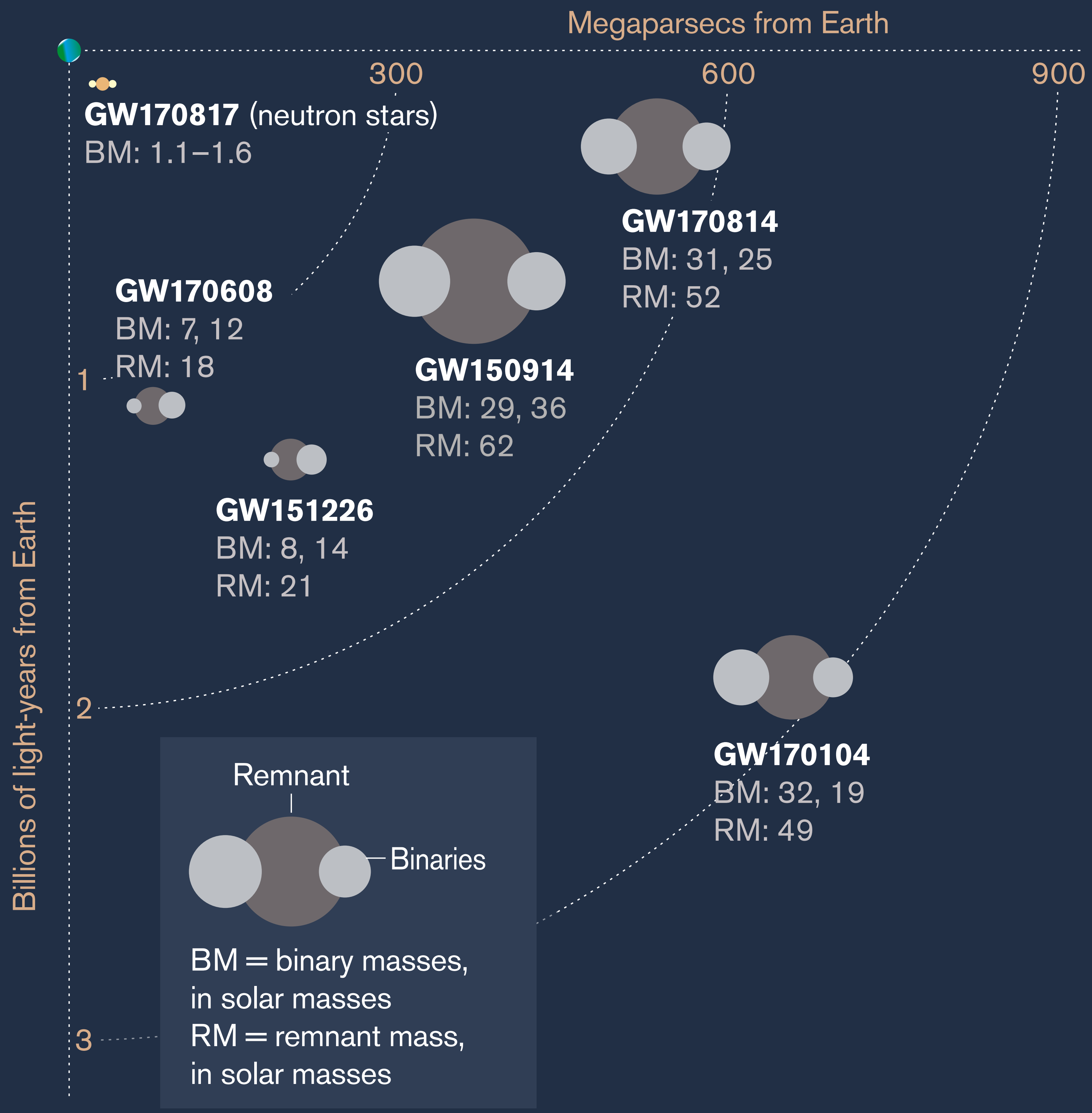


The difference between the strength of the received wave and that of the predicted one indicates how far the waves have travelled through space.

NIK SPENCER NATURE; SOURCE: LIGO/VIRGO

ALREADY DETECTED BY LIGO AND VIRGO

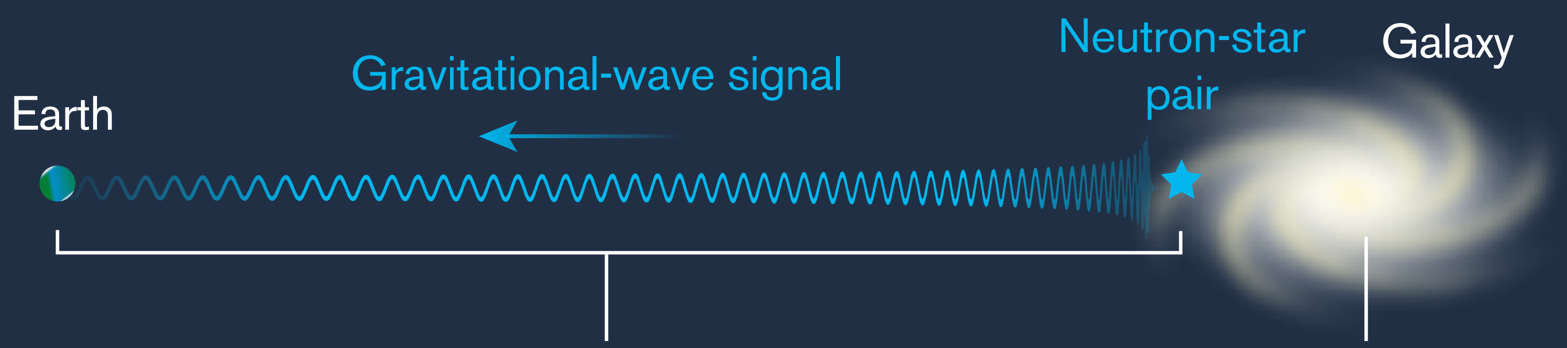
Here are the binary mergers that the observatories have picked up so far. Each discovery was named with the date it was detected.



NIK SPENCER NATURE; SOURCE: LIGO/VIRGO

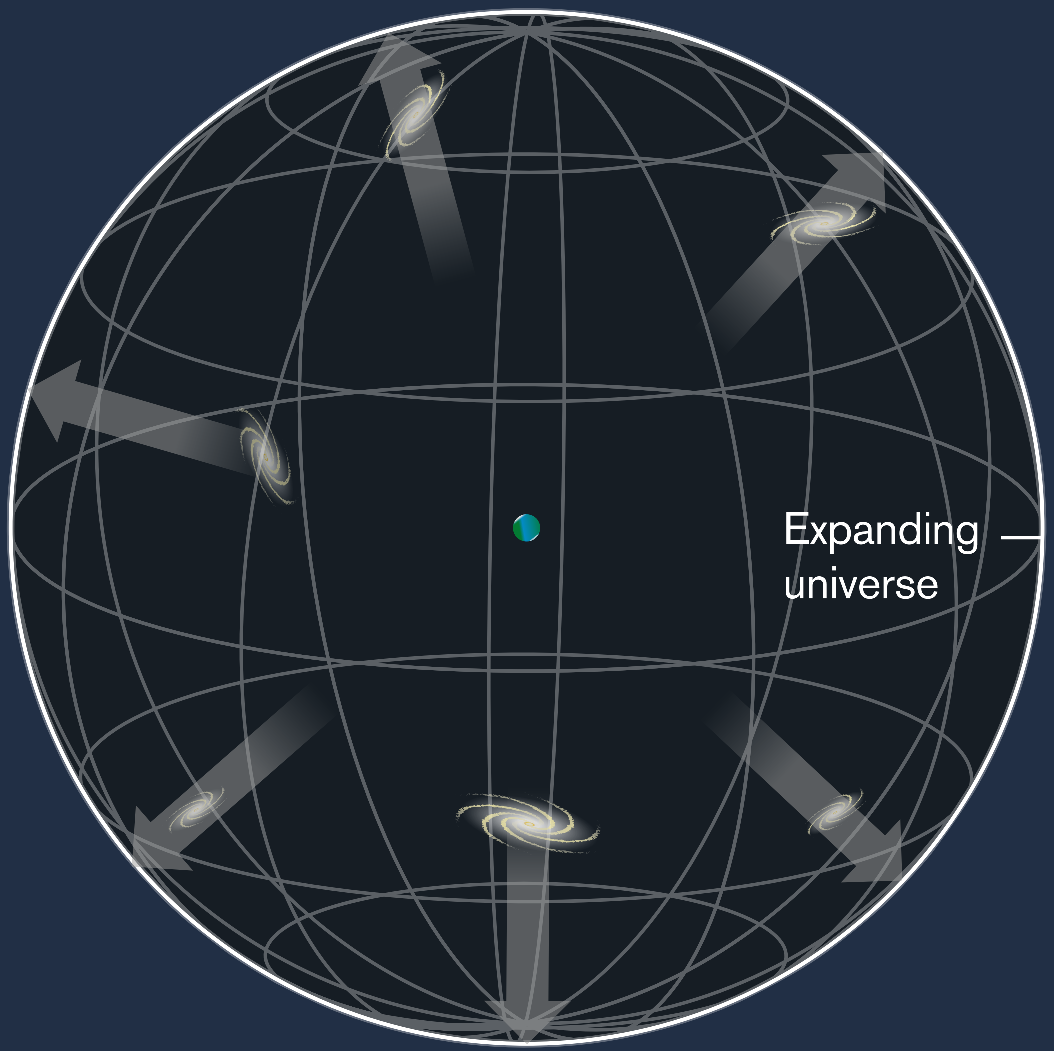
COSMIC SIGNPOSTS

Neutron-star mergers are new tools for measuring the Hubble constant—the current expansion rate of the universe.

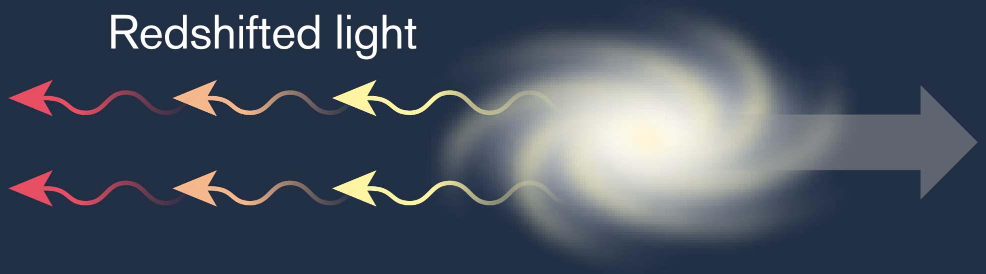


The gravitational-wave signal can be used to gauge the distance from the earth to the former neutron-star pair.

Because the merger event also releases light, conventional telescopes can be used to help pinpoint where it happened.



Then, standard astronomical techniques can be used to measure how fast the galaxy and those around it are speeding away from the earth.



The velocity and distance data—ideally from many such mergers—can be combined to calculate the Hubble constant, which relates distance and speed (galaxies twice as distant recede twice as fast).

NIK SPENCER NATURE

merger should occur somewhere at least a few times per year. Scientists are also pursuing a separate way of detecting gravitational waves from pairs of these behemoths at earlier stages of their orbits. Using radio telescopes, they monitor pulsars inside the Milky Way and look for small variations in their signals caused by the passage of gravitational waves through the galaxy. Today there are three pulsar-timing arrays, in Australia, Europe and North America, and a fourth forming in China.

Thanks to LISA's planned sensitivity and the strong signals produced by spiralling supermassive black holes, the observatory should be able to pick up gravitational waves from pairs of supermassive black holes months before they merge and see the merger in enough detail to test general relativity with high precision. After years of operation, LISA could accumulate enough distant events for researchers to reconstruct the hierarchical formation of galaxies—how small ones combined to form larger and larger ones—in the universe's history.

> **"If we don't see something that we hadn't thought of, I'd be disapointed."** —*Rainer Weiss*

On the ground, too, physicists are beginning some "grand new ventures," Weiss says. A U.S. team envisions a Cosmic Explorer with 40-kilometre detecting arms—10 times as long as LIGO's—that would be sensitive to signals from events much farther away, perhaps across the entire observable universe.

The concept for the Einstein Telescope in Europe calls for a detector with 10-kilometre arms arranged in an equilateral triangle and placed in tunnels 100 metres or so underground. The quiet conditions there could help to broaden the observatory's reach to frequencies one-tenth those detectable by current machines. That might allow scientists to find black holes beyond the range thought to be prohibited by pair-instability supernovae; at high enough masses, stars should have a different collapse mechanism and be able to form black holes of 100 solar masses or more.

If scientists are lucky, gravitational waves might even let them access the physics of the big bang itself at epochs that are not observable by any other means. In the first instants of the universe, two fundamental forces—the electromagnetic force and the weak nuclear force—were indistinguishable. When these forces separated, they might have produced gravitational waves that, today, could show up as a "random hiss" detectable by LISA, Schutz says. This hypothetical signal is distinct from a much longer-wavelength one from even earlier on, which might appear in the universe's oldest visible radiation: the cosmic microwave background. In 2014, a team reported that it had observed this effect with the BICEP2 telescope at the South Pole, but the researchers later acknowledged problems with that interpretation.

With the reopening of both LIGO and Virgo late this year, the next big discovery on Weiss's wish list is the signal from a collapsing star—something that astronomers might also observe as a type of supernova. But he has high hopes for what else might be on the horizon. "If we don't see something that we hadn't thought of," Weiss says. "I'd be disappointed."

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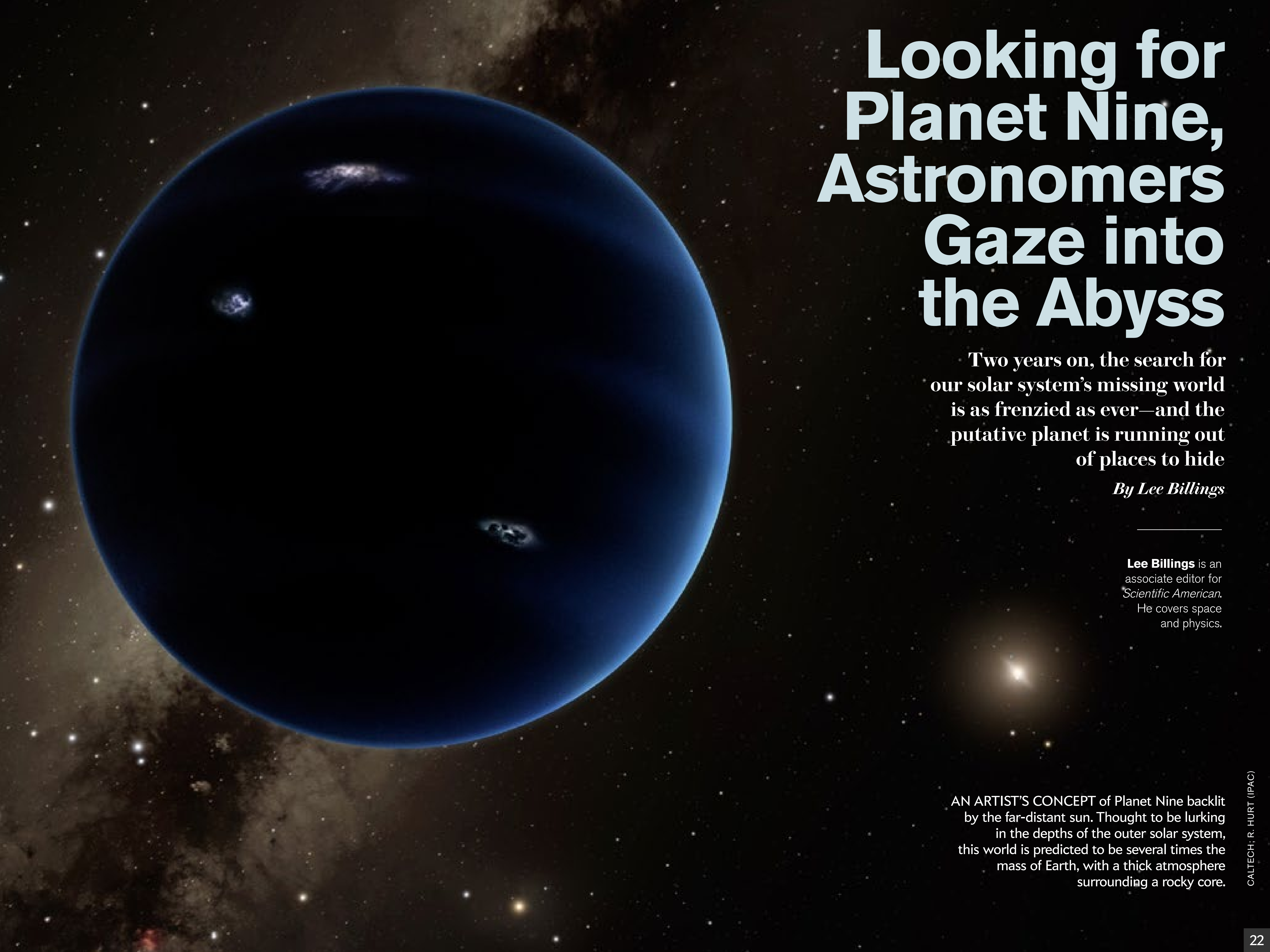
Looking for Planet Nine, Astronomers Gaze into the Abyss

Two years on, the search for our solar system's missing world is as frenzied as ever—and the putative planet is running out of places to hide

By Lee Billings

Lee Billings is an associate editor for *Scientific American*. He covers space and physics.



AN ARTIST'S CONCEPT of Planet Nine backlit by the far-distant sun. Thought to be lurking in the depths of the outer solar system, this world is predicted to be several times the mass of Earth, with a thick atmosphere surrounding a rocky core.

CALTECH; R. HURT (IPAC)

IT'S BEEN OVER TWO YEARS SINCE CALTECH ASTRONOMERS MIKE BROWN AND Konstantin Batygin made an explosive claim: based on the orbital motion of objects in the Kuiper Belt—a region beyond Neptune that is home to Pluto and other icy bodies—there must be a very big *something* much farther out, hidden save for its subtle gravitational tugs on the rest of the solar system.

Brown and Batygin's best models put this mysterious object at about 10 times Earth's mass, perhaps 20 times more distant from the sun than Neptune and currently drifting through what might be a 20,000-year orbit in a patch of sky near the constellation Orion. Brown and Batygin called it "Planet Nine," elevating it to the position once held by Pluto (which was demoted to "dwarf planet" status in 2006, when Brown discovered multiple Pluto-like worlds out past Neptune). Within months a small army of theorists and observers had thrown themselves into the search—which, so far, has come up empty. Planet Nine remains stubbornly in absentia.

Unknown planets far from the sun are not a new idea; they perennially pop up in astronomy. Such claims trace back to the 1800s and fostered the discoveries of Neptune and Pluto. What makes Planet Nine different is how much more we now know about the outer solar system—a vast and stygian abyss in which hiding a planet is still possible, although getting harder all the time. Out there twirl frozen bits of flotsam left over from our solar system's earliest moments. A big planet's gravity can act like a thumb on a scale, subtly but substantially tweaking the movements of these so-called trans-Neptunian objects (TNOs). As astronomers use new telescopes and other instruments to rapidly map this last frontier of the solar system, they keep finding what seems to be a Planet Nine–shaped hole in it.

Brown and Batygin's proposed planet handily explains orbital oddities observed in some TNOs. In their initial paper the pair showed how a recently discovered population of TNOs, bizarrely orbiting nearly perpendicular to the plane of the known planets, could be coaxed and kept there by the gravity of a far-out hidden world. Other newfound TNOs move in a telltale filigree of orbital resonances, periodically perturbing one another in a web of complex patterns that hint at further interactions with some great, unseen mass. Planet Nine's gravitational influence could even serve as a solution to the long-standing mystery of why the sun's axis of spin is tilted six degrees askew to the orbits of the inner planets.

Planet Nine also aligns with an emerging awareness that the solar system's early days were a chaotic mess, in which the early formation of Jupiter and Saturn scattered smaller and more embryonic worlds into the sun or the interstellar void. In this picture Planet Nine might have been an outbound world that plowed through enough debris to slow down and get trapped in the solar hinterlands. Or it could have been an alien outcast from another star, gravitationally captured when it wandered too close to our own. In an indirect way it could even be responsible for our existence—scattered inward rather than outward, it might have disrupted Earth's orbit, preventing life's genesis here.

Further afield, surveys of planets orbiting other stars have shown the most common worlds in our galaxy bear a passing resemblance to the putative Planet Nine—so-called "super-Earths" that are midway in size between Earth and Neptune, and appear around most stars we examine. If Planet Nine is real, it could be more than just another planet on the block; it could be the missing link between our familiar solar system and those we now see elsewhere in the Milky Way.

"I try not to be religious about my own results. It's important to keep a skeptical eye," Batygin says. "But I actually feel more comfortable than I did two years ago, because the theory still holds up beautifully. The more we look, the more we see a solar system that makes no sense without Planet Nine."

THE MOST MYSTERIOUS OBJECT IN THE SOLAR SYSTEM

IN THE MONTHS FOLLOWING the announcement, many of Planet Nine's most fervent seekers (Brown chief among them) predicted it would probably be found by the end of the following winter—that is, by now. In January of this year Brown was still bullish: based on "statistically rigorous calculations" incorporating all the available data, there is only a one-in-10,000 chance the planet is *not* out there, waiting to be found, he tweeted. In other words, Brown's best guess is Planet Nine has a 99.99 percent probability of being real.

Astronomer Scott S. Sheppard, a Planet Nine hunter at the Carnegie Institution for Science in Washington, D.C., recently ballparked the odds at 85 percent—an estimate consistent with his more conservative research style. In 2014, two years before Brown and Batygin's bombshell (and with far less fanfare), Sheppard and Gemini Observatory astronomer Chad Trujillo published their own claim of an undiscovered super-Earth in the outer solar system.

Sheppard and Trujillo's work concerned what may be—after Planet Nine—the second-most mysterious object in the solar system: a 1,000-kilometer-wide TNO called Sedna, discovered in 2003 by Brown, Trujillo and another colleague.

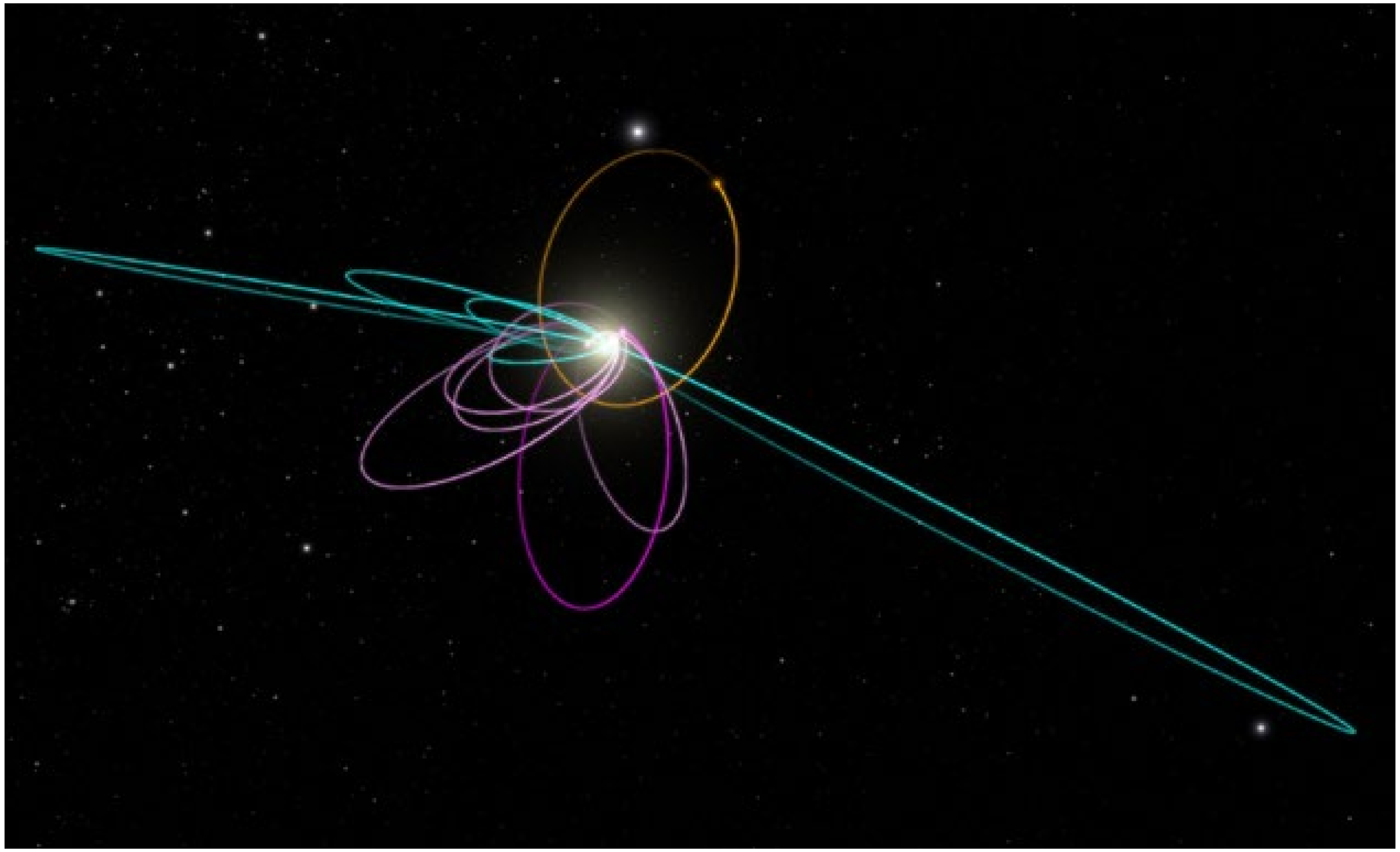
Sedna occupies a bizarre 11,400-year "eccentric" orbit: an elongated ellipse that takes it more than 20 times farther out than Pluto and never brings it closer than twice Neptune's distance from the sun. Such an extreme orbit is probably a scar from a violent past, a sign that long ago Sedna was gravitationally hurled from its standard circling onto a wild new trajectory. In the outer solar system such orbits tend to be tethered at one end to whichever giant planet originally did the hurling. But Sedna's was not attached to Neptune. It seemed detached from everything, and nothing else seen orbiting the sun shared its strange orbital properties—that is, until Sheppard and Trujillo discovered a second detached and eccentric Sedna-like (but much smaller) object, 2012 VP113.

One "Sednoid" could have been a fluke; two suggested the existence of a large, scarcely glimpsed population of detached objects. How did they get there? One possibility, proffered early on by Brown and others, was that such bizarre orbits came from a chance close encounter with a passing star in our solar system's infancy. But a single obscure detail made Sheppard and Trujillo suggest the cause was instead a hidden planet: the Sednoids shared an uncanny alignment with several other recently reported "extreme" TNOs. All lived in eccentric orbits at a high angle to the disklike plane where the known planets exist, periodically swooping through that plane in their orbits—and all swooped through that plane just as they made their closest approach to the sun. In the arcane parlance of astronomy, they clustered around a common "argument of perihelion."

Mike Brown (left) and Konstantin Batygin (right) finalize their first paper postulating the existence of Planet Nine in this photo from December 2015.

KONSTANTIN BATYGIN

"Normally arguments of perihelion should be random, having any angle between the full 0-to-360 range of possible orientations. But these were all quite improbably clustered together," Trujillo recalls. "One of the things that can confine them into a narrow range like that is the presence of a massive planet farther out.... Scott and I did



At present, the clustered orbits of objects in the Kuiper Belt beyond Neptune provide the best evidence for Planet Nine's existence. Sedna's orbit (purple) as well as the orbits of several other objects (pink) suggest they have been pushed out by the hypothesized planet (orange). Planet Nine's gravitational influence could also explain another population of objects (blue) orbiting perpendicular to the plane of the solar system.

CALTECH/R. HURT (IPAC)

a few simple simulations that suggested this was a possibility, but we didn't go into much detail—we were primarily just reporting the discovery of 2012 VP113."

Two years later Brown and Batygin's papers burst into view, building on Sheppard and Trujillo's work with hundreds of simulations predicting a mass and orbit for the possible world—a treasure map for planet-hunting astronomers. The Planet Nine hypothesis was born, along with a friendly but fierce rivalry that persists to this day.

"This is science at its finest," Sheppard says. "We noticed something weird going on out there and showed why it could be due to a big planet. Then they built on that and actually got an orbit for this thing. I don't think we have anything to prove, but it would be fun to find the planet. Whoever happens to point their telescope at the right spot at the right time will do it."

A NEEDLE IN A CELESTIAL HAYSTACK

MOST HUNTERS AGREE that if Planet Nine were anywhere near the point closest to the sun, it would be bright enough to have already been found. Instead it is probably near aphelion—the outermost sweep of its orbit, where it moves the slowest and thus spends most of its time. Seen in Earth's sky, it might now appear as a tiny dot somewhat dimmer than one of Pluto's midsize moons, gliding almost imperceptibly against a starry backdrop. Fainter TNOs have already been found, meaning Planet Nine should be within reach of many telescopes around the world. But, as Batygin puts it, "the amount of real estate that is available for the planet to hide in is astronomically vast." That means some 400 square degrees of sky, or 2,000 times the area covered by the full moon.

To have a decent chance at discovery within this immense space, one needs a very large light-gathering mirror to peer deeply into the sky for dim objects as well as a wide field of view to quickly scan large chunks of the heavens for a needle in a celestial haystack. Only a few telescopes on the ground (and none yet in space) boast both.

Brown and Batygin use the facility best suited for this search—the 8.2-meter Subaru Telescope on the summit of Mauna Kea, a dormant Hawaiian volcano. Sheppard and Trujillo do, too, while hedging their bets with observations at several other large telescopes. Using Subaru's new wide-field, 870-megapixel Hyper Suprime-Cam, either team can cover six full moons' worth of sky per image. Each takes snapshots of the firmament across several consecutive nights, then uses a computer to look for any uncatalogued objects that slowly change position.

The search can only take place at certain times of year, chiefly during the Northern Hemisphere's autumn and winter, when the general region where Planet Nine might live is high in the sky. So these rivals tend to observe almost back-to-back, one team arriving practically as the other is packing up to leave. Earlier the two teams shared data and split the survey region into parcels that one or the other would observe. But now they keep to themselves, blindly overlapping their monitoring of any given piece of sky—not out of distrust but simply to ensure the collective search is as thorough as possible. Instead of observing any given segment of sky just once, the rivals are opting to watch each one twice or more by virtue of their independence.

High-altitude weather sometimes fouls the narrow observational windows, and both teams' recent observing sessions at Subaru have been decidedly unlucky. Near-continual snow and hail blotted out the sky for Brown and Batygin on one fruitless run last December; their final night was particularly grim, when an igloo-like shell of ice frozen to Subaru's protective dome prevented them from even accessing the telescope. On another trip in January poor weather prevented Sheppard and Trujillo from making 70 percent of their planned observations. During Brown and Batygin's most recent outing in February persistent high-altitude winds smeared the stars into pancakelike shapes, scuttling the search. "I like pancakes," Brown quipped on Twitter, "but not this many." Plagued by poor weather, what began as a sprint to the finish has turned into a longer slog.

The Milky Way and the constellation of Orion rise above the Subaru Telescope atop the dormant volcano Mauna Kea in Hawaii. Subaru is the premier observatory searching for Planet Nine, which is thought to lurk somewhere in this broad swath of sky.

SEBASTIAN EGNER, SUBARU TELESCOPE AND NAOJ

FROM THE ARCHIVES

ONE OF THE MOST SWEEPING data sets now narrowing down Planet Nine's possible hiding places does not come from a telescopic search at all—but rather from NASA's Cassini orbiter at Saturn, which plunged into the ringed planet in September 2017 after a 13-year stay. That was long enough for the spacecraft to have recorded any faint perturbations a faraway planet could induce in Saturn's motion around the sun. After Batygin and Brown's announcement a team at the NASA Jet Propulsion Laboratory, led by the physicist William M. Folkner, searched for such anomalies amid the positional data Cassini beamed back during its mission, but found none. This means if Planet Nine exists and is about 10 Earth masses, it must be on an even longer, more eccentric orbit than thought and nearing an aphelion perhaps twice as far out as was first forecast in 2016. That great distance would make it even harder to see. Alternatively, it could be smaller than 10 Earth masses and still close to Brown and Batygin's canonical predicted orbit.

Or it could simply not exist.

"The stinging possibility here is that Planet Nine is just frickin' far out, and then we have to wait for a new generation of better telescopes to find it," Batygin says. "Another possibility I try not to think about too much is that it's in the galactic plane." That's the disk of the Milky Way that arcs like a glowing backbone through the night

Cerro Tololo Inter-American Observatory (CTIO) sits beneath a shower of stars in this long-exposure photo. Multiple teams use instruments on CTIO's Blanco Telescope (leftmost dome) to hunt for Planet Nine. If the planet continues to elude astronomers into the 2020s, the last, best hope for finding it will be the Large Synoptic Survey Telescope, a facility now under construction near CTIO.

REIDAR HAHN FERMILAB

sky. A fraction of Planet Nine's proposed orbit passes through this region, where the dim, glacially creeping planetary dot could hide in a thick fog of background stars.

Only one near-future facility can easily pierce the Milky Way's luminous veil: the Large Synoptic Survey Telescope (LSST), a behemoth of an observatory with an 8.4-meter wide-field mirror hooked up to a three-gigapixel camera. Currently under construction in Chile and set to begin its survey in 2022, during each night's observations the LSST will capture 20 terabytes' worth of panoramic views of the sky overhead to create a celestial time-lapse movie of unprecedented depth and detail. Its expansive view is likely to uncover hundreds if not thousands of additional extreme TNOs, providing a flood of hard data to further test Brown and Batygin's hypothesis. Even if Planet Nine is rather dim, particularly far away and in front of the galactic plane, the most crucial evidence for or against its existence should pop out of LSST's colossal database within a few years of the survey's debut—presuming it is not found before then.

In the meantime Cassini's is not the only archival data being used in the ongoing search. A team led by astronomer David Gerdes at the University of Michigan is taking a different approach: looking for the planet within the accumulated images from the Dark Energy Survey (DES), a project now in its fifth and final year. Designed to map an eighth of the night sky, DES's view coincidentally overlaps with Brown and Batygin's best guess for Planet Nine's approximate celestial location. The project's workhorse is the Dark Energy Camera, a 570-megapixel instrument with a field of view twice as large as that of Subaru's. It is mounted on the four-meter Victor M. Blanco Telescope at Cerro Tololo Inter-American Observatory in the Chilean Andes, just a short hike away from LSST's construction site. The DES equipment can cover twice as much sky as Subaru in any given snapshot. But because its telescope is about half the size, it must take much longer exposures—a situation that arguably gives Subaru a slight edge.

Other broadly similar archive-based searches are in various stages of completion—chiefly one overseen by the University of California, Berkeley, astrophysicist Peter Nugent using data from a small telescope at Palomar Observatory and another from Berkeley astronomer Aaron Meisner and colleagues using data from NASA's space-based Wide-field Infrared Survey Explorer (WISE). There is even a "citizen science" Web site devoted to letting anyone—even you, dear reader—pore through WISE images for the elusive planet. And behind all the observations a vast and diverse ecosystem of numerical simulations hums along on powerful supercomputers, trying to further narrow the search for Planet Nine by modeling its gravitational effects on the solar system across multibillion-year timescales.

"We are carpet-bombing the sky to see what falls out," Gerdes says. "Two years on, the first thing we can say about Planet Nine is that it's not low-hanging fruit, but we're still shaking the tree."

OVERCOMING BIAS

AND SO THE SEARCH GOES ON, sustained by a steady trickle of smaller discoveries: TNOs with weird orbits that seem to fit the patterns theorists insist such a planet would create.

Many have come from the Outer Solar System Origins Survey (OSSOS), a recently completed project using a 387-megapixel camera on the 3.6-meter Canada-France-Hawaii Telescope, which sits near Subaru on Mauna Kea. During its four-year run OSSOS found several new extreme TNOs by deeply staring at a few-hundred-square-degree chunk of sky. Surely, then, Planet Nine's metaphorical thumb on the outer solar system's scale should have left fingerprints all over the OSSOS data. And indeed, in a paper published last summer, the OSSOS team announced three of their newfound extreme TNOs were consistent with the clustering patterns underpinning the Planet Nine hypothesis—but a fourth one was not. Including this outlier in their analysis and accounting for potential biases in their observations, the team concluded the TNO clustering first identified by Sheppard and Trujillo in 2014 could well be illusory.

That is, due to the seasonality of observing runs and inclement weather on Mauna Kea and other major mountaintop observatories, OSSOS and other surveys might simply have an easier time finding extreme TNOs in the region of sky that supports the Planet Nine hypothesis. If so, given that the total number of known extreme TNOs is still very low—anywhere from 10 to just under 30, depending on which definitions are used—the true, more typical distribution of such objects would only become clear after many more are found and any biases accounted for. "We cannot reject a uniform distribution [of extreme TNOs] with our new discoveries," says Michele Bannister, an astronomer and OSSOS team member at Queen's University Belfast in Northern Ireland. "We can't say there's no Planet Nine, but we can say that its proposed effects are not present at a statistically significant level in our independent data set.… It's an increasingly big ask to continue hiding a 10-Earth-mass planet out there, now that all these surveys are being completed."

> **"We are carpet-bombing the sky to see what falls out."**
> *—David Gerdes*

Few if any prominent Planet Nine hunters are swayed, however. Brown and Batygin reject the OSSOS team's implication that other TNO searches are unreliable due to vaguely defined biases, and they note that even if biases are rampant, their effects should average out when collectively considering surveys with widely divergent methodologies. If all but one survey (OSSOS) shows clustering, they say, that clustering is likely genuine.

Gerdes, the leader of the archival DES search, acknowledges all present surveys suffer some degree of observational bias that must be carefully accounted for. But he says the jury is still out as to their significance. According to a 2017 analysis by his team, there is only a few-percent chance the orbital alignments they have observed among the extreme TNOs would occur in the absence of Planet Nine. "Is 'a few percent' large or small?" Gerdes asks. "It depends on your definition—if there was a few percent chance of rain, you'd go ahead with the picnic. If a few percent of all airline flights crashed, you'd never get on a plane."

If the prize is a new planet—and with it a whole new understanding of the solar system—even Planet Nine's naysayers concede a significant chance of failure would be worth the risk. "You have to be most careful around the most alluring hypotheses," Bannister says. "They are seductive because they are beautiful. It would be enchanting—amazing—to have an extra planet to study. We would observe it with all our telescopes. We would write proposals to send spacecraft there very quickly. But we can't forget we are talking about a realm of the solar system that is still very hard to explore. We must take care with what the data tries to tell us, because we are mapping the deep."

Regardless of whether or not Planet Nine exists, Bannister says, its unfolding story is really a tale of discovering how our little corner of the cosmos truly came to be. "We will write the history book of our solar system based on what we find out there in the next several years, and it is already clear the system we see today is not as it was formed," she says. "That won't change whether we have nine planets instead of eight."

Astronomers Boggle at a Distant Galaxy Devoid of Dark Matter

The newfound object NGC 1052-DF2 defies easy explanation and could lead to breakthroughs in ourunderstanding of how galaxies form and evolve

By Rebecca Boyle

THE "ULTRA-DIFFUSE" galaxy NGC 1052-DF2, seen here in an image from the Hubble Space Telescope, is about the same size as our Milky Way but contains just 1 percent as many stars. Strangely, it also appears to be empty of dark matter.

NASA, ESA AND P. VAN DOKKUM YALE UNIVERSITY

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A GALAXY IS MUCH MORE THAN A radiant agglomeration of stars. To modern astrophysicists, galaxies are more notable for their dark sides: their hidden material that is only "seen" by its gravitational pull upon the shiny stuff it seems to vastly outweigh. So-called dark matter is as much a defining feature of galaxies as stars and gas, and is thought to provide the gravitational seeds from which galaxies assemble and grow.

A galaxy without dark matter—or without some bizarre effect of gravity that would mimic dark-matter behavior—would be a very weird thing indeed. Finding such a thing would be like finding smoke but no fire, effect without cause. Yet that is what Yale University astronomer Pieter van Dokkum and his colleagues have just found, they report in a study published in March in *Nature*.

The galaxy, called NGC 1052-DF2, is about 65 million light-years away. It is almost as big as the Milky Way but is "ultra-diffuse," meaning it contains just a vanishing fraction of the stars found in our galaxy—only 1 percent, in this case. That stellar sparseness means it does not look much like a typical spiral galaxy, but rather a loosely connected, ghostly blob of star-pocked gas and dust. If it contained an amount of dark matter typical for a galaxy of its size, the dark matter's gravity would hasten the motions of several star clusters that surround it. Instead, van Dokkum's team found those star clusters moving languidly around NGC 1052-DF2, a sign that there may well be very little or no dark matter within that galaxy at all. That suggests dark matter can be decoupled not only from regular, visible matter, but from entire galaxies—a phenomenon astronomers have never seen until now.

"If it's true that a galaxy exists where there is hardly any dark matter, I think that's a problem for all theories about galaxy formation," says Erik Verlinde, a theoretical physicist at the University of Amsterdam who has proposed an alternative to dark-matter-dominated gravity and was not involved in the research. "Even if you believe in a modified theory of gravity, you would expect to see something different from what has been observed here. It's a problem for almost every theory that's out there."

Dark matter has never been seen or measured directly because it does not emit light. Its presence is instead inferred through the gravitational pull it exerts on any normal matter around it. Astrophysicists think dark matter's gravity is crucial for forming the universe's large-scale structure of filaments and sheets of galaxy clusters, and scientists have even measured how clumps of it act as gravitational lenses, magnifying light from far-distant background galaxies. Some physicists have postulated that there is no such thing as dark matter, however, and that what we perceive as giant, starlight-bending clumps of heavy, invisible material is actually something else that is profoundly misunderstood.

Only discovered in 2015, ultra-diffuse galaxies are thought to be particularly useful cosmic laboratories for understanding dark matter. Surely, astronomers thought, dark matter must play a role in forming these objects so devoid of normal star stuff. That thinking led van Dokkum and his colleagues to build the Dragonfly Telephoto Array, a telescope in New Mexico created for the express purpose of scrutinizing ultra-diffuse galaxies. The researchers initially used Dragonfly to study a different galaxy, one appearing to possess an almost inconceivably gargantuan amount of dark matter, which was a weird result in and of itself. When van Dokkum and his team found NGC 1052-DF2, they expected to see something similar.

"Instead we saw the opposite, leading to this remarkable conclusion that there's actually no room for dark matter at all in this thing," van Dokkum says. "It's not something we were looking for or expecting. At all. But you go in the directions the data take you, even if it's in contradiction to what you've found before."

In Dragonfly images, NGC 1052-DF2 looked like a standard ultra-diffuse galaxy. But when the team compared them to a better image from the Sloan Digital Sky Survey, they found a surprising mismatch. What had seemed to be dim basic galactic structures in Dragonfly's view appeared as point-like sources in the Sloan image. To resolve the discrepancy, the team scrutinized the galaxy with the Hubble Space Telescope, the W.M. Keck

Observatory and the Gemini Observatory, the latter two on Mauna Kea in Hawaii.

The point sources proved to be 10 globular clusters—compact and spherical groupings of stars orbiting the galaxy's core. The researchers then set about measuring the movements of the clusters as a way to estimate the galaxy's total mass. Simply put, the velocity at which clusters orbit a galaxy is related to the amount of matter—normal or dark—that a galaxy contains. Using information from the Keck telescopes, the team found the globular clusters were moving much more slowly than expected.

Adding up the clusters' motions and NGC 1052-DF2's mass, they realized there might be no dark matter behind this particular galactic curtain. All the clusters' movements could be explained solely by the mass of the galaxy's observed stars.

It is possible that these measurements are imperfect, however, says Michael Boylan-Kolchin, an astronomer at the University of Texas at Austin who was not involved in the new study. "The alternative possibility is that the globular clusters, or the objects they think are globular clusters, aren't really measuring the total mass in the way they think," he says. "The key thing is to see whether the globular clusters really are tracing the mass of the galaxy as a whole."

> **"The alternative possibility is that the globular clusters, or the objects they think are globular clusters, aren't really measuring the total mass in the way they think."**
>
> ***— Michael Boylan-Kolchin***

Assuming the results are right, there are a few theories to explain how galaxies like NGC 1052-DF2 could come together untouched by dark matter's hidden hand. It could be that NGC 1052-DF2 was once a placid mass of gas and has been recently perturbed by another unseen galaxy nearby, sparking star formation. Or, van Dokkum speculates, perhaps this ultra-diffuse, dark-matter-free galaxy arose from two streams of gas that collided and compressed to form a scattering of stars. Another idea, first proposed more than two decades ago by Yale astronomer Priyamvada Natarajan, then at the University of Cambridge, suggests that galaxies like NGC 1052-DF2 may form from galaxy-sized gobs of gas clumping together in jets ejected by feasting supermassive black holes. NGC 1052-DF2 does reside in a region where such things could conceivably occur, lying near a giant elliptical galaxy with a supermassive black hole at its heart.

Alternatively, in the absence of any direct dark-matter detections, some theorists have suggested its existence is illusory—and that something else drives galaxy evolution and gravitational lensing. Some have proposed tweaking the laws of motion first codified by Isaac Newton, developing a class of competing theories called Modified Newtonian Dynamics, or MOND. More recently, Verlinde suggested an alternative called "emergent gravity," in which gravity is a byproduct of quantum fluctuations and dark energy (another scarcely understood phenomenon, one that seems to be causing the universe's expansion to accelerate).

In a paradoxical twist of the sort that makes astrophysics special, NGC 1052-DF2's lack of dark matter is potentially a good thing for the theory as a whole. That is because even if dark matter is not real, the observations that hint at its existence are. If the large-scale universe is dominated by subtle alterations to the force of gravity, or to a fluctuating force field of dark energy, these effects would not discriminate and would manifest in all galaxies—NGC 1052-DF2 included. Yet in this strange galaxy, the projected signatures of these exotic effects are not seen.

Here, "the absence of dark matter is evidence of its existence," van Dokkum says. "There is no way around it. It can be in a galaxy or not in a galaxy, but it is not a field, or some alternative thing that manifests itself rather than being a substance."

Verlinde disagrees that the new galaxy puts his ideas or MOND to rest. "I indeed believe there is no dark matter that needs to be added to explain these observations. There might be a change in the ways that gravity works, compared to what Einstein and Newton would have said, but let's not immediately draw conclusions," he says. "I think it's too early to say."

Follow-up observations, including more detailed views of the globular clusters, should help astronomers settle the question and better understand these clusters' relationship to the galaxy. Future observatories under construction, such as the European Extremely Large Telescope in Chile's Atacama Desert, or NASA's James Webb Space Telescope, should be able to take such measurements.

"How did we get a gas cloud of that size that was able to form a galaxy, that was able to have enough gravity?" says Risa Wechsler, an astronomer at Stanford University who was not involved in the new research. "There's no question it's interesting. It's totally weird."

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SPACE

Space Technology Could Change the Balance of Power in Africa

Nations from Morocco to Nigeria to South Africa and more are beginning to reap the geopolitical advantages of going into orbit

The Milky Way, in the night skies over Namibia.

PAUL & PAVEENA MCKENZIE GETTY IMAGES

IN 2013, DURING A VISIT by French president François Hollande to Morocco's capital Rabat, a deal was made in secret for France to build a satellite for the Moroccan government. On November 7, 2017, four years after this deal was signed, Mohammed VI-A, Africa's first high-resolution imaging satellite, was launched, giving Morocco a new kind of power in North Africa.

The launch of Mohammed VI-A reflects a new way nations in Africa are growing their economic, social and military capabilities. Instead of conforming to the status quo of the past or accepting one-sided trade and geopolitical agreements, they are turning to space. For Morocco, the satellite, which is nominally to be used for mapping, natural disaster management and more, raised eyebrows in Algeria and Spain over its potential for spying as well.

Several other countries in Africa are also making moves in space. South Africa orbited its first satellite in 1999 and recently launched the continent's first private satellite, developed in part by high school girls. (South Africa was also home to one of NASA's stations for its Deep Space Network, built in the 1960s.) Ethiopia opened East Africa's first observatory in 2015 and has set a time line of launching its own satellite within a few years. Nigeria has launched several since 2003 and is planning to launch Africa's first nanosatellite. Egypt will loft a new Russian-built satellite in 2019, and in 2016 the African Union approved a proposal to connect the different space agencies operating throughout the continent.

FOREIGN COUNTRIES EYE THE GRAND PRIZE

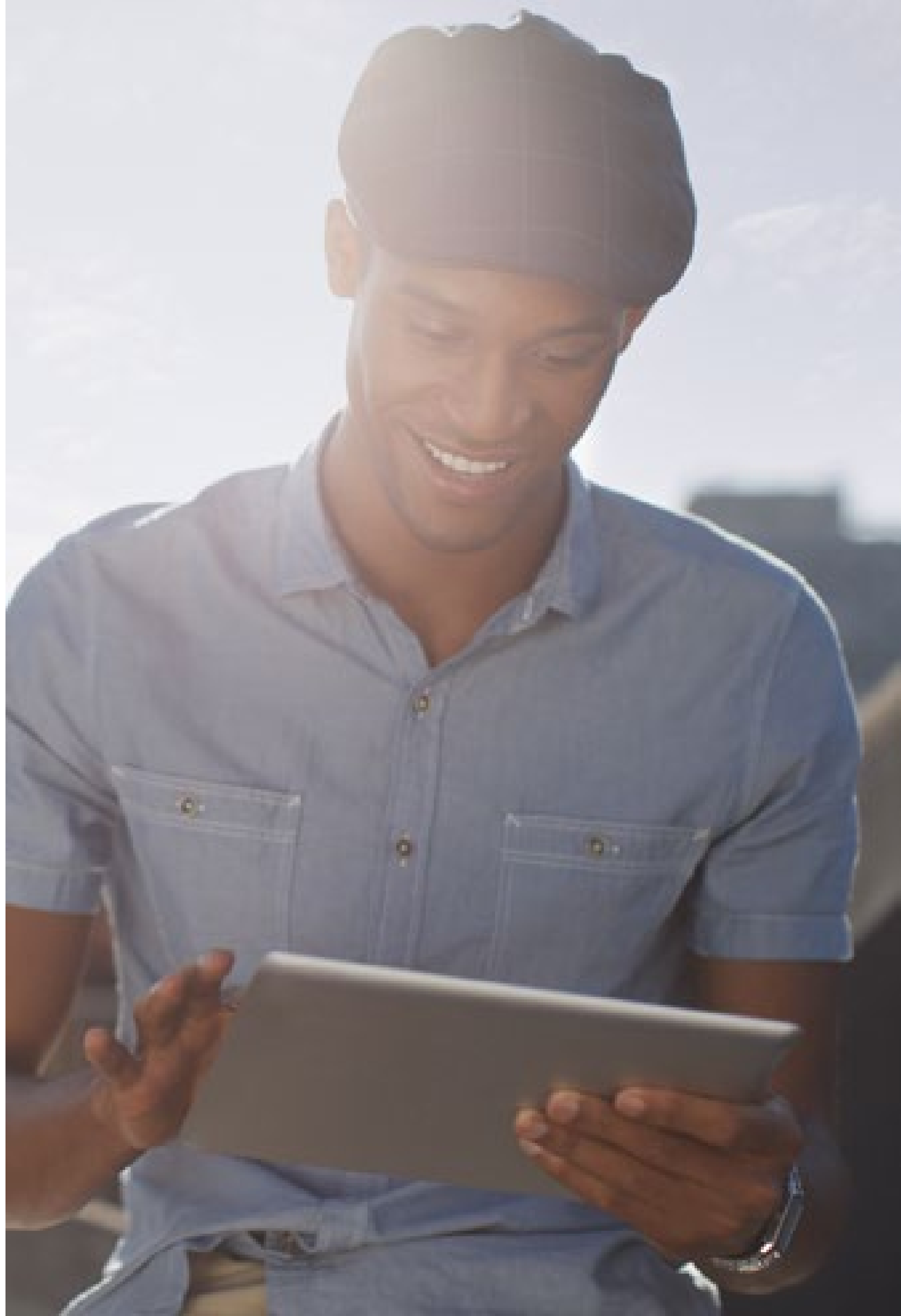
While countries in Africa pursue their own individual plans for space, foreign nations continue to play an important role in helping Africa go orbital. The U.S., Japan, China, India and Russia are offering their know-how and infrastructure throughout the continent. For example, in June 2017, Ghana launched its first CubeSat satellite, called GhanaSat-1, to crack down on illegal mining and theft of resources. While the probe was designed by Ghana's All Nations University College, it was launched thousands of miles away, from NASA's Kennedy Space Center in Florida. And Japan's space agency, JAXA, provided training and resources to move the project forward.

In Nigeria, meanwhile, China is helping turn the capital city Abuja's space dreams into reality. It began in 2007 when Chinese engineers built and launched a commercial satellite for the African nation—the first time China had done that for another nation. It followed with a communications satellite in 2011 and in 2016 entertained a delegation from Nigeria to talk about logistics and investment for the country's plan to send an astronaut into space in the 2030s. India has launched four satellites for Algeria, while Russia launched a satellite for Egypt in 2014 and is helping to develop a second satellite.

While experienced spacefaring nations are trying to extend their influence, African nations themselves could use their increasing sophistication with space technology to grow their own influence, hoping to change the continental balance of power. For Morocco, Mohammed VI-A is both a public and a private tool—a way to map areas for agriculture and disaster management, and a way to assess military bases and troop numbers in neighboring countries. But the nation may well go beyond this and offer its existing and future capabilities to its neighbors for both political and economic ends. Rabat could, in principle, offer imagery of protests by dissidents or of areas that might have untapped diamond, gold or oil deposits. Through its satellite program, Morocco could thus become far more influential across Africa.

As African nations gain sophisticated space capabilities, they might even end up competing with their more experienced counterparts. For example, although the African Union has been unable to launch a continent-wide space agency, it can begin setting continent-wide space goals, such as having a network of African Internet satellites in service by 2035. That could bring it into conflict with the U.S. company SpaceX, which has proposed its own Internet satellites as early as 2019.

In short, what African nations expect to achieve in space could influence the geopolitical agenda of countries across Asia, North America and Europe. For every satellite and craft that is launched, an array of nations will be affected positively and negatively. In that way, space is not just changing the balance of power in Africa, but could ultimately be changing the destinies of entire countries.



Yuri Milner is the founder of Breakthrough Initiatives. In partnership with Stephen Hawking, Milner has advanced a program of scientific and technological exploration probing the big questions of life in the universe and intergalactic space exploration.

SPACE

Stephen Hawking: The Universe Does Not Forget, and Neither Will We

His work distinguished him as one of the greatest physicists of our generation; his character distinguished him as one of its greatest men

LWP KOMMUNIKÁCIÓ FLICKR (CC BY 2.0)

THE GREATEST SCIENTISTS are remembered not only for their discoveries but for their characters. To make the biggest imaginative leaps you need not just intellect but a particular set of values: courage, honesty, a certain rebelliousness, and ceaseless curiosity. In individuals as different as Galileo, Darwin and Einstein, these values were present.

Stephen Hawking, who passed away on March 14, exemplified this pattern. His work distinguished him as one of the greatest physicists of our generation. His character distinguished him as one of its greatest men.

I first met Professor Hawking in 1987, when he attended a physics conference in Moscow. There was excitement in the air. For us younger physicists, he was already a revered figure. His work on black holes had built an elegant bridge between quantum theory and general relativity. And it had shocking implications: that black holes are not completely black—they emit radiation (now called “Hawking radiation”)—and that any information falling into a black hole is scrambled and lost forever.

This may not seem like a big deal—if you were careless enough to drop this article in a black hole, would you expect it to remain readable? But to physicists it was deeply unsettling. The laws of nature depend on events being predictable, in principle, from their pasts. If black holes are “wells of forgetfulness,” as Hawking put it recently, in which the past is lost for good, can nature be said to have laws at all? “It’s like the universe losing its cell phone,” Hawking said. “Worse than that—losing its memory.”

Back at that Moscow conference, we were all aware that he had achieved these insights in spite of his debilitating illness. But it was one thing to hear about him, another to see him in person. Although I eventually quit physics—we can’t all be as good as Stephen Hawking, after all—he made a deep and permanent impression on me that day. His words were mediated by his interpreter, but the quality of the man came through loud and clear. Here was both a great mind and one that absolutely embodied those scientific values of courage, honesty, curiosity and rebelliousness. (This last one, I suspect, played a big part in enabling him to outlive his prognosis by 55 years.)

These values often took him well beyond the bounds of academia. They led him to speak out about culture, politics and existential risks facing humanity. He was just as committed to the public understanding of science as he was to science itself, whether it was via popular books, lectures or TV shows. Indeed, he reportedly turned down a knighthood as a protest against insufficient funding for science.

Happily, in 2013 he did agree to accept the Breakthrough Prize, which I had founded a year earlier, in part to raise awareness of the funding issue and the significance of fundamental science. The prize recognized his immense influence on the course of modern physics. In the last two decades, the issues he raised about black holes and information have become perhaps the most fertile area of physics, where many expect the next big breakthrough to emerge. The famous string theorist Leonard Susskind wrote of this work, “I believe that in time, when the repercussions are fully understood, physicists will recognize it as the beginning of a great scientific revolution.”

In recent years, I had the good fortune to spend more time with Professor Hawking when he partnered with me to launch two science initiatives: Breakthrough Listen, a new astronomical search for evidence of intelligent life beyond Earth; and Breakthrough Starshot, the first practical attempt to design a space probe that could travel to another star. By now in his mid-seventies, his curiosity was still as fierce as ever. He supported these projects because he was burning to know whether we are alone in the universe, and whether humanity can survive our current challenges and reach out for the stars.

Unusually for a physicist, he was also still producing important science. In 2016 he and his collaborators published a major new paper on black holes and information. By then, with characteristic honesty and intellectual courage, he had decided that he had drawn the wrong conclusion from his early work. He was now convinced that information survives—that the universe does not forget.

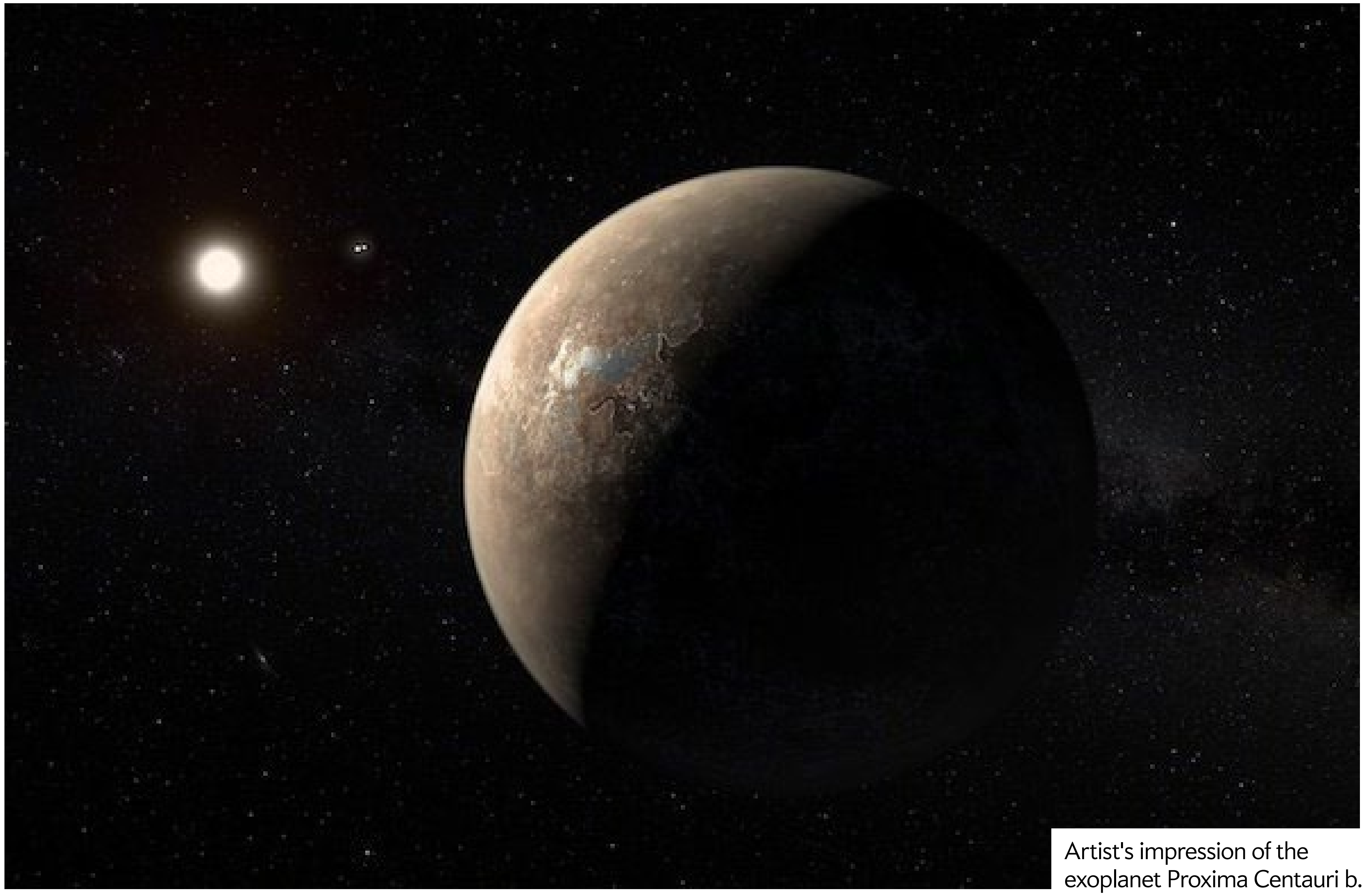
One thing is certain: for as long as there is science, the legacy of Stephen Hawking, the scientist and the man, will be remembered.

Abraham Loeb is chair of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the advisory board for the Breakthrough Starshot project.

SPACE

Escape from Proxima b

A civilization in the habitable zone of a dwarf star like Proxima Centauri might find it hard to get into interstellar space with conventional rockets



Artist's impression of the exoplanet Proxima Centauri b.

ESO

ALMOST ALL SPACE MISSIONS launched so far by our civilization have been based on chemical propulsion. The fundamental limitation here is easy to understand: a rocket is pushed forward by ejecting burnt fuel gases backwards through its exhaust. The characteristic composition and temperature of the burnt fuel set the exhaust speed to a typical value of a few kilometers per second. Momentum conservation implies that the terminal speed of the rocket is given by this exhaust speed times the natural logarithm of the ratio between the initial and final mass of the rocket.

To exceed the exhaust speed by some large factor requires an initial fuel mass that exceeds the final payload mass by the exponential of this factor. Since the required fuel mass grows exponentially with terminal speed, it is not practical for chemical rockets to exceed a terminal speed that is more than an order of magnitude larger than the exhaust speed, namely a few tens of kilometers per second. Indeed, this has been the speed limit of all spacecraft launched so far by NASA or other space agencies.

By a fortunate coincidence, the escape speed from the surface of Earth, 11 kilometers per second, and the escape speed from the orbit of Earth around the sun, 42 kilometers per second, are close to the speed limit attainable by chemical propulsion. This miracle allowed our civilization to design missions, such as Voyager 1 and 2 or New Horizons, that could escape from the solar system into interstellar space. But is this fortune shared by other civilizations on habitable planets outside the solar system?

Life as we know it requires liquid water, which can exist on planets with a surface temperature and a mass similar to Earth. Surface heating is needed to avoid freezing of water into ice, and an Earth-like gravity is needed to retain the planet's atmosphere, which is also essential, since ice turns directly into gas in the absence of any external atmospheric pressure.

Since the surface temperature of a warm planet is dictated by the flux of stellar irradiation, the distance of the habitable zone around any arbitrary star scales roughly as the square root of the star's luminosity. For low-mass stars, the stellar luminosity scales roughly as the stellar mass to the third power. The escape speed scales as the square root of the stellar mass over the distance from the star.

Taken together, these considerations imply that the escape speed from the habitable zone of a star scales inversely with stellar mass to the power of one quarter. Paradoxically, the gravitational potential well is deeper in the habitable zone around lower-mass stars. A civilization born near a dwarf star would need to launch rockets at a higher speed than we do in order to escape the gravitational pull of its star, even though the star is less massive than the sun.

As it turns out, the lowest-mass stars happen to be the most abundant of them all. It is therefore not surprising that the nearest star to the sun, Proxima Centauri, has 12 percent of the mass of the sun. This star also hosts a planet, Proxima b, in its habitable zone at a distance that is 20 times smaller than the Earth-sun separation. The escape speed from Proxima b to interstellar space is about 65 kilometers per second. Launching a rocket from rest at that location requires the fuel-to-payload weight ratio to be larger than a few billion in order for the rocket to escape the gravitational pull of Proxima Centauri.

In other words, launching one gram's worth of technological equipment from Proxima b into interstellar space requires a chemical fuel tank that weighs millions of kilograms, similar to that used for liftoff of the space shuttle. Increasing the final payload weight to a kilogram, the scale of our smallest CubeSat, requires a thousand times more fuel than carried by the space shuttle.

This is bad news for technological civilizations in the habitable zone of dwarf stars. Their space missions would barely be capable of escaping into interstellar space using chemical propulsion alone.

Of course, the extraterrestrials could take advantage, as we do, of gravitational assists by optimally designing the spacecraft trajectory around their host star and surrounding planets. In particular, launching a rocket in the direction of motion of the planet would reduce the propulsion boost needed for interstellar escape down to the practical range of 30 kilometers per second. Extraterrestrials could also employ more advanced propulsion technologies such as light sails or nuclear engines.

Nevertheless, this global perspective should make us feel fortunate that we live in the habitable zone of a rare star as bright as the sun. Not only do we have liquid water and a comfortable climate to maintain a good quality of life, but we also inhabit a platform from which we can escape easily into interstellar space. We should take advantage of this fortune to find real estate on extrasolar planets in anticipation of a future time when life on our own planet will become impossible.

This unfortunate fate will inevitably confront us in less than a billion years, when the sun will heat up enough to boil all water off the face of Earth. With proper planning we could relocate to a new home by then. Some of the most desirable destinations would be systems of multiple planets around low-mass stars, such as the nearby dwarf star TRAPPIST-1, which weighs 9 percent of a solar mass and hosts seven Earth-sized planets.

Once we get to the habitable zone of TRAPPIST-1, however, there would be no rush to escape. Such stars burn hydrogen so slowly that they could keep us warm for 10 trillion years, about a thousand times longer than the lifetime of the sun.

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SPACE

To Keep NASA's Golden Age Alive, We Need More Telescopes–but Far Less Expensive Ones

A focus on costly space telescopes is hurting the field

STARTING AROUND 50 YEARS AGO, astronomy began a winning streak of amazing discoveries. We found the cosmic microwave radiation left over from the big bang back in the 1960s, for instance, and in recent years we have identified thousands of planets orbiting distant stars. But the good times may be about to stop rolling. There is reason to fear that astronomy is ending its long run of lifting the veil on cosmic wonders.

Our early successes came from looking through new windows across a vast range of wavelengths invisible to the naked eye. The first radio, x-ray, ultraviolet and infrared telescopes were small, but everything we saw through them was new and mysterious. The next generation of telescopes leaped forward in capabilities, leading to the discoveries of neutron stars, black holes, dark matter, dark energy—the list goes on.

But this greater power came at a cost. Each new generation of telescopes carried a price tag several times higher than that of the one before. Today a single telescope can take almost a full decade's worth of NASA's budget for "big astronomy." A case in point is the James Webb Space Telescope, now scheduled for launch in 2020. Webb's price tag ballooned from what was originally supposed to be just about $1 billion to nearly $9 billion, crowding out nearly everything else. Without other major missions to fall back on, the only response to technical problems with Webb was to keep throwing more money at them.

MATTHEW HARRISON CLOUGH

The glory of our golden age has been that we can access the entire electromagnetic spectrum at a single point in time from various instruments. The discovery of gravitational waves from the merger of two neutron stars is a perfect example: ground-based detectors spotted these ripples in spacetime, but follow-up observations with gamma-ray, x-ray and visible-light telescopes gave us a far better understanding of how the event unfolded. Ideally we need several comparably sensitive “flagship” telescopes, on a par with Webb—and they need to be flying at the same time.

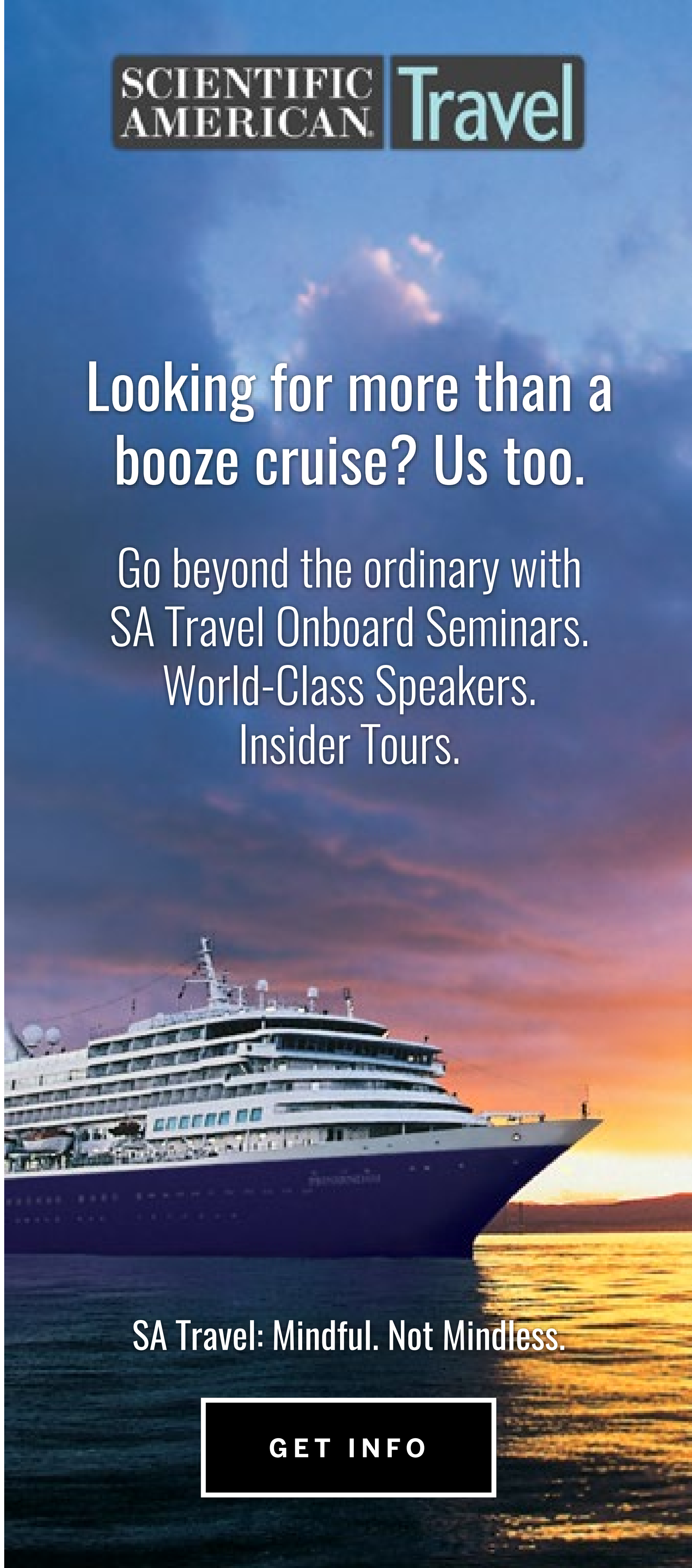
Yet such flagships are designed to last only about five years (although that can often be stretched to 10). When the infrared-sensitive Webb flies, it will be 10 to 100 times more powerful than its predecessors, the Hubble and Spitzer space telescopes. But if new flagships cost as much as Webb, it will be a decade before even one of them can be launched. By then, Webb itself will likely be on its last legs. Every discovery it makes will take more than 10 years to follow up. At that point, we will have forgotten what it was that we wanted to know in the first place.

But it does not have to be this way. Once a decade astronomers set priorities about what new space telescopes to build, and the next time we do so, in the “Astro2020” survey, we should require multiple new missions. There are at least half a dozen ideas for much cheaper telescopes—not as powerful as Webb-scale flagship telescopes but dramatically better than their predecessors. These range from gamma-ray telescopes that can detect merging neutron stars to x-ray and ultraviolet telescopes for probing intergalactic space and more to a far-infrared telescope we can use to understand how stars and planets form. And unlike Webb, they are not just affordable; all of them can be completed within 10 years.

The downside of this approach is that highly desirable but extremely expensive flagship telescopes along the lines of Webb must be postponed until the commercial space industry comes fully of age. SpaceX, for example, already launches satellites at one third of the traditional cost, and soon, maybe, that will drop to as little as one fifth. That is a sizable saving by itself.

Cheaper launch services also take the pressure off engineers to relentlessly shave mass from the telescopes themselves by using the lightest and most expensive possible components. Without such a restriction, costs could plausibly be cut by two thirds. Shrinking costs makes a doubling of flagship launch rates feasible.

As this commercial revolution continues, an even higher rate of flagship missions could come about. If we embrace such a strategy, the good times needn’t stop rolling, and the golden age of astronomy doesn't have to end.



Celestial Movement

The sky is always changing. The planets move overhead as they trace their paths around the sun, and the moon rotates through the heavens as it circles our own world. Though the stars that provide their backdrop stay fixed in relation to one another, they too spin above as Earth makes its daily revolution and its yearly passage around the sun. To appreciate this ever-changing view, grab these sky maps, go outside at night, and look up!

JOHN SIRLIN GETTY IMAGES

Astronomical Events

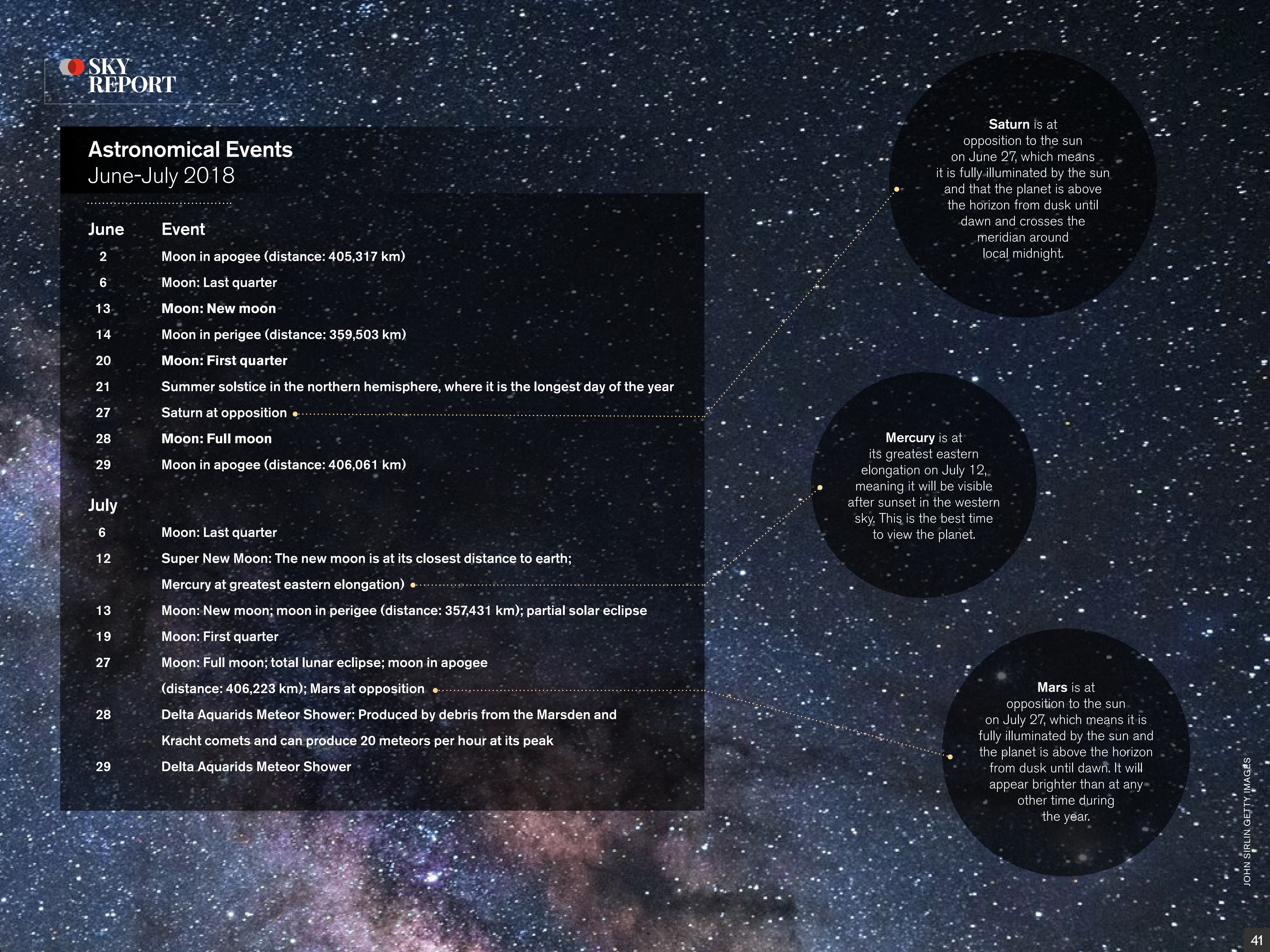
June-July 2018

June	Event
2	Moon in apogee (distance: 405,317 km)
6	Moon: Last quarter
13	**Moon: New moon**
14	Moon in perigee (distance: 359,503 km)
20	**Moon: First quarter**
21	Summer solstice in the northern hemisphere, where it is the longest day of the year
27	Saturn at opposition
28	**Moon: Full moon**
29	Moon in apogee (distance: 406,061 km)
July	
6	Moon: Last quarter
12	Super New Moon: The new moon is at its closest distance to earth; Mercury at greatest eastern elongation)
13	Moon: New moon; moon in perigee (distance: 357,431 km); partial solar eclipse
19	Moon: First quarter
27	Moon: Full moon; total lunar eclipse; moon in apogee (distance: 406,223 km); Mars at opposition
28	Delta Aquarids Meteor Shower: Produced by debris from the Marsden and Kracht comets and can produce 20 meteors per hour at its peak
29	Delta Aquarids Meteor Shower

Saturn is at opposition to the sun on June 27, which means it is fully illuminated by the sun and that the planet is above the horizon from dusk until dawn and crosses the meridian around local midnight.

Mercury is at its greatest eastern elongation on July 12, meaning it will be visible after sunset in the western sky. This is the best time to view the planet.

Mars is at opposition to the sun on July 27, which means it is fully illuminated by the sun and the planet is above the horizon from dusk until dawn. It will appear brighter than at any other time during the year.



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SKY REPORT

June

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system, and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.

The reference point is 100° W and 40° N and the exact time is 10 p.m. EST or 9 p.m. CST.

●	●	●	•	•	·	·
−1	0	1	2	3	4	5

Apparent magnitudes

- ⁘ Open Cluster
- ⁛ Globular Cluster
- ꩜ Galaxy
- ■ Nebula

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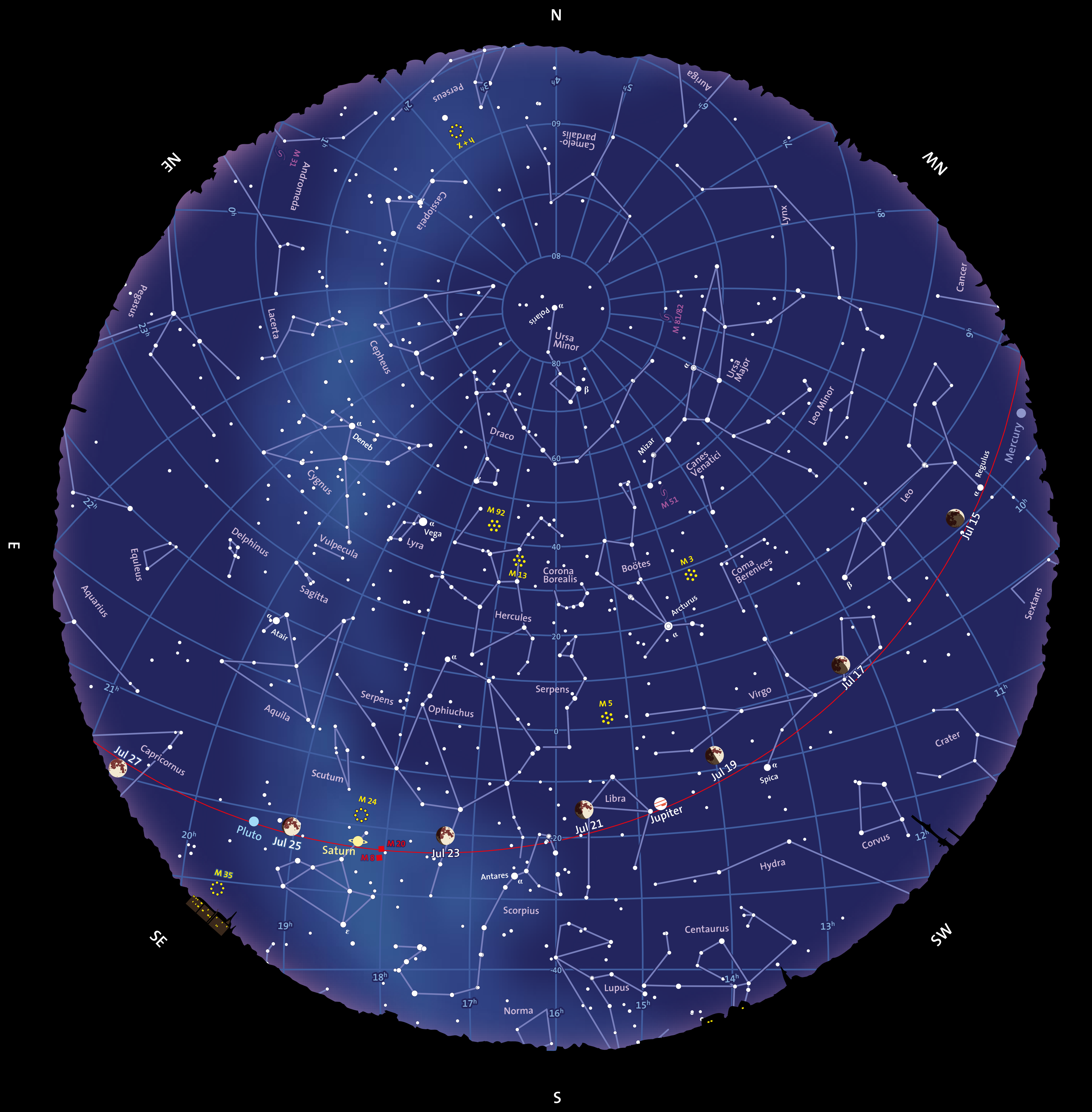
July

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system, and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.



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●	●	•	•	•	·	·
–1	0	1	2	3	4	5

Apparent magnitudes

⁘ Open Cluster
⁘ Globular Cluster
ๆ Galaxy
🟥 Nebula

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