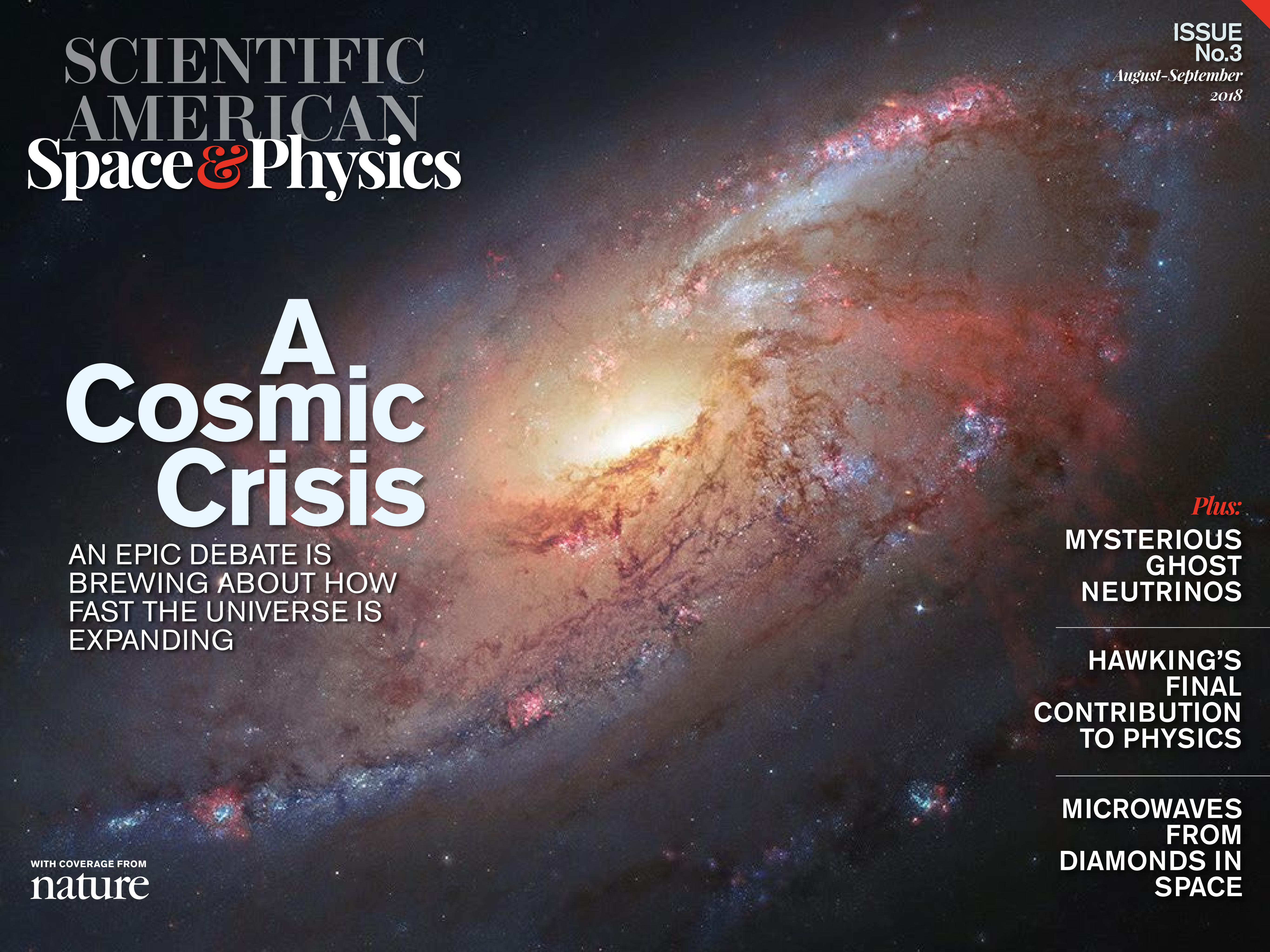

SCIENTIFIC AMERICAN Space & Physics

ISSUE
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2018

A Cosmic Crisis

AN EPIC DEBATE IS BREWING ABOUT HOW FAST THE UNIVERSE IS EXPANDING

Plus:

MYSTERIOUS GHOST NEUTRINOS

HAWKING'S FINAL CONTRIBUTION TO PHYSICS

MICROWAVES FROM DIAMONDS IN SPACE

WITH COVERAGE FROM
nature

FROM THE EDITOR

A Rage to Master the Universe

In March of this year, the world mourned the passing of legendary physicist and cosmologist Stephen Hawking. His vast contributions to the field don't need to be rehashed here, but his work advanced the understanding of the origins of the universe, the nature of black holes and the very makeup of the cosmos. Though severely physically disabled at the end of his life from ALS, Hawking and his collaborators Thomas Hertog and James Hartle were still knee-deep in developing an alternative theory of the universe—that the universe is approximately uniform on the largest scales. Alexander Hellemans sat down with Hertog to discuss this latest work [see "A Conversation with Thomas Hertog: One of Stephen Hawking's Final Collaborators].

What strikes me about Hawking, and the many other researchers in the field, is the relentless drive to keep going, especially in one of the most mysterious, and sometimes, mindboggling areas of inquiry. It's the kind of obsessive "rage to master" that psychologists observe in savant child artists.

Elsewhere in this issue, Lee Billings covers the growing debate among physicists who are trying to reconcile two data sets that tell divergent stories about how fast our universe is expanding [see "Cosmic Conflict"]. The biggest discoveries in physics are still ahead of us, and their pursuers keep raging on.

Andrea Gawrylewski
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SPACE & PHYSICS

Your Opinion Matters!

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On the Cover

A mosaic image of the spiral galaxy M106, created by Robert Gendler who combined archive images from the Hubble Space Telescope archives and his own groundbased images.

ON THE COVER: NASA, ESA AND THE HUBBLE HERITAGE TEAM (STSCI, AURA), AND R. GENDLER, HUBBLE HERITAGE TEAM; THIS PAGE: LIZ TORMES

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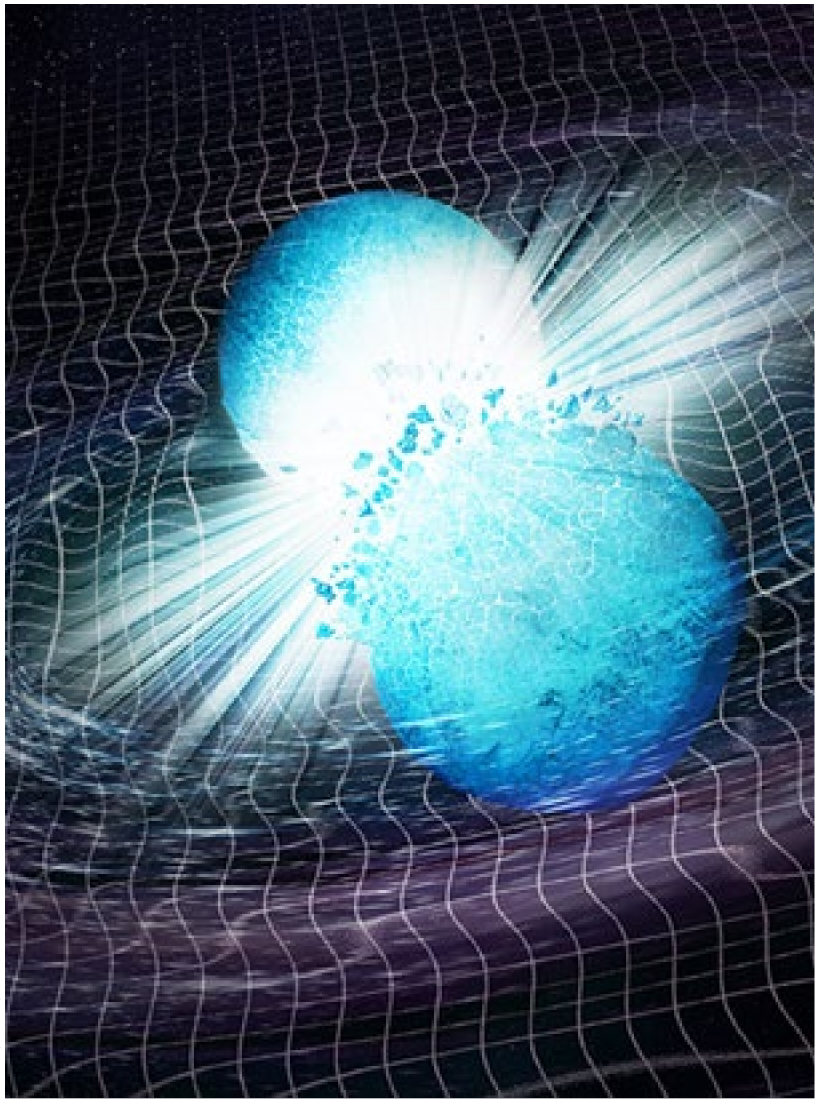

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STEVE BRONSTEIN GETTY IMAGES

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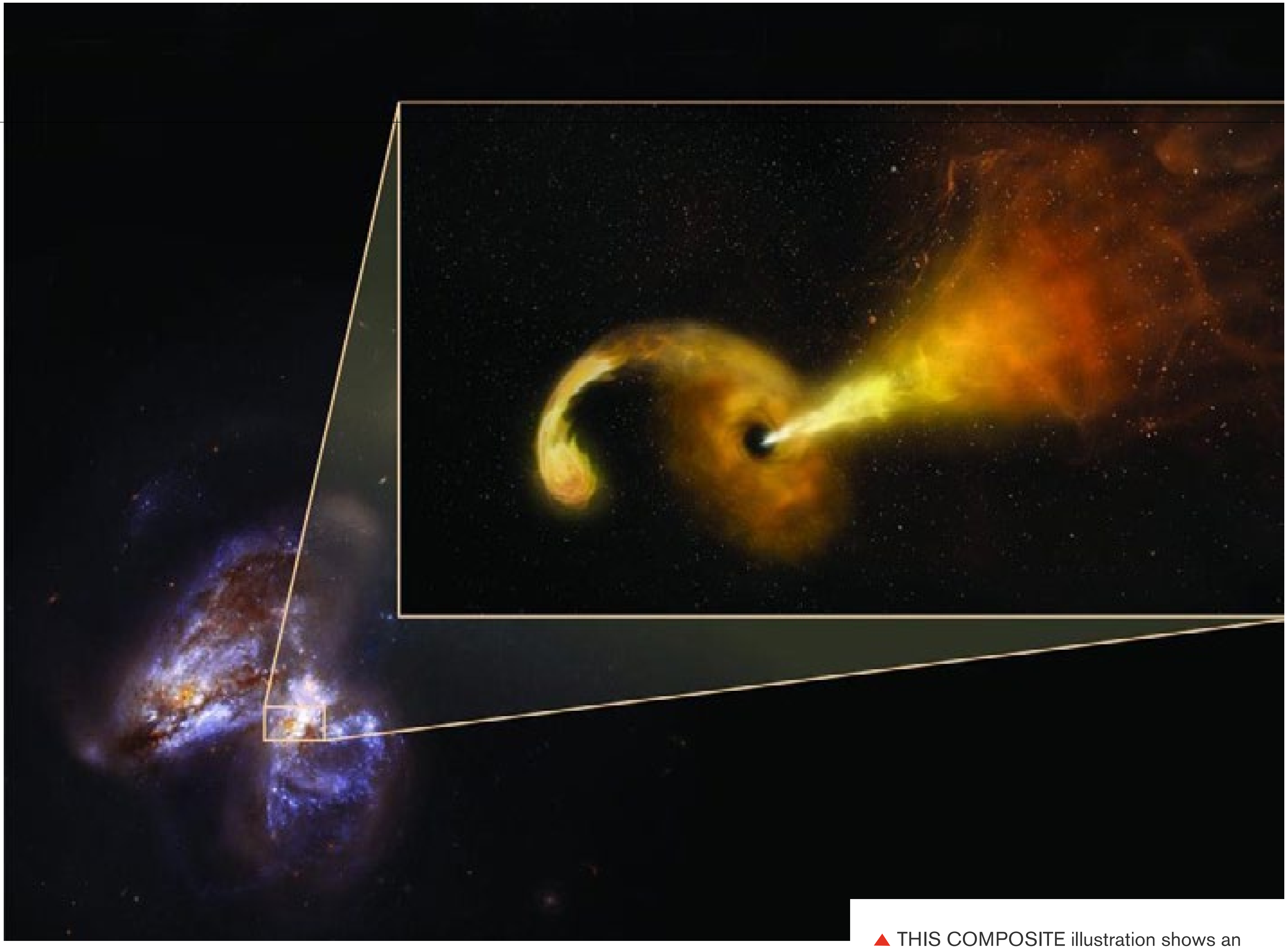
Giant Black Hole Swallows a Star and Belches Out a Superfast Particle Jet

A decade-long international effort to track a star's death by black hole could lift the veil on galaxy formation in the early universe

Marshaling a decade's worth of data from telescopes around the world, scientists have captured new details of a gargantuan black hole feasting on a hapless star, watching as the black hole consumed its prey and burped out a jet of material moving at a significant fraction of the speed of light. The results were published in the June 14 edition of *Science*, and could help researchers better understand how black holes grow and influence their galactic surroundings.

"Never before have we been able to directly observe the formation and evolution of a jet from one of these events," says study co-author Miguel Pérez-Torres of the Institute of Astrophysics of Andalusia in Spain.

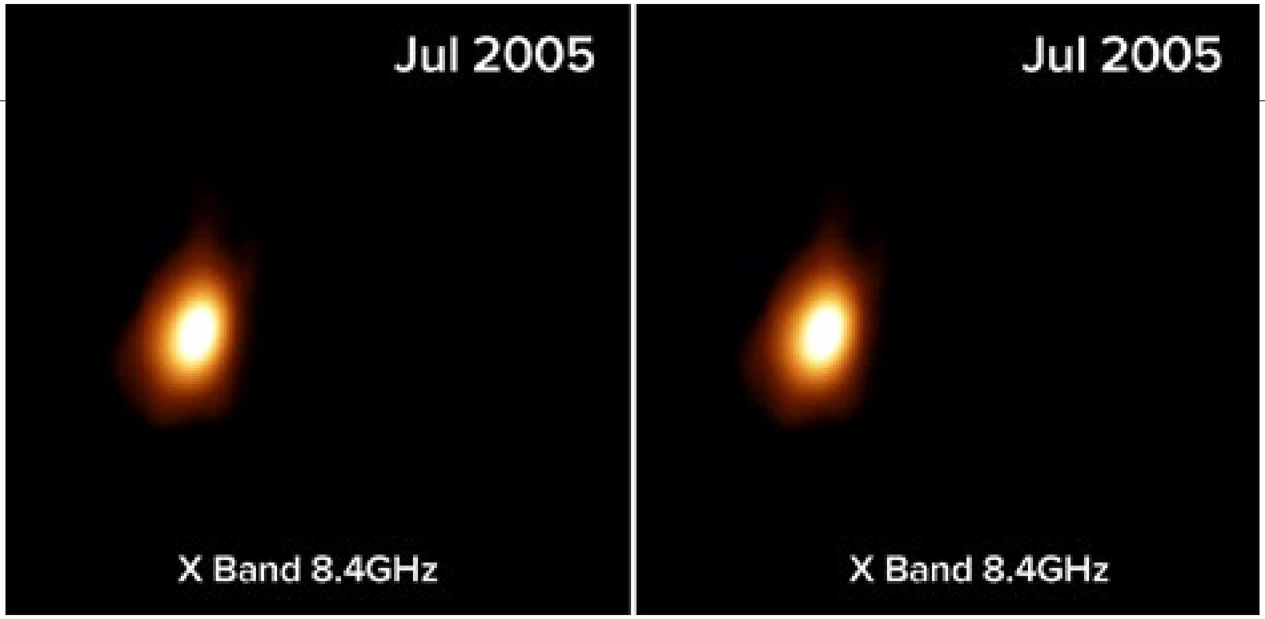
The discovery's first inklings emerged in January 2005, when a team led by astronomer Seppo Mattila of the University of Turku in Finland detected a brilliant pointlike source of infrared light from within Arp 299, a pair of merging galaxies some 150 million light-years from Earth. That July another team led by Pérez-Torres, reanalyzing previously gathered data, confirmed a bright source of radio waves from the same location.



▲ THIS COMPOSITE illustration shows an artist's conception of a a tidal disruption event (TDE), a supermassive black hole devouring a star, superimposed over a Hubble Space Telescope image of a pair of merging galaxies called Arp 299. In a TDE, a black hole's gravity shreds a passing star, pulling material into a spinning disk and launching a jet of particles outward at very high speeds. Astronomers discovered a TDE in Arp 299 produced from a 20-million-solar-mass supermassive black hole feasting on a star more than twice the mass of our Sun.

SOPHIA DAGNELLO, NRAO, AUI, NSF; NASA AND STSCI

Both had been hunting for supernovae in the vicinity of Arp 299's colliding galactic cores, a dust-shrouded region filled with clouds of gas and newborn massive stars generated by the ongoing merger. A supernova was, at first, exactly what they thought they found. These cataclysmic stellar explosions are particularly bright in visible light and in x-rays. In Arp 299's murky center, most of that light would be absorbed by dust and reradiated in the infrared; the remnant would then leak out as radio waves. But follow-up infrared observations with NASA's Spitzer Space Telescope showed the source was far too bright to be a supernova, blazing with light that would outshine a typical small galaxy by several hundred-fold. That suggested the source was not a supernova at all, but rather a tidal disruption event (TDE)—a star being torn apart by a supermassive black hole.



▲ A Dust-Enshrouded Tidal Disruption Event with a Resolved Radio Jet in a Galaxy Merger," by Seppo Mattila et al., in *Science*. Published online June 14, 2018

In a TDE roughly half of the ripped-up star is flung away from the black hole, whereas the other half plunges to its doom, piling up around the hole's maw in a whirling disk of glowing debris that can be mistaken for a supernova. There is no mistaking, however, the other signature of a TDE: twin jets of star stuff ejected from near the black hole at nearly light speed by intense magnetic fields twisting and breaking like rubber bands. Ramming into the diffuse gas of the interstellar medium, the jets would produce copious radio waves potentially visible from Earth. So Mattila, Pérez-Torres and 34 additional collaborators organized an international campaign using a global network of radio telescopes to obtain high-resolution radio images of the source, patiently monitoring its size and shape in search of a jet. In 2011 that patience began to pay off as the point source became lopsided at radio wavelengths, perhaps due to the emission of a jet. By the end of 2015, the point had expanded into a streak; the team clocked its growth at roughly 50,000 miles per second—a quarter of the speed of light. After years of scrutinizing their data and carefully modeling how light and jets from a TDE would propagate through Arp 299's dusty core, the team was left "with one plausible explanation," Mattila says. "The infrared and radio emissions came from the disruption of a hapless star being devoured by the supermassive black hole when it passed too close to this cosmic monster." The TDE, in turn, pinpoints the 20-million-solar-mass supermassive black hole's exact position within Arp 299's core, and also reveals the size of the devoured star, which was between two and six times heavier than our sun.

The most surprising thing about their newfound TDE, Mattila and Pérez-Torres say, is it was discovered at all. Astronomers have detected and studied a handful of other TDEs in recent years, but most of these were found due to their brightness in visible light rather than via infrared and radio emissions. "Tidal disruptions are very rare events, and usually one needs to monitor an extremely large number of galaxies in order to detect them," Pérez-Torres says. Finding one shrouded by dust in the merging galaxies of Arp 299, he adds, hints TDEs may be far more frequent in such places. In colliding galaxies, stars formed from gas funneled toward a central supermassive black hole might spark TDEs with relative regularity. The energy pouring out from those TDEs, in turn, could have profound effects, acting to stimulate or suppress star formation in the merging pair.

Additionally, Mattila notes, systems like Arp 299 were much more common in the distant universe, when the formation and evolution of galaxies were in earlier stages. "The event we have discovered could thus

MATTILA, PÉREZ-TORRES, ET AL.; BILL SAXTON, NRAO, AUI AND NSF

be just the tip of the iceberg of a hidden population of TDEs that were more common when the universe was much younger than today," he says. Future infrared and radio observatories, he adds, could in the next decade allow astronomers to detect many more TDEs that are now "hidden by a curtain of dust," lifting the veil to allow deeper studies of galactic assembly across cosmic time.

—Lee Billings

Quantum Physics May Be Even Spookier Than You Think

A new experiment hints at surprising hidden mechanics of quantum superpositions

It is the central question in quantum mechanics, and no one knows the answer: what really happens in a superposition—the peculiar circumstance in which particles seem to be in two or more places or states at once? In May, a team of researchers in Israel and Japan proposed an experiment that could finally let us say something for sure about the nature of this puzzling phenomenon.

Their experiment, which the researchers say could be carried out within a few months, should enable scientists to sneak a glance at where an object—in this case a particle of light, called a photon—actually resides when it is placed in a superposition. And the researchers predict the answer will be even stranger and more shocking than "two places at once."

The classic example of a superposition involves firing photons at two parallel slits in a barrier. One fundamental aspect of quantum mechanics is that tiny particles can behave like waves, so that those passing through one slit "interfere" with those going through the other, their wavy ripples either boosting or canceling one another to create a characteristic pattern on a detector screen. The odd thing, though, is this interference occurs even if only one particle is fired at a time. The particle seems somehow to pass through both slits at once, interfering with itself. That's a superposition.

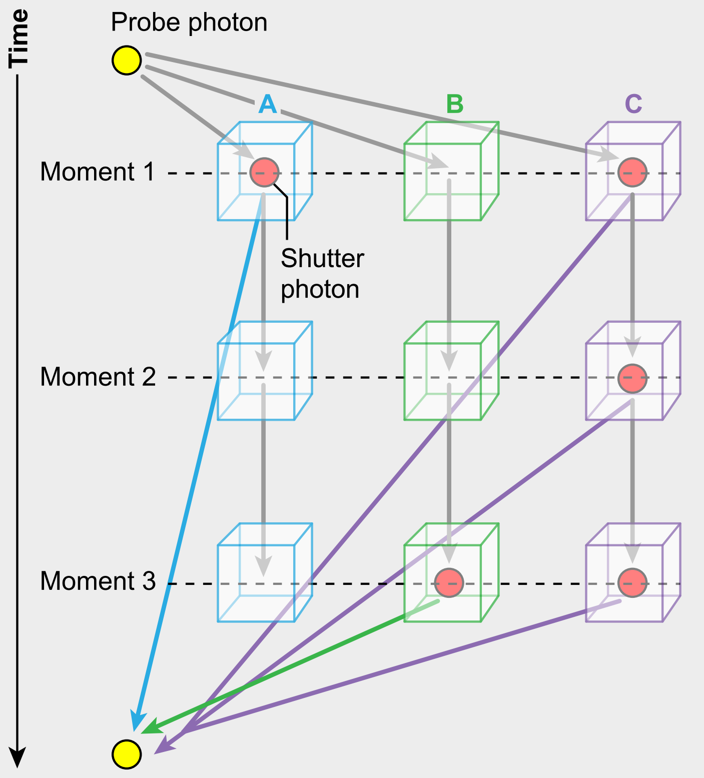
Superposition—the notion that tiny objects can exist in multiple places or states simultaneously—is a cornerstone of quantum physics. A new experiment seeks to shed light on this mysterious phenomenon.

TAI GINDA GETTY IMAGES

It gets weirder: measuring which slit such a particle goes through will invariably indicate it only goes through one—but then the wavelike interference (the "quantumness," if you will) vanishes. The very act of measurement seems to "collapse" the superposition. "We know something fishy is going on in a superposition," says physicist Avshalom Elitzur of the Israeli Institute for Advanced Research. "But you're not allowed to measure it. This is what makes quantum mechanics so diabolical."

For decades researchers have stalled at this apparent impasse. They cannot say exactly what a superposition is without looking at it; but if they try to look at it, it disappears. One potential solution—developed by Elitzur's former mentor, Israeli physicist Yakir Aharonov, now at Chapman University, and his collaborators—suggests a way to deduce something about quantum particles *before* measuring them. Aharonov's approach is called the two-state-vector formalism (TSVF) of quantum mechanics, and it postulates that quantum events are in some sense determined by quantum states not just in the past, but also in the future. That is, the TSVF assumes quantum mechanics works the same way both forward and backward in time. From this perspective, causes can seem to propagate backward in time, occurring after their effects.

The Jumpy Shutter



A probe photon (*yellow, left*) is sent in a superposition through the three boxes, A, B and C, simultaneously to see if the shutter photon (*red*) is inside them. If it is, the probe photon is reflected: This lets the probe "report" on where the shutter photon is without looking at it directly. The shutter photon is placed in a superposition that makes its location within the boxes vary through time: At t_1 (moment 1) it is in A and C but not B; at t_2 it is only in C (and definitely not in A or B); and at t_3 it is in B and C but not A. The result: Although in C in all times, the shutter photon seems to be first in A but not B, then to vanish from A, then to reappear in B. So this superposition is not "in all places at once" but rather in some places some of the time.

AMANDA MONTAÑEZ

One needn't take this strange notion literally. Rather, in the TSVF one can gain retrospective knowledge of what happened in a quantum system by selecting the outcome: instead of simply measuring where a particle ends up, a researcher chooses a particular location in which to look for it. This is called post-selection, and it supplies more information than any unconditional peek at outcomes ever could. This is because the particle's state at any instant is being evaluated retrospectively in light of its entire history, up to and including measurement. The oddness comes in because it looks as if the researcher, simply by choosing to look for a particular outcome, causes that outcome to happen. But this is a bit like concluding that if you turn on your television when your favorite program is scheduled, your action causes that program to be broadcast at that very moment. "It's generally accepted that the TSVF is mathematically equivalent to standard quantum mechanics," says David Wallace, a philosopher of science at the University of Southern California who specializes in interpretations of quantum mechanics. "But it does lead to seeing certain things one wouldn't otherwise have seen."

Take, for instance, a version of the double-slit experiment devised by Aharonov and co-worker Lev Vaidman in 2003, which they interpreted with the TSVF. The pair described (but did not build) an optical system in which a single photon acts as a "shutter" that closes a slit by causing another "probe" photon approaching the slit to be reflected back the way it came. By applying post-selection to the measurements of the probe photon, Aharonov and Vaidman showed, one could discern a shutter photon in a superposition closing both (or indeed arbitrarily many) slits simultaneously. In other words, this thought experiment would in theory allow one to say with confidence the shutter photon is both "here" and "there" at once. Although this situation seems paradoxical from our everyday experience, it is one well-studied aspect of the so-called nonlocal properties of quantum particles, where the whole notion of a well-defined location in space dissolves.

In 2016 physicists Ryo Okamoto and Shigeki Takeuchi of Kyoto University verified Aharonov and Vaidman's predictions experimentally using a light-carrying circuit in which the shutter photon is created using a quantum router, a device that lets one photon control the route taken by another. "This was a pioneering experiment that allowed one to infer the simultaneous position of a particle in two places," says Elitzur's colleague Eliahu Cohen of the University of Ottawa in Ontario.

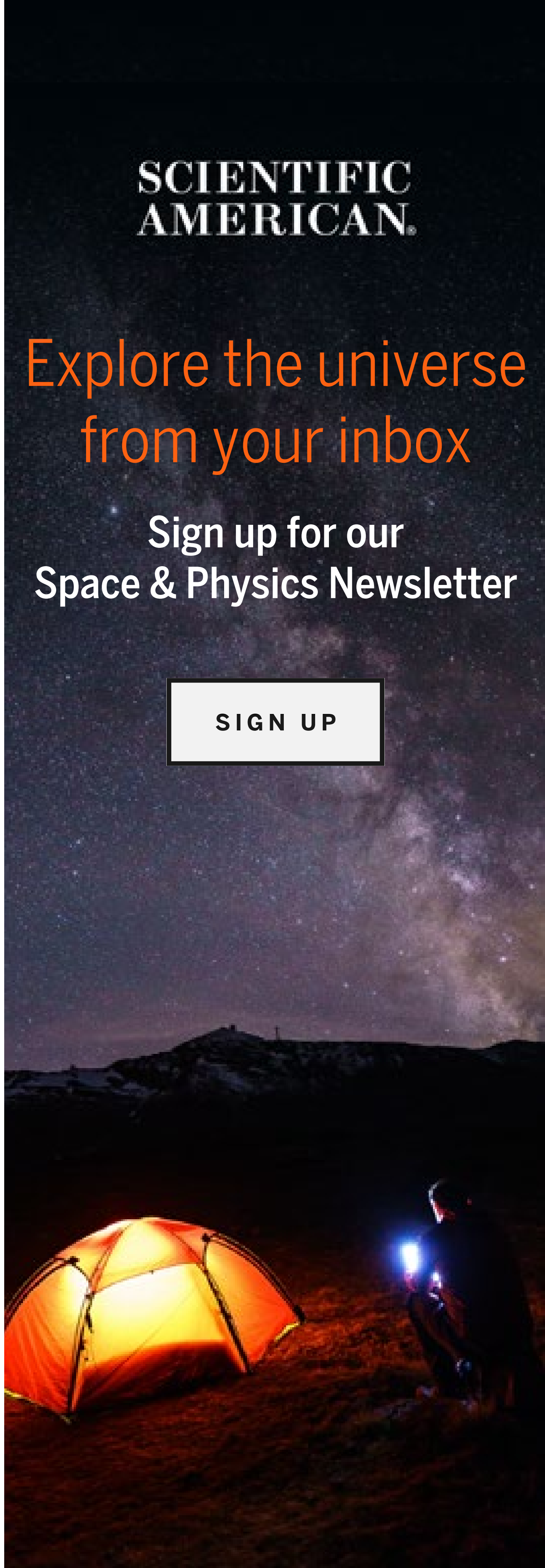
Now Elitzur and Cohen have teamed up with Okamoto and Takeuchi to concoct an even more mind-boggling experiment. They believe it will enable researchers to say with certainty something about the location of a particle in a superposition at a series of different points in time—before any actual measurement has been made.

This time the probe photon's route would be split into three by partial mirrors. Along each of those paths it may interact with a shutter photon in a superposition. These interactions can be considered to take place within boxes labeled A, B and C, one of which is situated along each of the photon's three possible routes. By looking at the self-interference of the probe photon, one can retrospectively conclude with certainty the shutter particle was in a given box at a specific time.

The experiment is designed so the probe photon can only show interference if it interacted with the shutter photon in a particular sequence of places and times: Namely, if the shutter photon was in both boxes A and C at some time (t1), then at a later time (t2) only in C, and at a still later time (t3) in both B and C. So interference in the probe photon would be a definitive sign the shutter photon made this bizarre, logic-defying sequence of disjointed appearances among the boxes at different times—an idea Elitzur, Cohen and Aharonov proposed as a possibility last year for a single particle spread across three boxes. "I like the way this paper frames questions about what is happening in terms of entire histories rather than instantaneous states," says physicist Ken Wharton of San Jose State University, who is not involved in the new project. "Talking about 'states' is an old pervasive bias whereas full histories are generally far more rich and interesting."

That richness, Elitzur and colleagues argue, is what the TSVF gives access to. The apparent vanishing of particles in one place at one time—and their reappearance in other times and places—suggests a new and extraordinary vision of the underlying processes involved in the nonlocal existence of quantum particles. Through the lens of the TSVF, Elitzur says, this flickering, ever-changing existence can be understood as a series of events in which a particle's presence in one place is somehow canceled by its own "counterparticle" in the same location. He compares this with the notion introduced by British physicist Paul Dirac in the 1920s, who argued that particles possess antiparticles, and if brought together, a particle and antiparticle can annihilate each other. This picture at first seemed just a manner of speaking but soon led to the discovery of antimatter. The disappearance of quantum particles is not annihilation in this same sense, but it is somewhat analogous: these putative counterparticles, Elitzur posits, should possess negative energy and negative mass, allowing them to cancel their counterparts.

So although the traditional "two places at once" view of superposition might seem odd enough, "it's possible a superposition is a collection of states that are even crazier," Elitzur says. "Quantum mechanics just tells you about their average." Post-selection then allows one to isolate and inspect just some of those states at greater resolution, he suggests. Such an interpretation of quantum behavior would be, he says, "revolutionary" because it would entail a hitherto unguessed menagerie of real—but very odd—states underlying counterintuitive



quantum phenomena.

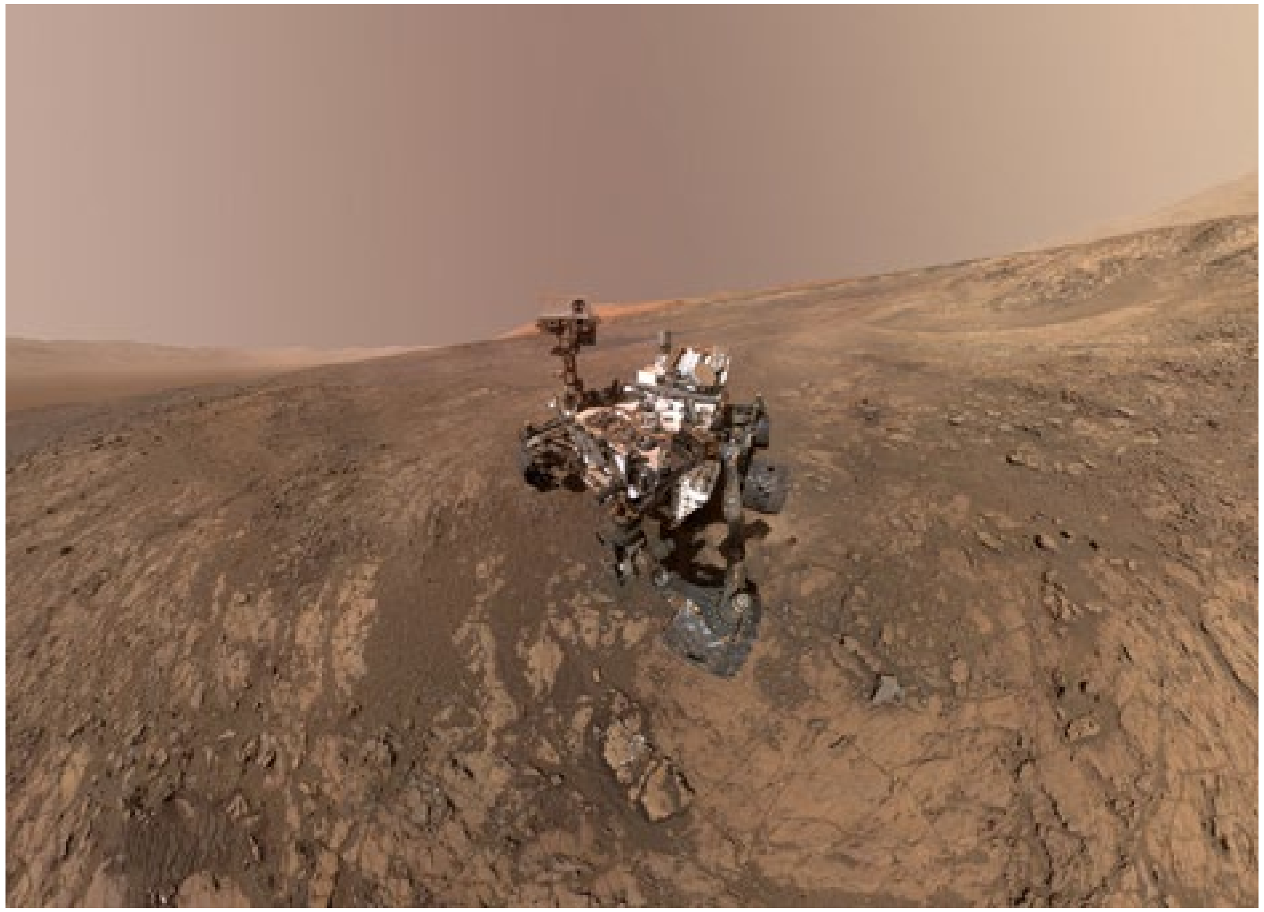
The researchers say conducting the actual experiment will require fine-tuning the performance of their quantum routers, but they hope to have their system ready to roll in three to five months. For now some outside observers are not exactly waiting with bated breath. “The experiment is bound to work,” says Wharton—but he adds it “won’t convince anyone of anything, since the results are predicted by standard quantum mechanics.” In other words, there would be no compelling reason to interpret the outcome in terms of the TSV F rather than one of the many other ways that researchers interpret quantum behavior.

Elitzur agrees their experiment could have been conceived using the conventional view of quantum mechanics that prevailed decades ago—but it never was. “Isn’t that a good indication of the soundness of the TSVF?” he asks. And if someone thinks they can formulate a different picture of what is really going on in this experiment using standard quantum mechanics, he adds, “well, let them go ahead!”

–Philip Ball

Curiosity Rover Uncovers Long-Sought Organic Materials on Martian Surface

After decades of searching, scientists are at last closing in on the sources of carbon-rich material in the Red Planet’s air and soil



▲ Gale Crater’s rim looms on the horizon in this self-portrait snapped on Mars by NASA’s Curiosity rover in January 2018.

NASA, JPL-CALTECH AND MSSS

Nearly six years into its survey of a site called Gale Crater on Mars, NASA’s Curiosity rover has delivered what may be the biggest discovery yet in its quest for signs of habitability and life: Organic molecules are abundant in Red Planet rocks, and the simplest organic molecule, methane, seasonally blows through the thin Martian air. On Earth, such carbon-rich compounds are one of life’s cornerstones.

Both discoveries emerged from Curiosity’s Sample Analysis at Mars (SAM) instrument, a miniaturized chemistry lab and oven that roasts dollops of air, rock and soil to sniff out each sample’s constituent molecules. Samples of ancient mudstone yielded a diversity of organic molecules in SAM’s oven—and in a separate study, five years’ worth of atmospheric samples gathered by SAM tracked fluctuating levels of methane that peaked in the Martian summer. The results are reported in a pair of papers published in June in *Science*.

Although tantalizing, the two findings remain far from definitive when it comes to past or present life on Mars. Methane is ubiquitous in places like the atmospheres of gas-giant planets. It can also arise from lifeless interactions between flowing water and hot rocks, whereas other simple organic molecules are known to exist in some meteorites and interstellar gas clouds. “Short of taking a picture of a fossil in a rock on Mars, [finding life there] is extremely difficult to do scientifically,” says Chris Webster, a chemist at NASA’s Jet Propulsion Laboratory and lead author of the methane study.

MARS'S MISSING CARBON

That Mars possesses organic molecules is not surprising. Like every planet in our solar system, it receives a steady rain of carbon-rich micrometeorites and dust from space. Yet when NASA's twin Viking probes landed on Mars in 1976, their studies suggested something startling: Martian soil, it seemed, contained less carbon than lifeless lunar rocks. "It was a big surprise," says Caroline Freissinet, an astrobiologist and co-author on Curiosity's mudstone study at the Atmosphere, Media, Spatial Observations Laboratory (LATMOS) in France. "It slowed down the whole Mars program, unfortunately."

Ever since, scientists have ardently hunted for Mars's missing carbon—or at least an explanation for its absence. A crucial clue came in 2008, when NASA's Phoenix lander found perchlorate salts—highly reactive molecules containing chlorine—in soil samples near the Martian north pole. Combined with high-energy ultraviolet light and cosmic rays streaming in from space, perchlorates would destroy any organic material on the surface, leaving little to be seen by carbon-seeking landers and rovers. Perhaps, some researchers speculated, Mars's remaining organics—and thus any signs of past or present life—were locked away in its subsurface depths.

In 2015, however, Curiosity made the first tentative detection of organic molecules on Mars, finding evidence of chlorine-contaminated carbon compounds in soil samples heated to more than 800 degrees Celsius in SAM. But early into the rover's mission, researchers discovered that carbon-rich chemical reagents were leaking out of some of SAM's components, potentially contaminating nearby samples. To combat the contamination, the Curiosity team focused on finding more chlorine-containing organics, and limited subsequent SAM runs to temperatures between 200 and 400 degrees C.

In their new work the team checked to see what this restrictive process might have missed. After carefully accounting for background contamination from SAM, Freissinet and her colleagues baked 3-billion-year-old mudstone samples at over 500 degrees C, a temperature at which perchlorates should have fully burned away. In the ashes that remained they found thiophenes—relatively small and simple ringlike molecules containing both carbon and sulfur. The latter element, it is thought, came from a sulfur-rich mineral called jarosite that previous Curiosity investigations had revealed in 3.5-billion-year-old deposits in Gale Crater—laid down at a time when the crater was warm, wet and apparently habitable. The researchers suspect the thiophenes' carbon came from as-yet-unidentified larger organic molecules, which had been trapped and preserved inside the jarosite for perhaps billions of years.

Despite this latest discovery's patchwork nature, George Cody, a geochemist at the Carnegie Institution for Science who was not involved in the work, considers it an impressive step forward. The presence of these larger molecules, he says, hints at well-preserved reservoirs of carbon hidden at and just below the Martian surface—a prospect that bolsters the case for future missions to collect samples and return them to Earth. "If you can do this on Mars, imagine what you can do with analytical facilities available to us on Earth," he says.

METHANE SPIKES AND CHANGING SEASONS

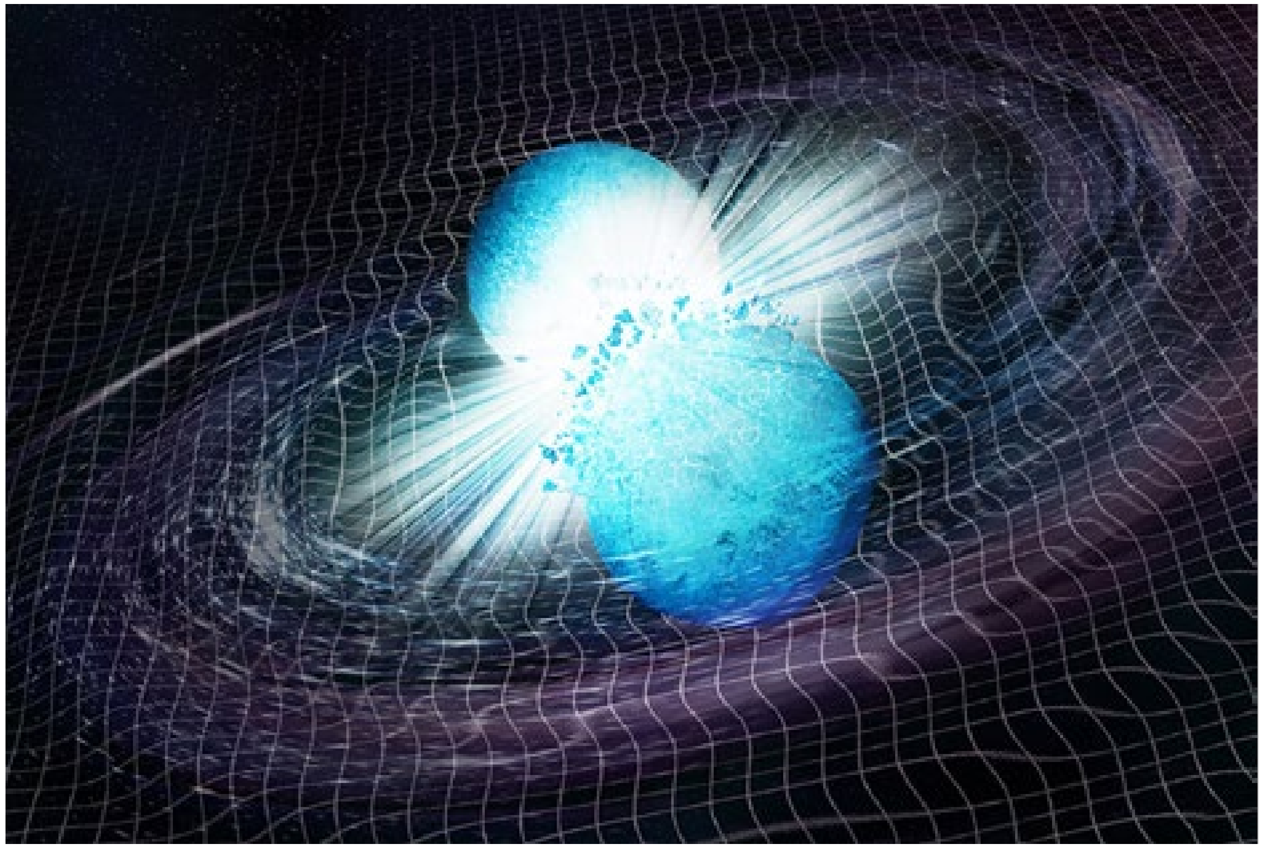
In the meantime Curiosity has undertaken what Webster calls "the most important measurements of Mars methane made to date." The carbon-containing gas is significant because most methane on Earth is produced by methanogen microbes, which are common in oxygen-poor environments. Methane is also quickly broken down by ultraviolet radiation, so any of the gas discovered on Mars was probably released recently. Using SAM, Webster and his colleagues have found a persistent background level of methane in the atmosphere above Gale Crater over the last five years of about 0.4 part per billion—a scarcely detectable trace, to be sure, but enough to pique astrobiologists' interest. Tellingly, the methane levels appear to periodically spike in time with Martian seasons, being about three times higher in the sunny summertime than in the darker, colder winter.

This periodicity is, to Webster, the most exciting part of his team's results. Previous research had seen evidence for sporadic methane plumes on Mars, but never seasonally recurring events. "It's like having a problem with your car," he says. "If it doesn't repeat, you can't find out what it is." The methane, he and his colleagues speculate, could come from aquifers melting during the Martian summer, releasing water that flows over rocks deep underground to produce fresh gas. Or it could be ancient, belched out billions of years ago by geologic or biological processes and then trapped in matrices of ice and rock that unfreeze when warmed by the sun. And, of course, there is always the chance that Martian methanogens still slumber in the planet's subsurface even today, periodically awakening during clement periods to produce their gaseous calling card.

Other scientists who did not take part in the research had mixed reviews on findings' significance in the search for life. Michael Mumma, an astrobiologist at NASA Goddard Space Flight Center, considers the measurements important and says they provide ground-truth evidence for his independent (and controversial) detections of Martian methane plumes using Earth-based telescopes. But Marc Fries, a planetary scientist who curates the cosmic dust collection at NASA Johnson Space Center, takes a more skeptical view. He points out that carbon-rich meteorites and dust could generate the reported amounts of methane as they fell into the Martian atmosphere and that the year-to-year periodicity is not wholly consistent with the timing of the Martian seasons. "A rigorous approach based on available evidence starts with the scientifically responsible default explanation that Mars is and always has been lifeless," Fries says. "Testing a hypothesis to the contrary requires a very strong body of evidence." Such tests could come soon, via data from the joint European and Russian ExoMars Trace Gas Orbiter. It arrived at Mars in 2016 and is now mapping concentrations of methane and other gases from on high.

For his part Webster says he has no preference among the different explanations, and believes it will take a long time before any final conclusions can be drawn. Such incremental progress is the whole point of NASA's Mars exploration program, Freissinet notes. "It's step by step," she says. "Mission after mission."

—Adam Mann



NASA, CXC, TRINITY UNIVERSITY AND D. POOLEY ET AL. ILLUSTRATION: NASA, CXC AND M. WEISS

▲ This illustration captures the moment two neutron stars spiral together and collide. Astrophysicists have used gravitational waves produced from such mergers to probe the interiors of neutron stars and to set new limits on the formation of black holes.

Gravitational Waves Reveal the Hearts of Neutron Stars

Scientists are mapping the extreme interiors of exotic stars with unprecedented clarity, and setting new boundaries on the births of black holes

Inside a neutron star—the city-size, hyperdense cinder left after a supernova—modern physics plunges off the edge of the map. There, gravity squeezes matter to densities several times greater than those found in the nucleus of an atom, creating what theorists suspect could be a breeding ground for never-before-seen exotic particles and interactions. But densities this high cannot be probed by laboratory experiments, and remain too challenging for even today's most powerful computers to tackle.

So when the universe deigned to

help out, astronomers jumped at the chance. In August 2017 the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), along with a European detector named VIRGO, picked up gravitational waves reverberating through spacetime from the merger of two neutron stars some 130 million light-years from Earth. Those waves, reanalyzed in May 2018 by the LIGO-VIRGO team, provide some of the best hints yet about the nature of the merger's progenitors—and what neutron star stuff actually is.

As the two stars circled toward mutual doom, shedding orbital energy into gravitational waves, they also began raising tides on each other's surfaces. Those tidal interactions sucked away even more orbital energy, tightening the neutron stars' orbit and hastening their collision. The strength of those tides, baked into the gravitational waves detected by LIGO-VIRGO, depended on each neutron star's internal structure, which physicists model using an "equation of state." For a neutron star an equation of state mathematically describes how the star's innards react to changes in density, pressure and temperature.

The new study follows up on an initial calculation released last October by the same team, which had failed to detect these tides in the gravitational wave signal at all. "Our first analyses were fairly 'eyes wide open'—we made few assumptions," says Jocelyn Read at California State University, Fullerton, who leads LIGO's "extreme matter" team.

On the second go-round, though, the team looked at more orbits of the two objects and added in some additional constraints. Namely, they assigned both objects identical equations of state—a reasonable assumption, given that all available data about the merger make it all but certain that the collision's source was a pair of neutron stars.

Next, they tested possible equations of state that could explain the data, adding other sensible, real-world requirements. For instance, pressure and density changes could not create sound waves moving faster than the speed of light inside a neutron star (or any other object, for that matter). And the equation of state had to also fit the heaviest confirmed neutron star, which weighs in at roughly 1.97 solar masses. If neutron star material could not sustain sufficiently high pressures, such an object would not be a neutron star at all—it would have long ago collapsed into a black hole.

Taking all that into account, the new analysis finds the two neutron stars involved in the merger, each weighing perhaps 1.4 solar masses, were rather small for that weight: about 12 kilometers in radius. That would match previous controversial x-ray measurements of neutron star radii. And it hints that midsize neutron stars possess relatively low interior pressures compared with the 1.97–solar mass heavyweight, which must have higher pressures to provide a stiff backbone against such crushing gravity.

Compared with lab measurements of matter at much lower densities, the new data show tentative hints of an upward bend in how pressure increases in denser and denser matter. Such a bend would not be expected if neutron stars are made solely of neutrons and protons—in that case, pressure should just increase smoothly. "There could be some interesting structure in the equation of state emerging," Read says, adding the caveat that the data are also still consistent with a steady growth of pressure, corresponding to a "boring" neutron star made of only protons and neutrons. If physicists can confirm a bend like this in the equation of state, though, it might be a clue matter changes phase at very high densities, much like water changing from liquid to solid at sufficiently low temperatures. In neutron stars such a phase transition could arise from neutrons breaking apart into a soup of their constituent particles, quarks.

The new study echoes the findings of a previous analysis of the same event published in April by a team led by graduate student Soumi De at Syracuse University, but with twice the precision. "That's encouraging, that this one event is not yet fully exploited," says James Lattimer, an astrophysicist at Stony Brook University and a co-author on the earlier paper.

Both Lattimer and Read's teams plan to keep reanalyzing last August's signal. "We haven't wrung everything we can out of this," Read says. Soon, signals of additional neutron star mergers are likely to emerge from gravitational-wave detectors, providing even more data for astrophysicists hoping to pin down these exotic objects' equation of state.

In the meantime there's another helpful result, published in *The Astrophysical Journal Letters* in May. In the aftermath of the 2017 neutron star merger, other astronomers scoured its wreckage with the Chandra X-Ray Observatory, hoping to glimpse its ultimate outcome: a single, heavier neutron star or a black hole.

A single giant neutron star weighing roughly 2.7 solar masses would have far outweighed the previous record holder, forcing the neutron star equation of state to accommodate an even tougher constraint. But it was not to be; the Chandra data revealed relatively few x-rays streaming from the merger's wreckage, an observation consistent with the formation of a black hole. According to Lattimer, that's interesting as its own limit—astronomers now know neutron star matter cannot possibly support so much weight. "I don't think I thought imaginatively enough about all the things that mergers are going to be able to tell us," he says.

— *Joshua Sokol*

Glittering Diamond Dust in Space Might Solve a 20-Year-Old Mystery

The Milky Way is strewn with sparkling, spinning microscopic diamonds, which might explain an unusual microwave glow


GETTY IMAGES

When astronomers first peered at the cosmos in microwave light, they knew they had stumbled on a window into the universe's earliest moments. After all, the cosmic microwave background—that hazy afterglow of the big bang released when the universe was a mere 380,000 years old—has allowed scientists to answer fundamental questions about where we came from. But microwave light has also raised an intriguing mystery closer to home. In 1996 astronomers noticed an inexplicable excess of microwaves emanating from our own galaxy. For over 20 years, this so-called anomalous microwave emission remained an enigma—until this year. A study

published in June in *Nature Astronomy* suggests spinning nanodiamonds might be the culprit.

Ten years ago, while studying nascent planetary systems forming in whirling disks of gas and dust around young stars, Cardiff University astronomer Jane Greaves noticed a few of those systems seemed to be faintly glowing with microwaves. She initially attributed the glow to flaws in her data but later reconsidered after hearing a colleague's talk about anomalous microwave emission. Returning to the telescope, she and her collaborators monitored 14 young star systems for mysterious microwave emissions, finally finding three radiating that telltale glow. Those same three systems, it turns out, are also the only three within Greaves's sample known to host nanodiamonds—pint-size, pyramid-shaped crystals containing only hundreds of carbon atoms, all sheened with an atoms-thin gloss of frozen hydrogen likely accumulated from the interstellar medium. "This really is a clue of nature telling us nanodiamonds are what is responsible" for the anomalous microwaves, she says.

But how can objects so tiny emit microwaves so mighty that they can be glimpsed across hundreds of thousands of light-years? The trick is that our galaxy is a turbulent place, in which tides and winds raised by the motions and activities of stars make any small object—be it a puny dust grain, a hefty molecule or even a wee diamond—jiggle and spin as it is jostled by other particles bumping into it. Should that object possess an asymmetrical electric charge (where one side has slightly more charge than the other), its spin could emit electromagnetic radiation in the form of microwaves. Disks around newborn stars host particularly speedy particles, further amplifying this effect.

Initially, astronomers suspected the minuscule objects responsible for the glow were organic molecules called polycyclic aromatic hydrocarbons (PAHs)—essentially the cosmic equivalent of soot, albeit produced by aging stars rather than smokestacks. Bruce Draine, an astronomer at Princeton University who was not involved in the study, had been a proponent of PAHs as the leading candidates for the microwave anomaly, but he knew that explanation lacked proof. He and his colleagues set out to find it, comparing distribution maps of PAHs and the anomalous microwaves throughout the Milky Way. An overlap between the high-density and low-density regions on both maps would have been smoking-gun evidence that PAHs were the culprit. "To our surprise, no such connection was seen," Draine says. His 2016 study declared PAHs innocent, and the emission became a mystery once again—at least, that is, until Greaves and her colleagues reported their new findings. Draine finds the nanodiamond hypothesis appealing, but notes that the correlation between the three stars' microwave glows and nanodiamonds in their disks might be mere coincidence.

Although Greaves and her colleagues calculated the odds of a chance association at just 0.01 percent, that calculation assumes all the stars were observed on equal footing, without any possible bias. But Aigen Li, an astronomer at the University of Missouri– Columbia who did not take part in the work, worries a bias may in fact exist because exist due to the fact not all stars are the same temperature. Nanodiamonds are usually visible to earthbound astronomers only when they circle extremely hot stars, he says, which means there could easily be other nanodiamond–hosting stars within Greaves's sample that fail to emit anomalous microwaves. Clive Dickinson, an astronomer at the University of Manchester in England, also not involved in the work, expresses similar concerns. He argues hot stars tend to ionize the gas around them to create plasma—clouds of charged particles that can also emit microwave radiation as they whiz through their orbits around the star. Without very careful modeling of this effect, it could lead to a case of mistaken identity and be associated with anomalous microwave emission. "Assuming that has been done correctly, then this is quite exciting—it's quite a cool result," Dickinson says.

To bolster their nanodiamon hypothesis, Greaves and her team next will try to observe both the anomalous microwave emission and nanodiamonds in colder, less suspect environments, such as the frigid clouds of interstellar gas and dust that dot our galaxy.

If ultimately validated as the true source of anomalous microwaves, maps of nanodiamonds throughout the Milky Way will become crucial for scientists hoping to scrub out its contaminating effects to perform deeper, more precise studies of the cosmic microwave background, revealing untold secrets of the universe's genesis. In some sense, says co-author Anna Scaife, an astronomer at Manchester, the microwave anomaly's vital importance for such studies makes astronomers' past disregard of nanodiamonds as its source all the more surprising. "A lot of the time in astrophysics we're narrowing down the details of things where we already understand the big picture, whereas this is a completely new association," she says. "This really is a step-change in our thinking, rather than just an incremental advance."

–Shannon Hall

A disagreement between two canonical measures of intergalactic distances could signal a renaissance in physics—or deep flaws in our studies of cosmic evolution

By Lee Billings

Cosmic Conflict: Diverging Data on Universe’s Expansion Polarizes Scientists

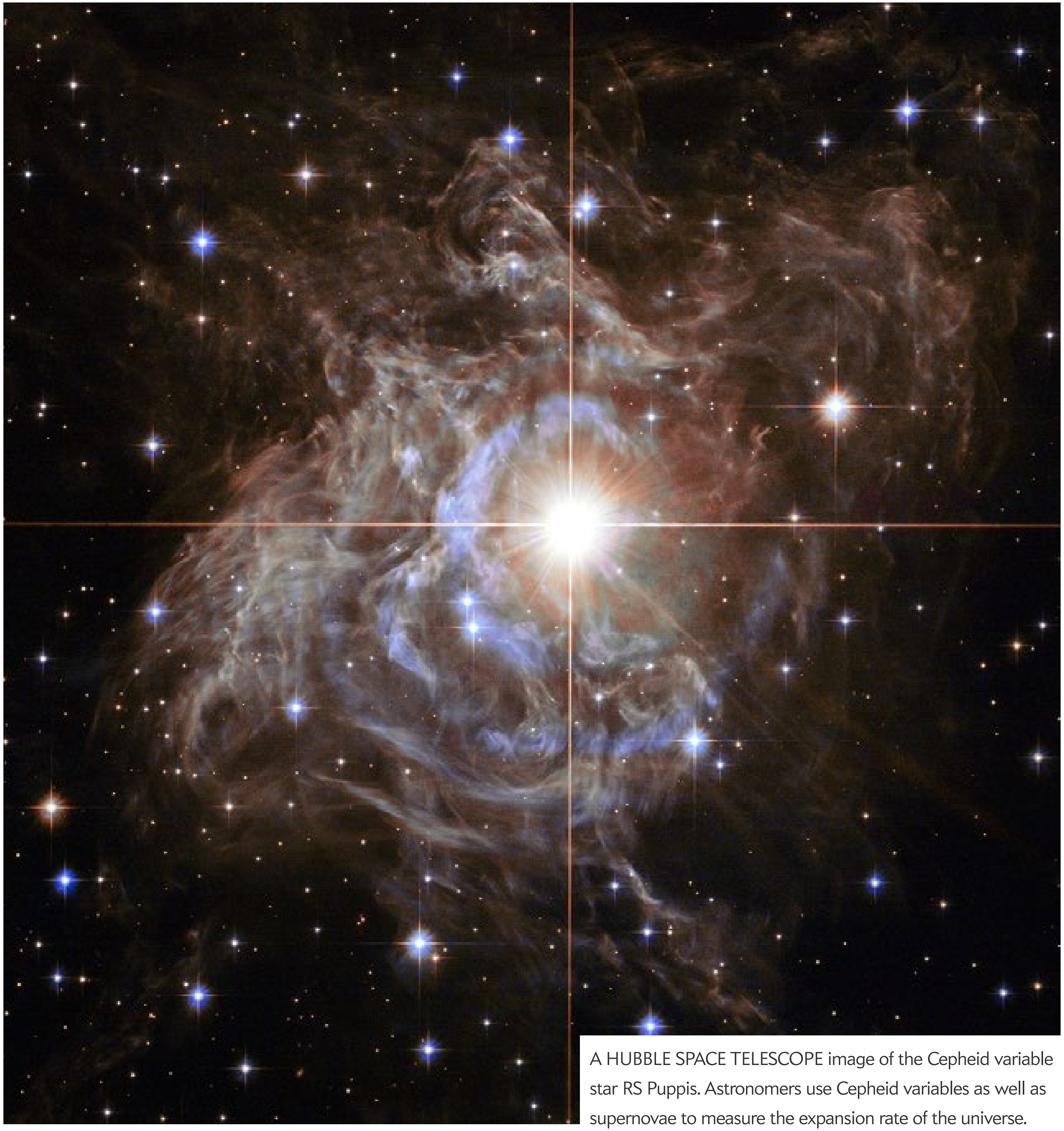
Lee Billings is an associate editor for *Scientific American*. He covers space and physics.

The spiral galaxy NGC 4258, as seen by the Hubble Space Telescope. Studies of this galaxy and many others suggest the universe is expanding fasater than expected based on standard cosmological models.

NASA, ESA AND THE HUBBLE HERITAGE TEAM (STSCI, AURA), AND R. GENDLER, HUBBLE HERITAGE TEAM

What began as a debate over astronomical measurements is on the verge of becoming a full-blown crisis in how we understand the cosmos. Two data sets—one from the newborn universe nearly 14 billion years ago, the other from stars as we see them today—are yielding contradictory answers to a deceptively simple question: How fast is the universe expanding?

The gap between answers is only 9 percent, but that far exceeds each data set's estimated uncertainties. Researchers on each side of the gap call it "the tension," and are digging in their heels about the validity of their observations. This tension is the stuff of scientific dreams—and nightmares. It hints that somewhere, somehow, our understanding of the laws of nature may be fundamentally flawed—with potentially profound implications for physics, and perhaps even the fate of all things.



A HUBBLE SPACE TELESCOPE image of the Cepheid variable star RS Puppis. Astronomers use Cepheid variables as well as supernovae to measure the expansion rate of the universe.

NASA, ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA) HUBBLE - EUROPE COLLABORATION

"If the tension isn't a fluke and it's not an error in measurement, it implies we're missing something in our models," says Adam Riess, an astrophysicist at Johns Hopkins University and the Space Telescope Science Institute. "Making this measurement for the early universe and then comparing it to today's is an end-to-end test of the whole story we've constructed about the universe. The trouble is, if something definitely doesn't fit, we don't know where exactly the story diverges."

The answer to the question of the universe's expansion rate is something called the Hubble constant, named after the astronomer Edwin Hubble, who discovered in the 1920s that the universe is expanding. Galaxies recede from us at speeds proportional to their distances, going faster the farther away they are. The Hubble constant codifies this relationship between cosmic distances and velocities. But in doing so it reveals much more, making it of interest not only to astronomers but also to cosmologists and physicists. Because the constant represents the expansion rate at any particular moment in the universe's long history, measuring its value over time provides an expansive view of how the universe evolves over the eons, giving researchers crucial clues to our cosmic origins and future. Somehow beckoned by the void, billions of outward-rushing galaxies also feel the collective gravitational pull of everything in the rearview mirror trying to tug them back. The Hubble constant reflects the sum total of all the stuff in the universe and the forces acting on it—weighing in on whether gravity or the void will ultimately win this intergalactic tug-of-war.

The universe's contents could eventually reverse the expansion—a scenario called the "big crunch," in which gravity pulls everything back into an infinitely hot and dense point like the one that birthed the big bang. Or the universe might steadily expand indefinitely, growing ever colder and more listless in a "big chill" that offers endless space and time—but ultimately very little to do. Or, just maybe the cosmic expansion will dramatically speed up, becoming so unruly that it bucks all its riders. Such an accelerating universe could sunder galaxies, then stars, then planets, atoms and subatomic particles until even the fabric of reality itself splits at its seams in a "big rip" that leaves practically nothing behind. Will the universe end in fire, ice or emptiness? The Hubble constant knows—but until the tension is resolved, the answer is unclear.

> **"This is the most important of the cosmological parameters."**
>
> *—Wendy Freedman*

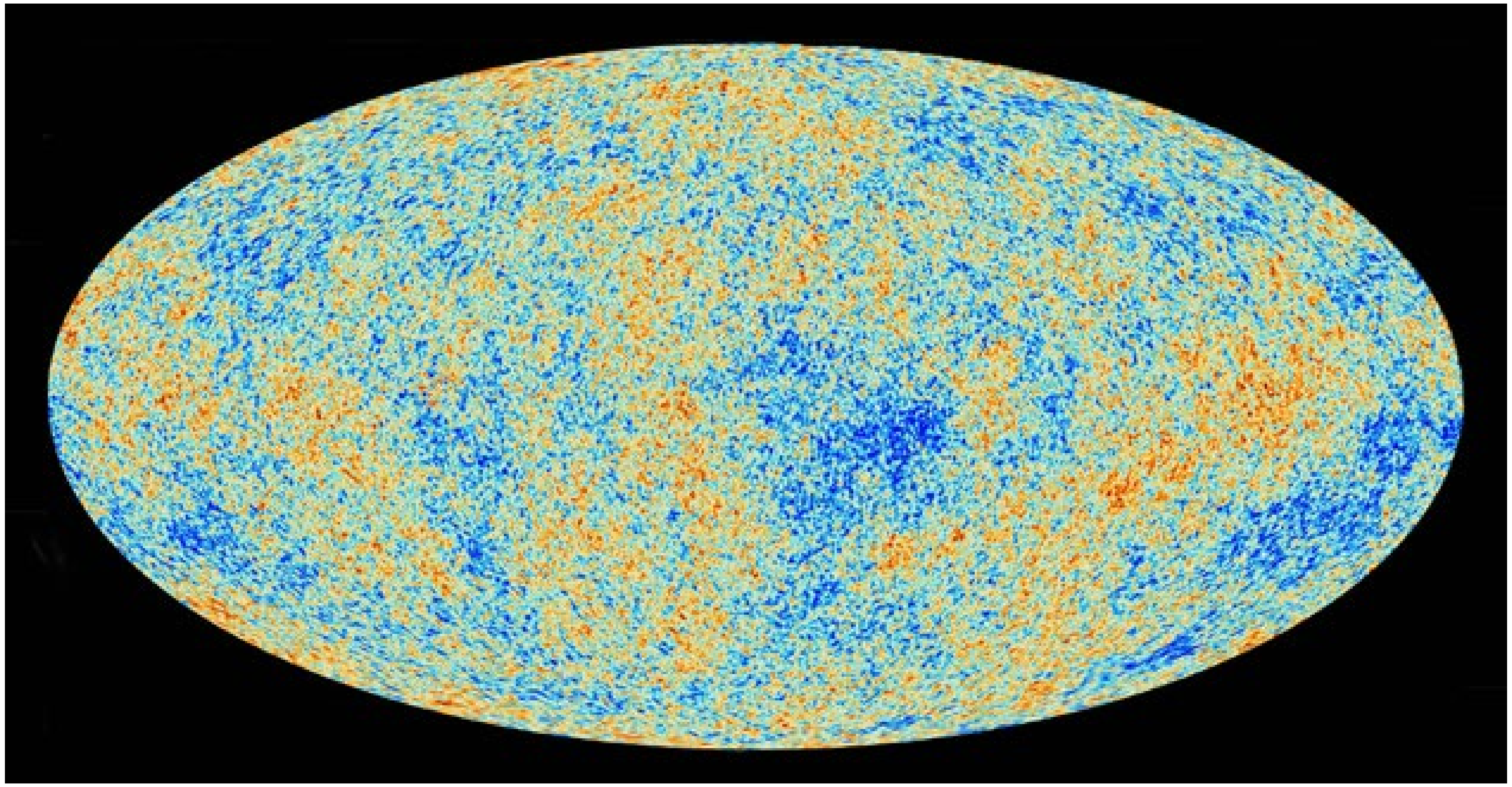
SUPERNOVA SHOE-GAZING

"This is the most important of the cosmological parameters," says Wendy Freedman, an astrophysicist at the University of Chicago who has spent her career pursuing the Hubble constant. "It is the anchor because it has the highest impact on the greatest number of things. This is a measurement that really matters." In the 1990s and early 2000s Freedman led a team that used the Hubble Space Telescope to provide what were then the constant's best-yet measurements. Others have since been improving on them.

For the past decade Riess has been at the forefront of that effort, leading a team of astronomers who are using telescopes on the ground and in space to further refine estimates of the Hubble constant, in a project called "SH0ES" (don't ask).

SH0ES's targets of choice are exploding stars called type Ia supernovae. These exploding stars flash with near-identical luminosity throughout the cosmos, making them ideal "standard candles" to gauge distances to other galaxies. By knowing how bright a type Ia actually is versus how bright it appears to be in their telescopes, scientists can calculate how much space lies between Earth and that far-off stellar cataclysm. They can also measure each supernova's redshift—the way the expansion of space between the supernova and Earth has stretched the supernova's light to longer, redder wavelengths. They then estimate the rate of expansion by comparing the redshifts and brightness of many supernovae scattered across the cosmos. To calibrate their supernovae measurements, however, the SH0ES team also uses another standard candle: Cepheid variable stars, which periodically pulsate in relation to their luminosity and offer superior distance measurements in the vicinity of the Milky Way.

Pairing the supernovae and Cepheid data has allowed the SH0ES team to get steadily more precise estimates for the Hubble constant, reducing the measurements' margin of error from 5 percent in 2009 to just 2.4 percent in 2016. Their latest effort, calibrated using new and improved Cepheid distance data from the European Space Agency (ESA) Gaia spacecraft, reduces the uncertainty to 2.2 percent. Over the years the SH0ES team's calculations of the Hubble constant have remained remarkably consistent: according to supernovae and



THE PLANCK SPACECRAFT'S all-sky map of variations in the cosmic microwave background (CMB), the oldest observable light in the universe. Estimates of the universe's expansion rate derived from Planck's data conflict with those from supernovae and other sources.

ESA AND PLANCK COLLABORATION

Cepheids, the universe is expanding at a rate of 73.5 kilometers per second per megaparsec (about 3.3 million light-years). That is, for every 3.3 million light-years of space between us and another galaxy, the latter will recede from us 73.5 kilometers per second faster.

The tension emerged from independent measurements made by another ESA craft—Planck. From 2009 to 2013 Planck created an unprecedentedly detailed map of the cosmic microwave background (CMB), the afterglow of the big bang's primordial fireball from when the universe was only 380,000 years old. The Planck team derived the Hubble constant from that bygone era by first modeling the sizes and motions of sound waves that should have rippled through the soup of charged particles that filled the early universe. Next, they compared those estimates with the actual echoes imprinted on the CMB. The comparison provided both the distance to the CMB and the scalar dimensions of its features, allowing the Planck team to clock the primordial universe's expansion rate at just 67.3 kilometers per second per megaparsec. That estimate, and its remarkable error margin of just 1 percent, hinge crucially on the well-established "standard model" of cosmology—a kludgelike theoretical construct that robustly predicts many observed features of both the CMB and the contemporary cosmos.

"This is like the pediatrician measuring and calculating that your kid will end up being six feet tall, but your child ends up growing to be six and a half feet," Riess says. "It means something else is going on—maybe your kid had a growth spurt or got hormone injections. In this case, it's the physics of our best cosmological model providing the growth chart. But who's to say we actually have that right?"

Having now passed yet another test via Gaia's Cepheid distance measurements, Riess says, the odds of the SH0ES Hubble constant measurement being a statistical fluke are just one in 7,000. Physicists typically consider a measurement significant when it reaches the one-in-a-million realm of statistical likelihood; at present, the SH0ES results remain short of that lofty standard, but are getting closer all the time. Meanwhile, the Planck team is not budging, either; the validity of its result, team members have consistently said, is practically unassailable.

BEYOND THE STANDARD MODEL

This is not the first time the universe's expansion has flummoxed scientists. In the 1920s the expansion itself came as a shock to most researchers, especially Albert Einstein. Contrary to his preference for a static cosmos, Einstein's theory of general relativity predicted a universe that would inevitably expand or collapse. To "fix" this he added a new term to his calculations: a sort of antigravity suffusing all of space that could act to preserve universal equilibrium. Einstein first dubbed it "the cosmological constant"—but later allegedly called it his "biggest blunder," following Hubble's discovery. Einstein's initial intuition was apparently vindicated beginning in the 1990s, when Riess and other astronomers found distant type Ia supernovae were dimmer (and thus farther away) than expected. A mysterious "dark energy" seemed to be causing the universe's expansion to accelerate; perhaps, many physicists speculated, the dark energy and the cosmological constant were one

THIS MONTAGE SHOWS light from five background galaxies being distorted by massive foreground galaxies closer to Earth. The distortion causes the background galaxies to appear as multiple images. Scientists in the H0LiCOW collaboration studied these objects to make an independent measurement of the universe's expansion consistent with earlier estimates based on supernovae and Cepheid variables.

NASA, ESA, HUBBLE AND SUYU ET AL

and the same. Measurements from the CMB and other sources rapidly confirmed dark energy's existence if not its exact nature, resulting in Riess and two others receiving the 2011 Nobel Prize in Physics.

Because its effects would be evenly distributed throughout all of space, as space itself expands the cosmological constant would become more powerful, ramping up the rate of acceleration to produce either a big chill or a big rip as the universe's ultimate fate. But that boost, it seems, would still fall short of the Hubble constant the SH0ES team and other groups observe in the universe today. So the current tension, Riess speculates, could be due to dark energy not being Einstein's cosmological constant at all (although he hastens to add such scenarios are not strongly supported by observations of galaxies midway between the CMB and the present). If dark energy is not Einstein's cosmological constant, it could potentially fuel an even speedier acceleration, easing the tension. In theory, such a nonstandard form of dark energy could also profoundly diminish or even reverse its effects in the future, leaving open the possibility that the universe could still experience a big crunch.

Other speculative explanations exist for the tension, each one another path researchers must follow through the maze of possibilities deciding the ultimate fate of the cosmos. They include as-yet-undiscovered varieties of fast-moving subatomic particles, the influence of hidden "extra" dimensions, or various interactions with dark matter—to name just a few. It could be that more than one type of physics beyond the standard model is at play in the apparent tension between Hubble constant estimates from opposite ends of the universe.

A CONSPIRACY OF ERRORS?

Then again, some skeptics say, the most likely explanation is simply mistakes made in measurements. The Planck team's party line, in particular, has been that errors in calibrating Cepheids and type Ia supernovae are probably to blame for the tension.

"We don't know what the answer is, but there really aren't any theoretical explanations jumping out at us as very reasonable," says Lloyd Knox, a Planck team member at the University of California, Davis. "Speaking solely for myself, if I had to place money on anything, I'd still guess the tension is a systematic error in the direct measurement of the Hubble constant [in the modern universe]." For instance, Knox says, the glare from background stars in distant galaxies can contaminate brightness measurements for Cepheids, sabotaging astronomers' rickety cosmic distance ladder near its base and throwing off dependent measures of greater distances. In contrast, Knox and others note, the Planck team's derivation of the Hubble constant aligns with multiple and extremely robust independent lines of evidence—such as the large-scale clustering of galaxies and the observed ratios of light elements generated in the first few moments after the big bang. And Planck's results, Knox says, were also recently validated via follow-up CMB studies using the South Pole Telescope.

Riess argues that time and time again tests performed by SH0ES and other teams have shown background stars are not a significant source of errors in Cepheid measurements. Furthermore, the SH0ES result comes with a wealth of corroborating data all its own: separate from supernovae and Cepheids, other measurements of the Hubble constant in today's universe arrive at a value close to the 73.5 found by SH0ES. In 2017 an international team dubbed H0LiCOW (again, don't ask) clocked the Hubble constant at 72 kilometers per second per megaparsec. They did so by measuring the delayed arrival times of light rays from far-distant galaxies as the rays' various paths through space were distorted by massive galaxies closer to Earth.

That result, says H0LiCOW team member Tommaso Treu, an astrophysicist at the University of California, Los Angeles, is based solely on basic geometry and Einstein's general relativity—and is thus wholly independent of factors that might sully SH0ES or Planck measurements. "In combination with the SH0ES result, this adds evidence for the tension," Treu says.

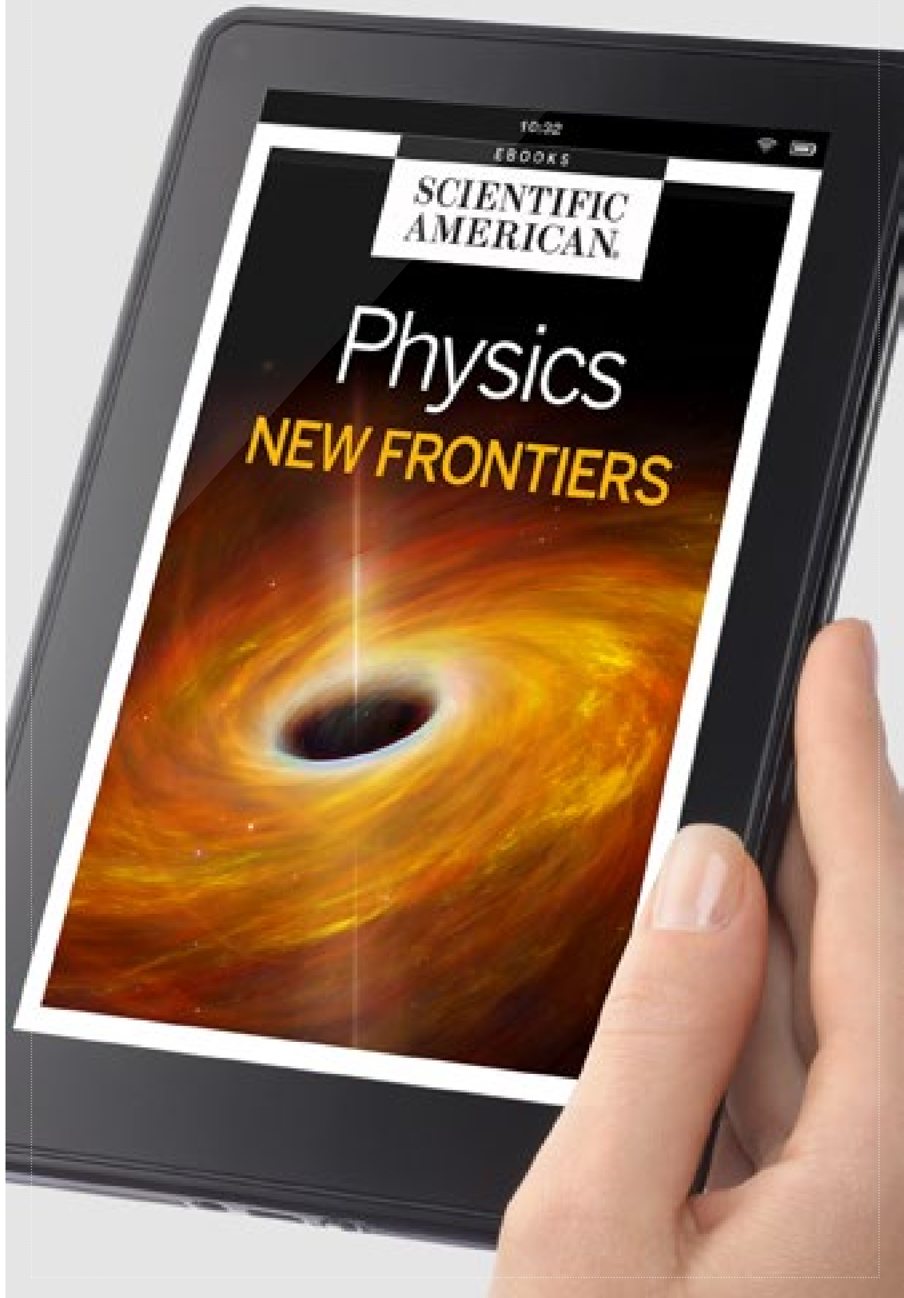
> **"We don't know what the answer is, but there really aren't any theoretical explanations jumping out at us as very reasonable."**
>
> *—Llyod Knox*

Taken together, Riess considers the evidence supporting his result to be almost overwhelming. For it to be wrong, he says, would require "a conspiracy of errors—multiple errors, one for every approach, that are independent but by some malevolence all the same size and in the same direction. And as Einstein said, "God is subtle, but he is not malicious."

David Spergel, an astrophysicist at Princeton University and the Flatiron Institute, believes it is time for teams on both sides to acknowledge uncertainties in their data may be greater than previously believed. "Historically, both astronomers and cosmologists have underestimated their errors; I think that's true for the measurements here, too," he says.

A resolution may be on the horizon. Spergel is one of the lead scientists planning NASA's Wide-Field Infrared Survey Telescope (WFIRST), a space observatory slated to launch in the 2020s with a primary goal of studying dark energy. The ESA is planning a similar mission, Euclid, that would complement WFIRST's studies. These missions could help resolve the tension by clarifying whether dark energy behaves like Einstein's cosmological constant or something wildly different. NASA's James Webb Space Telescope, slated to launch as early as 2020, could also provide an avalanche of new observations to constrain the constant, as will Gaia data releases in 2020 and beyond. Around the same time, other novel techniques are likely to mature as well. These would rely on surveys of previously inaccessible stellar populations or even observations of gravitational waves from large numbers of colliding neutron stars to obtain additional independent measurements of the Hubble constant.

For now, however, the tension remains—a figurative and literal symbol of how fast our understanding of the universe is accelerating, and how far we still have to go.



A Conversation with Thomas Hertog, One of Stephen Hawking's Final Collaborators

The theoretical physicist talks with *Scientific American* about the far-reaching implications of his final collaboration with his late friend and mentor

By Alexander Hellemans

GERD ALTMANN PIXABAY

Both quantum theory, which governs the subatomic realm, and Einstein's general relativity, which describes reality at cosmic scales, are often viewed as the most important developments in 20th-century physics. But there is another finding on par with these breakthroughs: the discovery that the universe is expanding and must have originated at a finite time in the past, a moment now called the big bang. General relativity and quantum theory both became vital tools for exploring how the universe evolves. They sparked new ways to understand how galaxies, stars, planets and ultimately living creatures came into being. Yet even in the bright light of these two revolutionary theories, the big bang's origins and earliest moments have remained shrouded in mystery. Any satisfactory explanation, it seems, would have to somehow reconcile the sometimes contradictory tenets of quantum theory with those of general relativity—while also explaining why so many observed properties of elementary particles, forces and fields appear to be fine-tuned to produce the rich diversity of phenomena in the universe we know. For celebrated late physicist Stephen Hawking, solving these mysteries was an obsession—one he shared with his closest friends and collaborators including Thomas Hertog, a theoretical physicist who obtained his Ph.D. at Cambridge University under Hawking's supervision with a thesis on the origin of the expansion of the universe. Today Hertog is a professor at the University of Leuven in Belgium (which is also the alma mater of Georges Lemaître, the astronomer and Roman Catholic priest who first introduced the idea of an expanding universe in 1927). Most recently Hertog was also the co-author of what has been widely reported as Hawking's final paper: a study titled "A Smooth Exit from Eternal Inflation?" that was completed shortly before Hawking's death and addresses how the universe might have begun. A few days after the publication of their joint paper on April 27 in the *Journal of High Energy Physics*, I met with Hertog in his office at the University of Leuven. We discussed the origins and conclusions of their paper—as well as the nature of its novel methods—which include findings from string theory, one of the most dominant emerging paradigms in 21st-century physics. [*An edited transcript of the interview follows:*]

We are all familiar with the big bang theory, which involves a kind of explosion that blossomed into the universe. What inspired you and Hawking to use a new and different approach to looking at the big bang?
The old big bang theory as developed by Georges Lemaître, [George] Gamow and others is based on Einstein's theory of general relativity. In this formulation the big bang was literally the beginning of time. But you could not say anything about what happened at the very beginning. The big bang was what people called a singularity—a point of infinite mass and density for which existing theories fall apart. Relativity was very good at describing the evolution of the universe once it existed but it couldn't say anything about its origin, although it implied there *was* an origin. In a sense [Einstein's theory of general relativity] predicted its own downfall. In our last paper we used quantum theory to get a handle on the beginning.

Why is it so important that we understand how the big bang happened?
The way cosmological history unfolds and how the laws of nature come into existence is heavily dependent on how exactly the universe got going. The laws of nature are not some sort of Platonic construct, separate and outside of reality. They have emerged as the universe expanded and cooled—and the way that happened depends very much on the precise physical conditions of the big bang. Now it happens that the universe we find ourselves in seems to be very delicately fine-tuned in order for complexity and life to emerge. This fine-tuning can be traced all the way back to the big bang, nearly 14 billion years ago. So something very special must have happened at that initial moment. We want to know what it was.

Could the idea of inflation—the enormous and sudden accelerated expansion of the universe after the big bang—help reveal those details?
Yes, and our theory is a possible completion of inflation. It explains how inflation could have started in the first place. Inflation in the early universe solves some major puzzles such as why the universe is large and uniform—and yet not *completely* uniform. The answer from inflation is that the near-uniformity is due to inflation's amplification of quantum fluctuations in the early universe. We can still see signs of these inflated fluctuations today, in patterns of tiny variations in the big bang's afterglow—the cosmic microwave background, emitted when the universe was only 380,000 years old. These variations went on to seed the formation of the galaxies.

Another consequence of inflation, it seems, is the creation of a multiverse; that is, of a universe incomprehensibly larger in extent than what we see within our own cosmic horizon—a

universe that is infinite. Other, far-distant regions of this multiverse beyond our cosmic horizon could have different physical laws, and would be too far separated from us for any communication or interaction to take place. What are your thoughts on that?

The problem is that inflation tends to work a little too well. Once it starts it is hard to stop everywhere, at least so it was thought. If inflation is eternal, if it keeps going forever, somewhere this leads to an ever-increasing amount of space growing at an exponential rate, dotted with an infinite number of "pocket universes" growing more slowly. This is the picture that our observable universe is not all that exists, but rather [is] one pocket of infinitely many universes, forming a multiverse. As you suggested, things like the values of certain key physical constants could vary randomly among the pocket universes, which would render moot any effort to get a deeper understanding of why our own observable universe is the way it is.

In our recent work, however, we argue there is no eternal inflation and that instead our universe is approximately uniform on the largest scales.

How did you arrive at this conclusion?

First we used string theory, a theoretical framework in which the elementary pointlike particles are replaced by strings. One of the vibrational states of the string corresponds to the graviton, the quantum-mechanical particle carrying the gravitational force. This suggests string theory constitutes at least a step towards a theory of quantum gravity. We evolved our universe backwards in time in our theory, and arrived at the singularity—the moment at which Einstein's equations break down. Rather than relying on Einstein's theory, at this point we used a relatively new concept from string theory, called the holographic principle, to project out the time dimension and view the entire situation in a timeless fashion. [*Editor's note: The holographic principle, in a nutshell, is the notion our reality may in fact be a hologram—that is, time, space and all its contents are reducible to information encoded on a two-dimensional surface at the boundary of our observable universe.*] We find this novel holographic viewpoint of the earliest phase of the universe does not lead to eternal inflation and a multiverse. Instead, a more or less unique and uniform universe emerges. Our new theory of "cosmogony," in contrast with the multiverse idea, makes definite predictions, which should in time enable it to be tested—at least to some extent. It therefore offers the hope we can achieve a deeper understanding of what makes our universe special and habitable.

How do you counter critics of string theory, who argue it cannot be tested?

I don't agree with this statement; it is not my intuition that string theory can't be tested. We may already have observations based on studies of the universe's large-scale structure and evolution that are telling us something about the nature of quantum gravity. Of course, further theoretical work will be needed to arrive at a mathematically rigorous, fully predictive framework for cosmology.

So, your paper's key predictions depend on the reality and nature of inflation. Will that be testable?

There are the obvious observables, yes. Just as it amplified tiny quantum fluctuations in the early universe, inflation should have amplified gravitational waves in the early universe, too. Gravitational waves are ripples in spacetime, first predicted by Einstein, that were finally observed just a few years ago—but the ones we have observed come from black holes and other stellar remnants in neighboring galaxies, not from the primordial universe. These amplified gravitational waves would leave their imprint on the polarization of the cosmic microwave background. Astronomers are actively trying to detect this polarization pattern.

So you are optimistic they will succeed?

Well, our theory certainly predicts that primordial gravitational waves should be there at some level.

The model that Stephen and I proposed in our final paper only deals with a very small sector of physics. We don't talk about particle physics. In the end, in a complete cosmology this will have to be incorporated. I am confident, however, that our work will lead to further predictions that can be tested.

Recently, in some of the press your joint research is mainly referred to as Hawking's work.

Yes, I have seen press reports referring to our joint work as "Hawking's final theory of the big bang." This is understandable, and I appreciate this final tribute to my late friend and mentor. As a matter of fact, Hawking and I, often together with our fellow physicist James Hartle, have always worked as a team. We never had any notion of a "leading" author. And so in keeping with the tradition in our domain of research, we listed the authors in alphabetical order on our papers.

Notwithstanding his physical limitations, Hawking was able to do great physics. What was his secret?

I certainly think intuition played a more prominent role in his work and his thinking than with many of our colleagues—by necessity. By intuition, I also mean his ability to ask the right questions. It is as if he could sort of distance himself a little bit from the messy calculations.

Evidence Builds for a New Kind of Neutrino

"Sterile neutrinos" that ignore all other particles might be showing up in experiments—and could even help solve the mystery of dark matter

By Clara Moskowitz

THE INTERIOR of the MiniBooNE detector is studded with photodetectors to capture the light signal created when a neutrino interacts.

FERMILAB

Clara Moskowitz is Scientific American's senior editor covering space and physics. She has a bachelor's degree in astronomy and physics from Wesleyan University and a graduate degree in science journalism from the University of California, Santa Cruz.

Physicists have caught ghostly particles called neutrinos misbehaving at an Illinois experiment, suggesting an extra species of neutrino exists. If borne out, the findings would be nothing short of revolutionary, introducing a new fundamental particle to the lexicon of physics that might even help explain the mystery of dark matter.

Undeterred by the fact that no one agrees on what the observations actually mean, experts gathered at a neutrino conference in June in Germany excitedly discussed these and other far-reaching implications.

Neutrinos are confusing to begin with. Formed long ago in the universe's first moments and today in the hearts of stars and the cores of nuclear reactors, the minuscule particles travel at nearly the speed of light and scarcely interact with anything else; billions pass harmlessly through your body each day, and a typical neutrino could traverse a layer of lead a light-year thick unscathed. Ever since their discovery in the mid–20th century, neutrinos were predicted to weigh nothing at all, but experiments in the 1990s showed they do have some mass—although physicists still do not know exactly how much. Stranger still, they come in three known varieties, or flavors—electron neutrinos, muon neutrinos and tau neutrinos—and, most bizarrely, can transform from one flavor to another. Because of these oddities and others, many physicists have been betting on neutrinos to open the door to the next frontier in physics.

Now some think the door has cracked ajar. The discovery comes from 15 years' worth of data gathered by the Mini Booster Neutrino Experiment (MiniBooNE) at Fermi National Accelerator Laboratory in Batavia, Ill. MiniBooNE detects and characterizes neutrinos by the flashes of light they occasionally create when they strike atomic nuclei in a giant vat filled with 800 tons of pure mineral oil. Its design is similar to that of an earlier project, the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos National Laboratory in New Mexico. In the 1990s LSND observed a curious anomaly, a greater-than-expected number of electron neutrinos in a beam of particles that started out as muon neutrinos; MiniBooNE has now seen the same thing in a neutrino beam generated by one of Fermilab's particle accelerators.

Because muon neutrinos could not have transformed directly into electron flavor over the short distance of the LSND experiment, theorists at the time proposed that some of the particles were oscillating into a fourth flavor—a "sterile neutrino"—and then turning into electron neutrinos, producing the mysterious excess. Although the possibility was tantalizing, many physicists assumed the findings were a fluke, caused by some mundane error particular to LSND. But now that MiniBooNE has observed the very same pattern, scientists are being forced to reckon with potentially more profound causes for the phenomenon. "Now you have to really say you have two experiments seeing the same physics effect, so there must be something fundamental going on," says MiniBooNE co-spokesperson Richard Van de Water of Los Alamos. "People can't ignore this anymore."

The MiniBooNE team submitted its findings on May 30 to the preprint server arXiv, and presented them in June at the XXVIII International Conference on Neutrino Physics and Astrophysics in Heidelberg, Germany.

A FOURTH FLAVOR

Sterile neutrinos are an exciting prospect, but outside experts say it is too early to conclude such particles are behind the observations. "If it is sterile neutrinos, it'd be revolutionary," says Mark Thomson, a neutrino physicist and chief executive of the U.K.'s Science and Technology Facilities Council who was not part of the research. "But that's a big 'if.'"

This new flavor would be called "sterile" because the particles would not feel any of the forces of nature, save for gravity, which would effectively block off communication with the rest of the particle world. Even so, they would still have mass, potentially making them an attractive explanation for the mysterious "dark matter" that seems to contribute additional mass to galaxies and galaxy clusters. "If there is a sterile neutrino, it's not just some extra particle hanging out there, but maybe some messenger to the universe's 'dark sector,'" Van de Water says. "That's why this is really exciting." Yet the sterile neutrinos that might be showing up at MiniBooNE seem to be too light to account for dark matter themselves—rather they might be the first vanguard of a whole group of sterile neutrinos of various masses. "Once there is one [sterile neutrino], it begs the question: How many?" says Kevork Abazajian, a theoretical physicist at the University of California, Irvine. "They could participate in oscillations and be dark matter."

The findings are hard to interpret, however, because if neutrinos are transforming into sterile neutrinos in MiniBooNE, then scientists would expect to measure not just the appearance of extra electron neutrinos, but a corresponding disappearance of the muon neutrinos they started out as, balanced like two sides of an equation. Yet MiniBooNE and other experiments do not see such a disappearance. "That's a problem, but it's not a huge problem," says theoretical physicist André de Gouvêa of Fermilab. "The reason this is not slam-dunk evidence against the sterile neutrino hypothesis is that [detecting] disappearance is very hard. You have to know exactly how much you had at the beginning, and that's a challenge."

> **"Once there is one [sterile neutrino], it begs the question: How many?"**
> ***—Kevork Abazajian***

ANOTHER MYSTERY?

Or perhaps MiniBooNE has discovered something big, but not sterile neutrinos. Maybe some other new aspect of the universe is responsible for the unexpected pattern of particles in the experiment's beam. "Right now people are thinking about whether there are other new phenomena out there that could resolve this ambiguity," de Gouvêa says. "Maybe the neutrinos have some new force that we haven't thought about, or maybe the neutrinos decay in some funny way. It kind of feels like we haven't hit the right hypothesis yet."

Unusually, this is one mystery physicists will not have to wait too long to solve. Another experiment at Fermilab called MicroBooNE was designed to follow MiniBooNE and will be able to study the excess more closely. One drawback of MiniBooNE is that it cannot be sure the flashes of light it sees are truly coming from neutrinos—it is possible that some unknown process is producing an excess of photons that mimics the neutrino signal. MicroBooNE, which should deliver its first data later this year, can distinguish between neutrino signals and impostors. If the signal turns out to be an excess of ordinary photons, rather than electron neutrinos, then all bets are off. "We don't know what would do that in terms of physics, but if it is due to photons, we know that this sterile neutrino interpretation is not correct," de Gouvêa says.

In addition to MicroBooNE, Fermilab is building two other detectors to sit on the same beam of neutrinos and work in concert to study the neutrino oscillations going on there. Known collectively as the Short-Baseline Neutrino Program, the new system should be up and running by 2020 and could deliver definitive data in the early part of that decade, says Steve Brice, head of Fermilab's Neutrino Division.

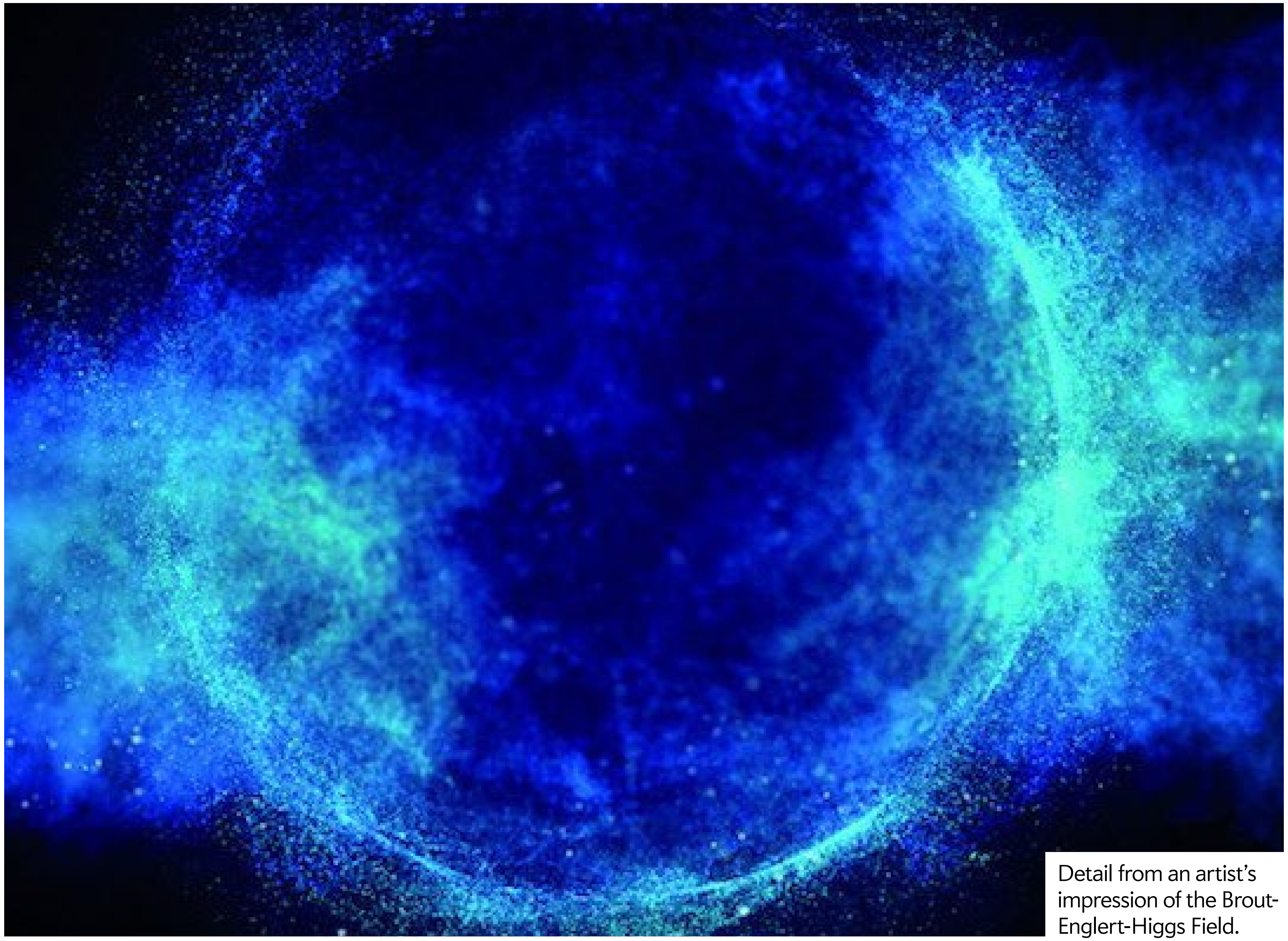
Until then physicists will continue to debate the mysteries of neutrinos—a field that is growing in size and excitement every year. The meeting in Heidelberg, for example, was the largest neutrino conference ever. "It's been a steady ramp-up over the last decade," Brice says. "It's an area that's hard to study, but it's proving to be a very fruitful field for physics."

Don Lincoln is a senior physicist at Fermilab who conducts research using data from CERN's Large Hadron Collider. He is author of several science books for the public, including his most recent one, The Large Hadron Collider: The Extraordinary Story of the Higgs Boson and Other Stuff That Will Blow Your Mind (Johns Hopkins University Press, 2014).

PHYSICS

New Higgs Boson Observations Reveal Clues on the Nature of Mass

For the first time, scientists have observed the famous Higgs boson, responsible for imparting mass, interacting with the heaviest particle in the universe



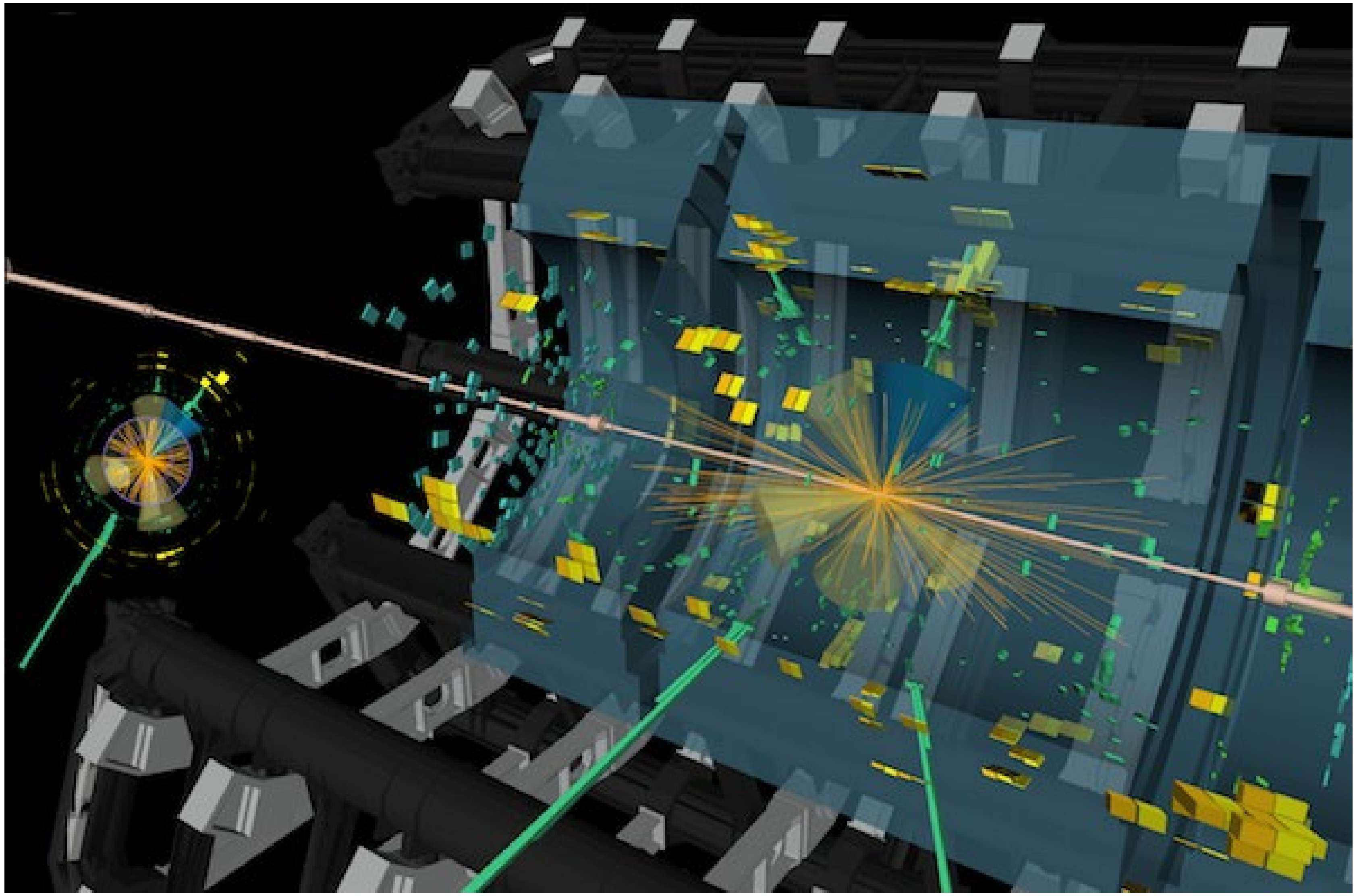
Detail from an artist's impression of the Brout-Englert-Higgs Field.

DANIEL DOMINGUEZ CERN

WHEN SCIENTISTS ANNOUNCED the discovery of the Higgs boson in 2012, it was a huge triumph for the Standard Model of particle physics, the leading theory of subatomic matter. The particle had been predicted to explain why other particles have mass. But finding this particle was not the end of its story—rather, it was a beginning. Additional measurements were needed to prove the particle scientists discovered was the same one predicted by the Standard Model and not something similar, but different. Furthermore, many details about how the Higgs works to bestow mass on other particles and why it has the properties it does remain mysterious.

In June physicists reported an important observation that could help us understand this fascinating particle and clarify the origins of the mass. Using the Large Hadron Collider (LHC), the world's most powerful particle accelerator, located at the CERN laboratory on the French—Swiss border, scientists observed collisions that produced not only Higgs bosons, but also a top quark and its antimatter counterpart, an anti–top quark.

These quarks are the heaviest known fundamental particles and had never before been seen along with Higgs bosons as the products of a collision. I am a scientist on one of the teams behind the announcement and we are all very excited. Until these measurements we had only indirect evidence of how top quarks and Higgs bosons interact. Now we can see these dealings up close.



Visualization of an event from the $t\bar{t}H(\gamma\gamma)$ analysis. The event contains two photon candidates displayed as green towers in the electromagnetic calorimeter, and six jets (b-jet) shown as yellow (blue) cones.

ATLAS AND CERN

MYSTERIES OF MASS

The Higgs boson was first predicted in 1964 along with an energy field—the Higgs field—that permeates the universe. When fundamental subatomic particles interact with this field, the thinking goes, they acquire mass. But interestingly, theoretical predictions suggest the Higgs boson itself should have a mass far higher than what we observe.

The reason for this is subtle. The Higgs boson's own mass comes from two sources: one part arises directly from its interactions with the Higgs field, but there is another indirect contribution. Like all subatomic particles, the Higgs boson can briefly transform into other particles—for instance, top quarks, W and Z bosons, and even pairs of Higgs bosons. While in this fluctuated state these transformed particles can also interact with the Higgs field and indirectly contribute to the Higgs boson's mass.

This contribution to the Higgs mass is expected to be enormous, unless the effects of the top quark and the W, Z and Higgs bosons can cancel out this mass very precisely. For now that seems unlikely (and certainly would be unexplained), so this presents a serious mystery. Thus, it is important to understand the interaction between Higgs bosons and top quarks to try to shed some light on this pressing conundrum.

Aside from the unanswered questions regarding the mass of the Higgs boson itself, there is another reason to be interested in the relationship between the top quark and the Higgs boson. The top quark is the particle that interacts most with the Higgs field. We know this because it is the heaviest known particle, and particles gain mass according to how strongly they deal with the field.

The intimate relationship between the top quark and the Higgs may offer us a favored route for discovering new particles in nature. Because of the mystery remaining around how the Higgs generates mass, it is entirely likely that undiscovered particles will first appear in collisions in which the Higgs field plays a prominent role. Thus, events in which the top quark and Higgs boson simultaneously appear are an attractive laboratory to investigate new physics.

SEARCHING FOR A NEEDLE IN A HAYSTACK

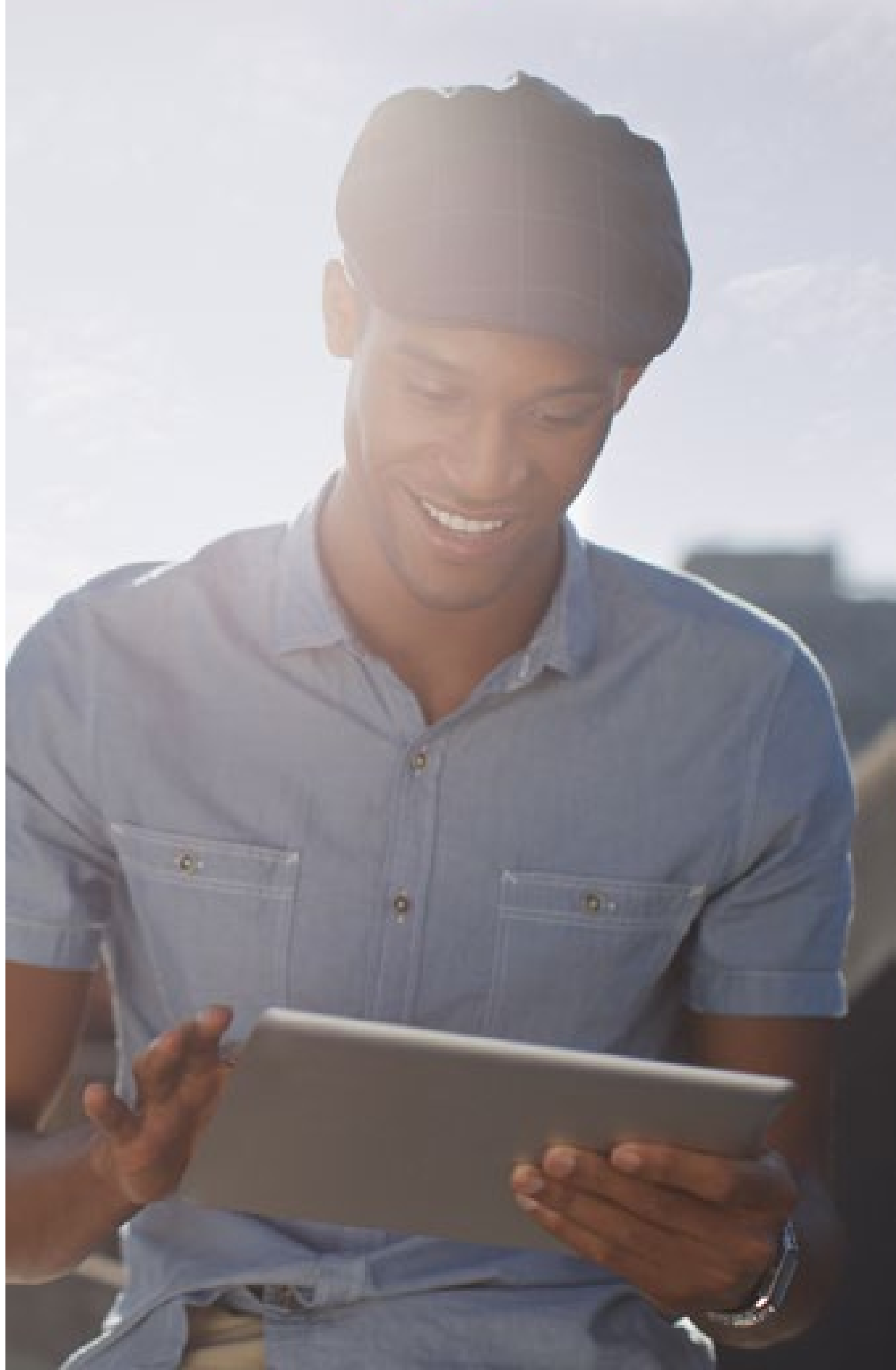
The new results come from two experiments operating at the LHC: CMS and ATLAS. The CMS collaboration's findings were published in *Physical Review Letters*; the ATLAS team submitted their observation for publication in June. Both experiments also gave presentations at the 2018 Conference on Large Hadron Collider Physics in June in Bologna, Italy.

Each experiment collided well over a quadrillion pairs of protons together and recorded over a billion of these collisions. Of these, only a few hundred collisions simultaneously produced a Higgs boson and a top quark—antiquark pair. Identifying those events was extremely challenging because top quarks are produced in only 1 percent of collisions in which Higgs bosons result.

Even these daunting numbers do not convey the true difficulty involved in these measurements. Both the top quark and antiquark each decay into three daughter particles and the Higgs boson decays into two. Thus, each event of the kind reported in June involved at least eight different objects. Sophisticated algorithms were needed to look at the eight objects and identify which daughter particles originated from which parent particles. This process employed complex statistical techniques, including neural networks and boosted decision trees. These measurements are truly breathtaking in terms of the intellectual effort that was needed to cut through the confusion.

The LHC will continue to collide protons through December, then will suspend operations for two years to install upgrades and refurbishments for both the accelerator and its experiments. It will be turned back on in 2021, and between then and 2030 the scientific collaborations at the LHC expect to record 30 times more data than they recorded from 2011 through 2018.

The prospect of an unparalleled amount of future data makes this a thrilling time for particle physicists. If there are surprises to be found in the physics surrounding the Higgs boson, the CMS and ATLAS teams will find them. Those of us who are involved in the process are incredibly excited by the discoveries the future might bring.



Sheri Wells-Jensen is an associate professor in the department of English at Bowling Green State University. Her research interests include astrobiology, linguistics and disability studies.

SPACE

The Case for Disabled Astronauts

In some situations, spacefarers with visual or other impairments could actually make a mission safer

STEVE BRONSTEIN GETTY IMAGES

EVERY SIX-YEAR-OLD wants to be an astronaut. This career goal is right up there with firefighter, detective, cowboy and ballerina. Before long, though, most recognize that they do not meet, and will in fact never meet, the nonnegotiable physical requirements for the job. They are too tall, or they have a weak knee, flat feet or some other slight but uncorrectable physiological irregularity that means they do not have what Tom Wolfe called "the right stuff."

Because there are thousands of applicants for each spot, space agencies can afford to be picky. It is not unlike the policy imagined by classic science fiction author Robert Heinlein, where those in change "can turn down a ship's captain just for low blood sugar before breakfast and a latent tendency to be short-tempered therefrom until he has had his morning porridge."

But this unapologetic demand for physiological near-perfection is not only unnecessary; it will actually become a serious liability as mission durations increase. Survival chances for any long-term mission will be dramatically improved by loosening these restrictions until all people, regardless of disability, are eligible to be astronauts.

I say this not because of some ineffable theoretical advantage of "diversity." I will use the example here of a totally blind astronaut, but a similar case could be made for other physical disabilities.

A blind person on a space station probably seems, *prima facie*, very frightening given that her colleagues might have to depend on her in an emergency. But blind adults are successful parents, teachers, scientists and chefs, and do not have more accidents than sighted people; there is no inherent danger associated with a blind person doing his or her job.

The key to success here lies in adapting instruments to output information in braille and/or audio along with visual displays. Joshua Miele, a researcher at the Smith-Kettlewell Eye Research Institute in San Francisco, notes that "creating an effective accessible interface is mostly a matter of understanding users and usability and incorporating that from the beginning. While it takes planning and good design, it's not rocket science."

Neither is it a new idea. Spacecraft are designed with redundancy: extra oxygen tanks, backup computers and failsafe after failsafe. Accessible instrumentation adapted for a blind astronaut—which would also serve a sighted astronaut in the dark—is just one more layer of protection against mission failure.

On a spacewalk in 2001, Canadian astronaut Chris Hadfield was temporarily blinded by a combination of soap and tears inside his helmet. The real problem was not that he was unable to see; it was that the current spacesuit design forces astronauts to over-rely on hand-eye coordination to the exclusion of other useful sensory information. For blind astronauts, the priority would be to design suits with better flexibility and increased tactile feedback, so the hands could be used more easily to explore and manipulate tools.

If humans functioned like robots, impartially absorbing all sensory input, there would be less advantage in employing a blind astronaut. But humans are not robots. Cultural and evolutionary factors have shaped how our brains prioritize perceptual information. For example, although blind people do not generally have measurably superior hearing, a blind person is *attentive* to audible input in a way that sighted people are not. If a blind and a sighted scientist are standing together in a park and a small bird flies overhead, the blind scientist might say: "Did you hear that bird?"

The sighted scientist might have *seen* the bird and noted its presence but failed to note the sound of its wings because that sound was unnecessary to his understanding of the situation. This offers no advantage in the pacific environs of the suburban park, but in life-or-death situations, the presence of a crew member who attends to nonvisual cues could save lives.

After all, in a serious accident, the first thing to go might be the lights. This generally means that the first thing a sighted astronaut must do for security is ensure visual access to the environment. He hunts for a flashlight, and if emergency lighting comes on, his eyes take a moment to adjust. Meanwhile, the blind astronaut is already heading toward the source of the problem. In the fire aboard the Russian Mir space station, in 1997 the crew struggled as smoke obscured their view. The blind astronaut, while still affected by the lack of good air, would not be bothered by either dim lighting or occluding smoke. She would accurately direct the fire extinguisher at the source of heat and noise.

As an armchair space observer, I mean no criticism of those involved in that accident; they did well, and we are all glad they survived. But it is our obligation to note ways in which spaceflight can be made safer, and they would have been safer with a blind crewmate aboard.

Another consequence of the systematic inclusion of blind astronauts would be altered procedures. One problem the Mir astronauts faced was that they could not find one of the fire extinguishers. The needs of a blind crew would necessitate rigorous policies designed to prevent disorganized clutter.

Of course, astronauts would still lose bone mass and be exposed to heightened levels of radiation, and a large decompression accident would still kill pretty much everyone. But some kinds of effects would be mitigated. A blind astronaut would not feel the nausea caused by the lack of a visual horizon or be disoriented by the profoundly intimidating view during space walks. Similarly, there would be little reason to worry about the damage microgravity does to vision as fluid accumulates in the eye, distorting the eyeball and in some cases pressing on the optic nerve.

Furthermore, when a crew spends extended time in space, there is always the possibility of injury or disease *resulting* in disability. The transition from active, confident, able-bodied person to active and confident person with a disability is a cognitively and emotionally complex task. Far from home, with no hope of replacement, a newly disabled pilot or scientist will find this necessary transition much more feasible if adaptive equipment is already in place and there are active and confident disabled crew members present to assist.

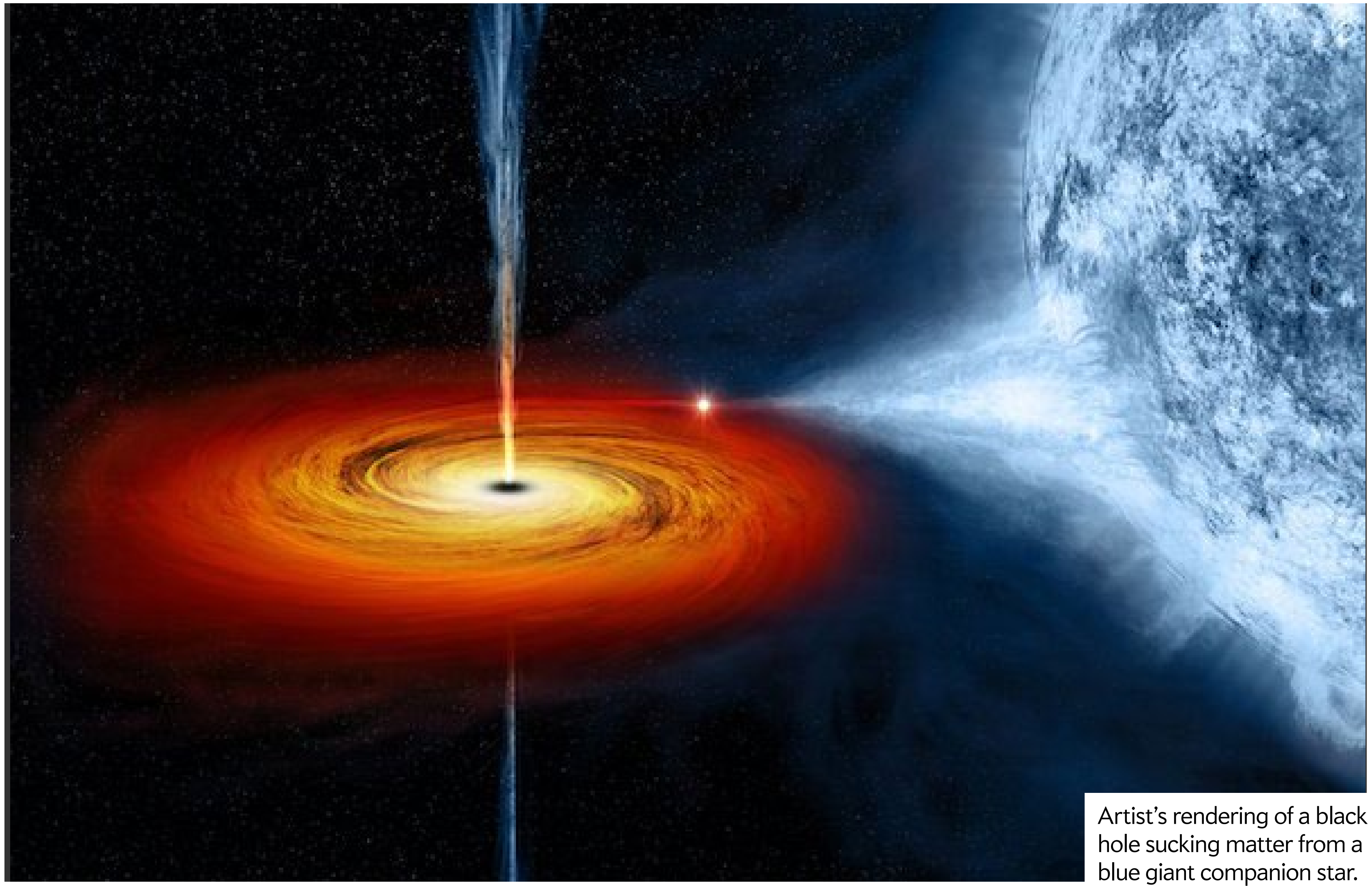
No otherwise-qualified disabled candidate should be automatically excluded from long-term space missions. In fact, for the good of the overall mission, I would strongly urge that disabled candidates be given a slight preference.

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

Maybe We Could "See" a Singularity After All

When black holes collide, interactions between their cores might leave an imprint on the resulting gravitational waves



Artist's rendering of a black hole sucking matter from a blue giant companion star.

X-RAY: NASA AND CXC; OPTICAL: DIGITIZED SKY SURVEY

THE SINGULARITIES AT THE centers of astrophysical black holes mark the breakdown of Einstein's theory of gravity, general relativity. They are the only breakdown sites accessible to experimentalists, since the only other known singularity, the big bang, is believed to be invisible due to the vast expansion that occurred afterward during cosmic inflation.

Every physicist knows these facts but very few discuss black hole singularities, as if the topic is taboo. The reason is simple: to explore the true nature of singularities we need a theory that unifies general relativity with quantum mechanics, and we do not have a unique, well-defined formalism for doing that. Even in the context of specific proposals for a unified model, such as string theory, the nature of black hole singularities is rarely discussed because of its mathematical complexity.

But perhaps the time is ripe now to open up this discussion, given that the 2017 Nobel Prize was awarded to the LIGO team for discovering gravitational waves from collisions of black holes. An observable quantum signal from the embedded singularities could guide us in the search for a unified theory.

This thought occurred to me during two back-to-back conferences that Harvard University hosted on May 7–11, one on gravitational wave astrophysics and the second the annual conference of Harvard's Black Hole Initiative. A few days earlier, the basement at my home was flooded because the sewer pipe was clogged by tree roots, and the five hours spent with a plumber in fixing this problem led me to realize that any water going down the drain collects somewhere.

Usually the sewer pipe takes the water to a town reservoir and we do not think about where it goes because we do not see the water once it leaves our property. But because the sewer pipe at my home was clogged, the water flooded my basement. I started thinking about the analogous problem of where the matter that makes a black hole collects. The reservoir in that case is the singularity.

True, the singularity of a stationary black hole is hidden behind an event horizon for any external observer. This "cosmic censorship" is a good reason for ignoring the observational consequences of singularities when probing the calm spacetime around isolated black holes—for example, while imaging the silhouette of Sagittarius A* at the center of the Milky Way with the Event Horizon Telescope.

But this does not imply that observers, more generally, can never study empirically the nature of singularities. When children get a birthday present wrapped in a box, they attempt to learn about its nature without seeing it directly by shaking the box and listening to its vibrations. Similarly, we can listen to the vibrations of a black hole horizon that is strongly shaken through its collision with another black hole, hoping to learn more about the nature of the singularities hidden inside. Future generations of LIGO detectors could serve as the "child's ears" in extracting new information from these vibrations.

A particularly interesting question is what happens when two singularities collide. How do they merge to a single singularity, and does this process have an imprint on the gravitational wave signal that is observable by LIGO? Naïvely, one might argue that computer simulations have already calculated the gravitational wave signals from black hole collisions and there is no hint about the content of the "event horizon box" in these signals.

But existing simulations suffer from two shortfalls. First, they cut out completely the region around the singularities by postulating that this region will not have observable effects; and second, they do not incorporate quantum mechanical modifications of general relativity. If there are observable signatures of merging singularities, existing computer simulations are, by construction, blind to them.

What would a singularity look like in the quantum mechanical context? Most likely, it would appear as an extreme concentration of a huge mass (more than a few solar masses for astrophysical black holes) within a tiny volume. The size of the reservoir that drains all matter that fell into an astrophysical black hole is unknown. We could envision the remnant singularity as a finite-size reservoir in equilibrium, similar to the halos of galaxies, where the motion of infalling particles is turned around and confined by their binding gravitational attraction.

One might assume that the outer boundary of the remnant object is some small fraction of its Schwarzschild radius, $2GM/c^2$ (which equals three kilometers times the black hole mass, M, in solar mass units), corresponding to a universal curvature scale at which Einstein's theory of gravity breaks down due to quantum corrections. In that case, the size of the object that replaces the singularity can be expressed in terms of its mass over the Planck mass (10^{-5} grams) times the Planck length (10^{-33} centimeter, or 10^{-20} times the size of a proton).

Now imagine two such singularities colliding as a result of the merger of two black holes. Although the collision of these objects might not be visible directly to an external observer (unless a "naked singularity" appears during the process), the interesting question is whether the collision will produce a transient burst of energy that is observable to the outside world through the vibrations it induces in the event horizon. Is that possible?

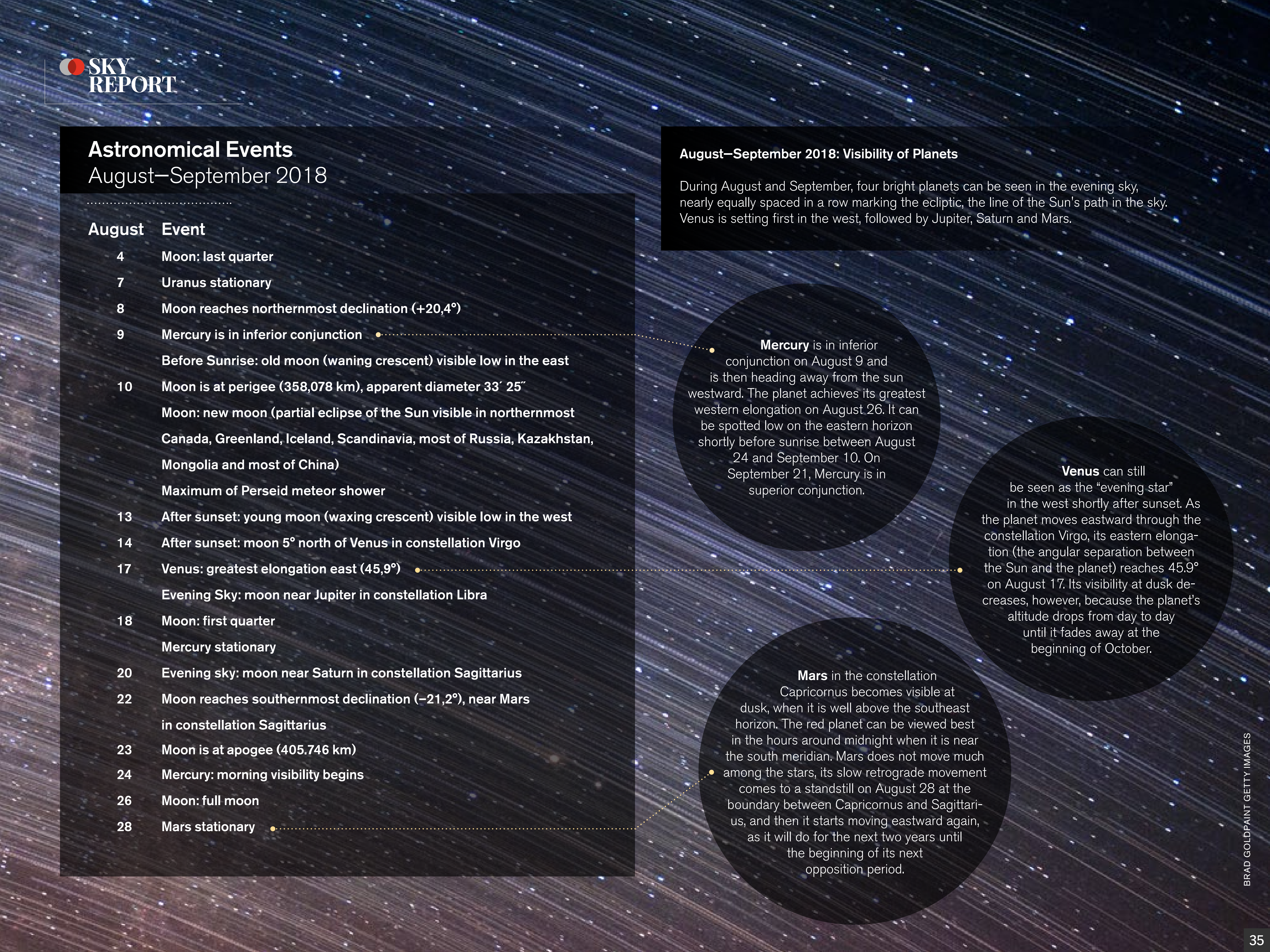
This is an extremely interesting question that should be discussed further. It could motivate gravitational wave observers to develop more sensitive detectors. At the very least, we might be able to outline the landscape of possibilities. Science is a work in progress, and most of the fun is in exploring uncharted territories

I often encourage my string theory colleagues to contemplate testing their theory by boarding a futuristic spacecraft that will take them into the event horizon of a nearby black hole. Perhaps future extensions of LIGO can save them the expense of this lengthy one-way trip.

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!

BRAD GOLDPAINT GETTY IMAGES


BRAD GOLDPAINT GETTY IMAGES

Astronomical Events
August–September 2018

August	Event
4	Moon: last quarter
7	Uranus stationary
8	Moon reaches northernmost declination (+20,4°)
9	Mercury is in inferior conjunction
	Before Sunrise: old moon (waning crescent) visible low in the east
10	Moon is at perigee (358,078 km), apparent diameter 33´ 25˝
	Moon: new moon (partial eclipse of the Sun visible in northernmost Canada, Greenland, Iceland, Scandinavia, most of Russia, Kazakhstan, Mongolia and most of China)
	Maximum of Perseid meteor shower
13	After sunset: young moon (waxing crescent) visible low in the west
14	After sunset: moon 5° north of Venus in constellation Virgo
17	Venus: greatest elongation east (45,9°)
	Evening Sky: moon near Jupiter in constellation Libra
18	Moon: first quarter
	Mercury stationary
20	Evening sky: moon near Saturn in constellation Sagittarius
22	Moon reaches southernmost declination (–21,2°), near Mars in constellation Sagittarius
23	Moon is at apogee (405.746 km)
24	Mercury: morning visibility begins
26	Moon: full moon
28	Mars stationary

August–September 2018: Visibility of Planets

During August and September, four bright planets can be seen in the evening sky, nearly equally spaced in a row marking the ecliptic, the line of the Sun's path in the sky. Venus is setting first in the west, followed by Jupiter, Saturn and Mars.

Mercury is in inferior conjunction on August 9 and is then heading away from the sun westward. The planet achieves its greatest western elongation on August 26. It can be spotted low on the eastern horizon shortly before sunrise between August 24 and September 10. On September 21, Mercury is in superior conjunction.

Venus can still be seen as the "evening star" in the west shortly after sunset. As the planet moves eastward through the constellation Virgo, its eastern elongation (the angular separation between the Sun and the planet) reaches 45.9° on August 17. Its visibility at dusk decreases, however, because the planet's altitude drops from day to day until it fades away at the beginning of October.

Mars in the constellation Capricornus becomes visible at dusk, when it is well above the southeast horizon. The red planet can be viewed best in the hours around midnight when it is near the south meridian. Mars does not move much among the stars, its slow retrograde movement comes to a standstill on August 28 at the boundary between Capricornus and Sagittarius, and then it starts moving eastward again, as it will do for the next two years until the beginning of its next opposition period.

BRAD GOLDPAINT GETTY IMAGES

Astronomical Events
August–September 2018

September	Event
3	Moon: last quarter
5	Moon reaches northernmost declination (+20,4°)
6	Saturn stationary
7	Neptune in opposition
8	Moon at perigee (361,350 km), apparent diameter 32´ 54˝
9	Moon: new moon
13	Evening sky: moon near Jupiter
16	Moon: first quarter
17	Evening sky: moon near Saturn
18	Moon reaches southernmost declination (–21,7°)
19	Evening sky: moon near Mars
20	Moon at apogee (404,880 km), apparent diameter 29´ 43˝
21	Mercury in superior conjunction
	Venus: greatest illuminated extent
23	Equinox
25	Moon: full moon
30	Moon near Aldebaran in constellation Taurus

August– September 2018: Visibility of Planets

During August and September, four bright planets can be seen in the evening sky, nearly equally spaced in a row marking the ecliptic, the line of the Sun's path in the sky. Venus is setting first in the west, followed by Jupiter, Saturn and Mars.

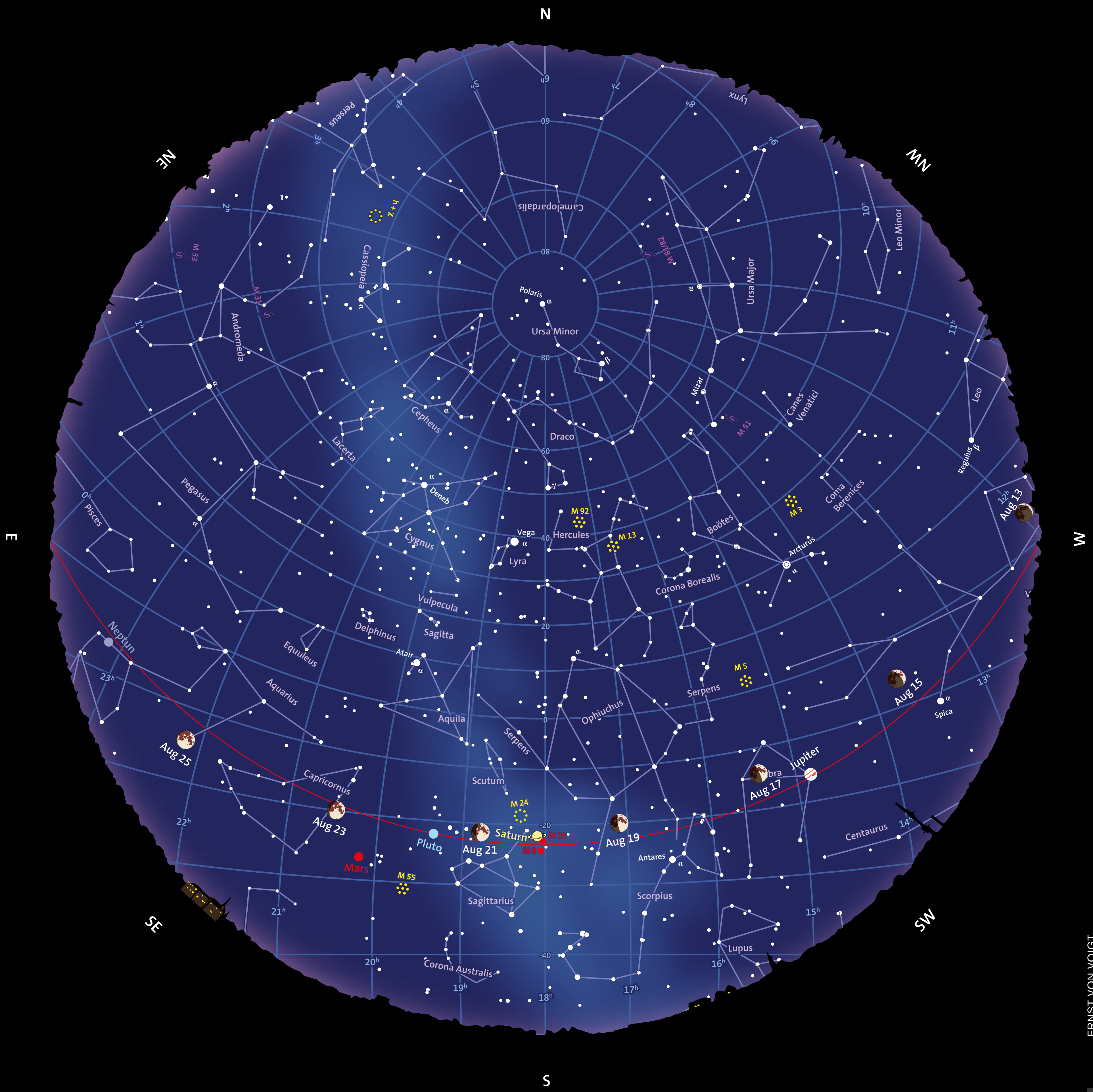
Jupiter is visible in the evening sky in early August for about three hours until it sets in the west. The gas planet, famous for the four Galilean moons which show up clearly in binoculars and its Great RedSpot which can be seen through telescopes, shines in the southwest at dusk. The planet moves slowly eastward in the constellation Libra and in mid-August we will see it just north of the star Zubenelgenubi (α^2 Lib). During September the planet's visibility decreases as the Sun comes nearer from the west. But at the end of the month Jupiter and Venus make up a bright duo low in the southwest shortly after sunset.

Saturn is the fourth bright planet you can see in the evening sky. It stands in the western part of the constellation Sagittarius. By the time it is getting dark, Saturn reaches its highest altitude in the south.

SKY REPORT

August

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

ERNST VON VOIGT

SKY REPORT

September

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

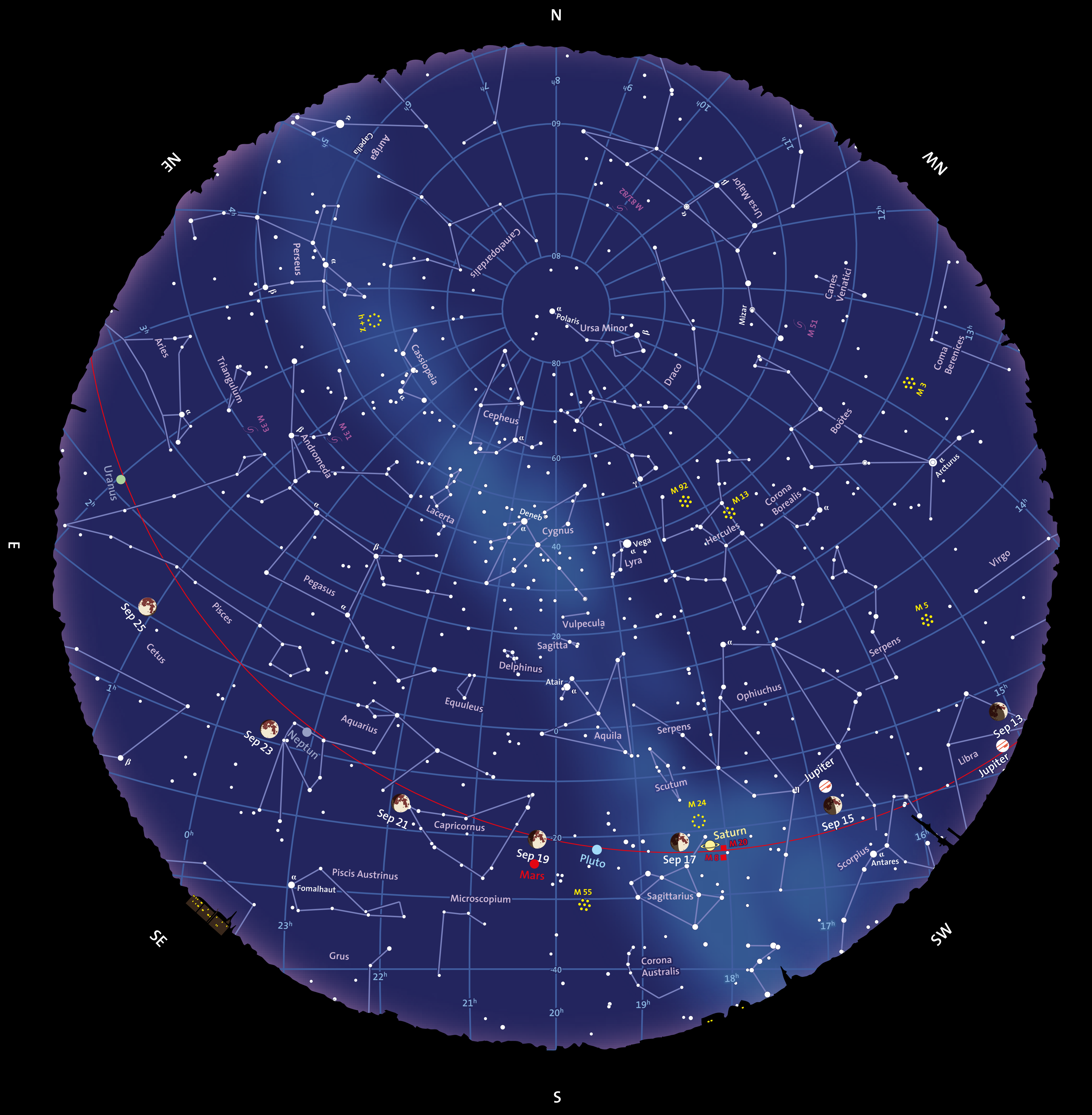
Apparent magnitudes

⁙ Open cluster

◌ Globular cluster

Galaxy

🟥 Nebula



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