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Plus:

A QUADRILLION NEW STRING THEORY EQUATIONS

ON THE TAIL OF INTERSTELLAR METEORS

EXPLORING A SINGLE QUANTUM REALITY

At Last

A 10-YEAR EFFORT PAYS OFF AND FINALLY REVEALS THE SHADOWY FACE OF A SUPERMASSIVE BLACK HOLE

WITH COVERAGE FROM nature

LIZ TORMES

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Theories Realized

About 1.3 billion years ago two black holes collided and sent undulating waves outward through spacetime like ripples on a pond. Here on Earth in the fall of 2015, a sensitive laser-based instrument recorded the waves and offered the first tangible evidence of black holes since Albert Einstein theorized their existence more than 100 years ago. And now, for the first time, scientists have taken a photograph of a black hole. As Lee Billings reports in "At Last," at least nine radio telescopes across the globe linked together and snapped the image of the black hole at the center of the Messier 87 galaxy. Aligning with Einstein's predictions, the center of the black hole is a dark shadow, surrounded by a vividly glowing ring of gas. As Carl Sagan once said, extraordinary claims require extraordinary evidence. And we can now say—more than ever—that we have the extraordinary evidence to conclude that black holes exist. Einstein, I surmise, would be pleased.

Elsewhere in the world of abstract theoretical physics, Anil Ananthaswamy reports that a group of mathematicians working on the "F-theory" branch of string theory has stumbled on a quadrillion—yes, three more zeros than a trillion—new potential solutions to string theory (see "Found: A Quadrillion Ways for String Theory to Make Our Universe"). And nearly 10 years on Christine-Maria Horejs and Giulia Pacchioni cover the many upgrades and future projects in the works at CERN (see "CERN's Next Big Thing"). The quarry of physics research is vast, and we are now netting some admirable catch.

Andrea Gawrylewski
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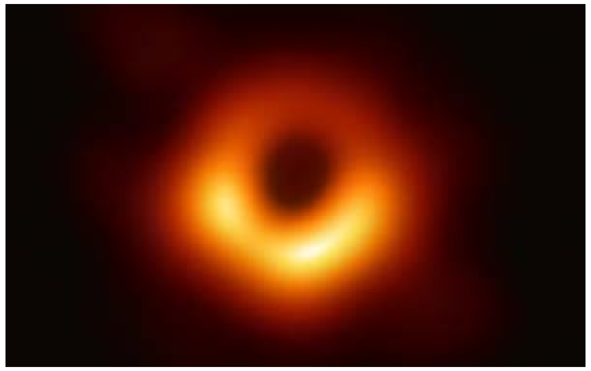

On the Cover

A 10-year effort pays off and finally reveals the shadowy face of a supermassive black hole

EVENT HORIZON TELESCOPE COLLABORATION ET AL. WIKIPEDIA

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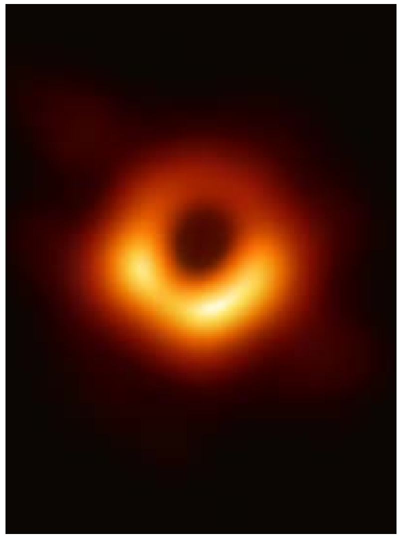

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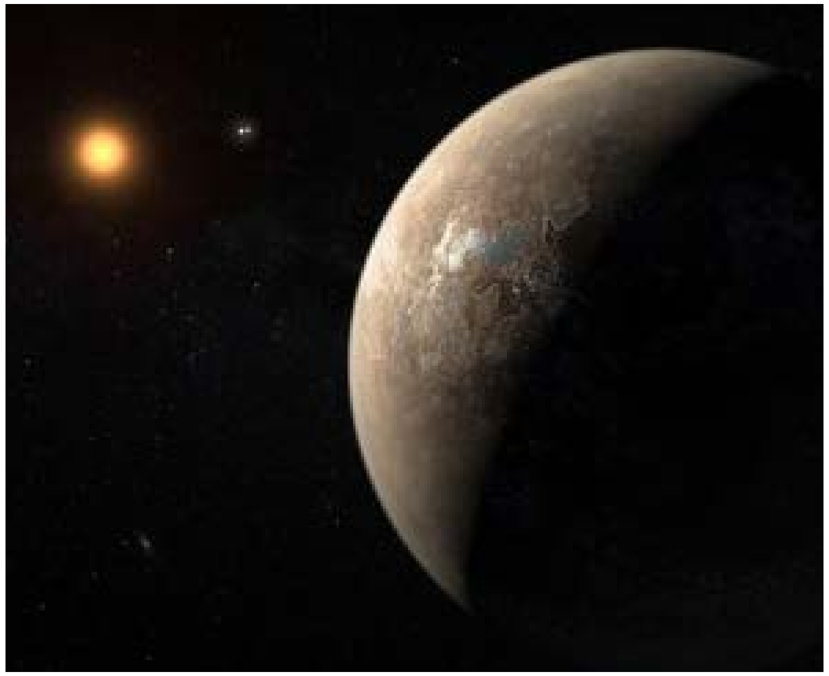
NEWS



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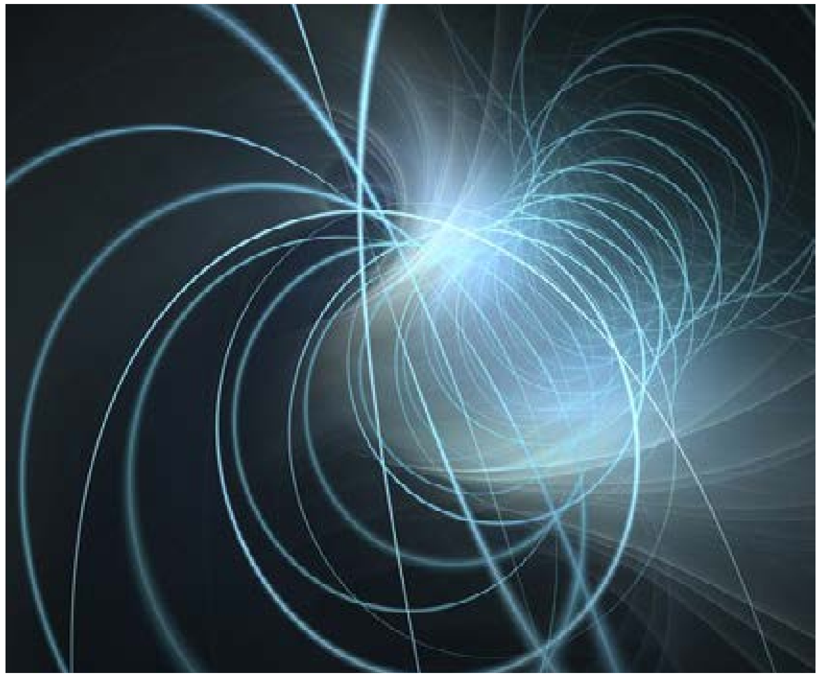


GETTY IMAGES

FEATURES

OPINION

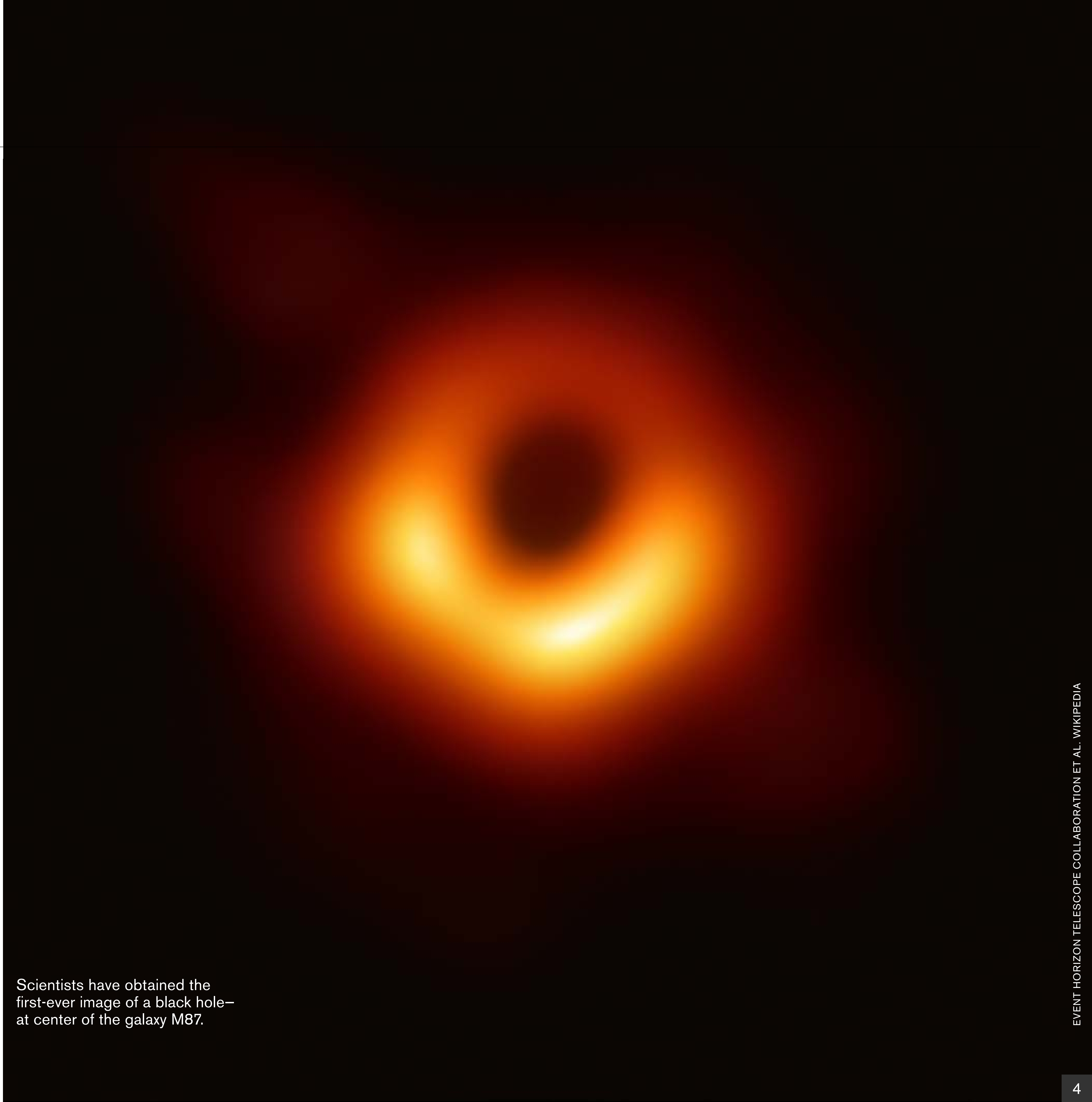
At Last, a Black Hole's Image Revealed

The Event Horizon Telescope captures one of the universe's most mysterious objects

AT SIX SIMULTANEOUS PRESS conferences around the globe, astronomers in April announced they had accomplished the seemingly impossible: taking a picture of a black hole, a cosmic monster so voracious that light itself cannot escape its clutches.

This historic feat, performed by the Event Horizon Telescope (EHT)—a planet-spanning network of radio observatories—required more than a decade of effort. The project's name refers to a black hole's most defining characteristic, an "event horizon" set by the object's mass and spin beyond which no infalling material, including light, can ever return.

"We have taken the first picture of a black hole," the EHT project's director, Sheperd Doeleman, said in a news release. "This is an extraordi-



Scientists have obtained the first-ever image of a black hole—at center of the galaxy M87.

EVENT HORIZON TELESCOPE COLLABORATION ET AL. WIKIPEDIA

nary scientific feat accomplished by a team of more than 200 researchers.”

The image unveils the shadowy face of a 6.5-billion-solar-mass supermassive black hole at the core of Messier 87 (M87), a large galaxy some 55 million light-years from Earth in the Virgo galaxy cluster. Such objects are a reflection of Einstein’s theory of general relativity, which predicts that only so much material can be squeezed into any given volume before the overwhelming force of its accumulated gravity causes a collapse—a warp in the fabric of spacetime that swallows itself. Left behind is an almost featureless nothingness that, for lack of better terms, scientists simply call a black hole.

Once thought to be figments of theorists’ wildest imaginings, black holes are now known to be crucial arbiters of cosmic structure, profoundly affecting the formation and evolution of stars and galaxies across the universe. The one in M87, for instance, is devouring a whirling accretion disk of material, which just outside the event horizon powers a star-scouring jet of intense radiation and relativistic particles blasting some 5,000 light-years out from the galaxy’s core.

Analyses of the image—published in a series of six papers in the *Astrophysical Journal Letters*—confirm that within the limits of the EHT’s present sensitivity the shape and behavior of M87’s black hole fits Einstein’s predictions.

“If immersed in a bright region, like a disc of glowing gas, we expect a black hole to create a dark region similar to a shadow—something predicted by Einstein’s general relativity that we’ve never seen before,” read a statement released by Heino Falcke, chair of the EHT Science Council. “This shadow, caused by the gravitational bending and capture of light by the event horizon, reveals a lot about the nature of these fascinating objects and allowed us to measure the enormous mass of M87’s black hole.”

But the best is yet to come; the EHT is planned to operate indefinitely and has also targeted the Milky Way’s central supermassive black hole, Sagittarius A*, in hopes of imaging our nearest, most familiar cosmic monster. Those results, project leaders say, will emerge from behind their own veil of secrecy in the future.

—Lee Billings

Inside the LIGO gravitational-wave detector in Hanford, Washington, engineers install hardware upgrades necessary for the facility’s latest observing run.

JEFF KISSEL, LIGO, CALTECH AND MIT

Gravitational-Wave Hunt Restarts—with a Quantum Boost

Detailed data on spacetime ripples are set to pour in from LIGO and Virgo’s upgraded detectors

THE HUNT FOR gravitational waves is on again—this time assisted by the quirks of quantum mechanics.

Three massive detectors—the two in the United States called LIGO and one in Italy known as Virgo—officially resumed collecting data on April 1, after a 19-month shutdown for upgrades. Thanks in part to a quantum phenomenon known as light squeezing, the machines promise not only to spot more gravitational waves—ripples in spacetime that can reveal a wealth of information about the cosmos—but also to make more detailed detections. Researchers hope to observe as yet undetected events, such as a supernova or the merging of a black hole with a neutron star.

The run, which will last until next

March, also marks a major change in how gravitational-wave astronomy is done. For the first time, LIGO and Virgo will send out public, real-time alerts on wave detections to tip off other observatories—and anyone with a telescope—on how to find the events, so that they can be studied with traditional techniques, from radio- to space-based x-ray telescopes. The alerts will also be available through a smartphone app. "Astronomers are really hungry," says David Reitze, a physicist at the California Institute of Technology in Pasadena and director of the Laser Interferometer Gravitational-wave Observatory (LIGO), which made the first historic detection of gravitational waves in 2015.

In their previous two observing runs, LIGO's twin detectors spotted 11 gravitational-wave signals, each emanating from an epic cosmic collision—10 from mergers between two black holes. The slightly smaller Virgo detector joined the network in 2017 and made important contributions to several detections—in particular, to the first sighting, in 2017, of waves created by two merging neutron stars. Data from the event helped astronomers to solve several cosmic mysteries.

The upgraded network should be able to detect many more events than it did in previous runs, going from an average of one detection per month to about one per week, says Reitze. Most of these events will probably be from black-hole mergers, but physicists are eager to see another neutron-star collision.

ENHANCED SENSITIVITY

The increased sensitivity will enable the detectors to better distinguish signals from the constant background of noise—providing physicists with more detail on the waves. This could in turn allow for precise tests of Albert Einstein's general theory of relativity, which predicted the existence of gravitational waves.

Future detections should reveal secrets about black holes that are in the process of merging, such as how fast they spin and in which direction, says Ilya Mandel, a theoretical astrophysicist at Monash University in Melbourne, Australia. "Maybe we can start teasing out some information about whether they preferentially align," he says.

If the black holes' rotational axes are parallel, that would suggest they have a common origin and started out as two stars orbiting together. Conversely, spins that are randomly aligned imply that the black holes formed separately and then began to orbit each other later on.

The upgrades have boosted the sensitivity of LIGO's machine in Livingston, Louisiana—already the most sensitive detector—by 40 percent. In 2017, technical snags hampered the other LIGO interferometer, in Hanford, Washington, and Virgo, but they have now partially caught up; Virgo, in particular, has roughly doubled the distance within which it can detect events, says Alessio Rocchi, Virgo's commissioning coordinator and a physicist at the National Institute for Nuclear Physics in Rome.

LASER UPDATES

The sensitivity boosts result largely from two changes in the lasers at the heart of the observatories.

Each LIGO detector is an L-shaped vacuum system that stretches over two four-kilometer-long arms; the Virgo machine near Pisa is similar, but has three-kilometer arms. Inside, laser beams bounce between mirrors at both ends. When gravitational ripples pass through Earth, they cause the lasers to change in length by tiny amounts.

To make signals stand out better from noise, LIGO and Virgo physicists have ramped up the power of their lasers and deployed for the first time a technique called "squeezed light," which is based on a quirk of quantum mechanics.

Empty space constantly bubbles with elementary particles that come into existence only to disappear moments later. At gravitational-wave observatories, these random fluctuations cause photons in the laser beams to hit the mirrors at unpredictable times. This has been the main obstruction to detecting gravitational waves that are of a high frequency, or pitch, at LIGO and Virgo. But physicists can use squeezed light to manipulate these fluctuations to their advantage—in this case, by shifting some fluctuations towards lower frequencies to improve the detection of high-frequency waves.

SQUEEZING LIGHT

Squeezed light has been a standard part of the toolbox of quantum-optics laboratories for decades, and since 2010, it has been in operation at the GEO600 detector, a test bed for LIGO with 600-meter arms near Hanover, Germany. That year, a team first tested squeezed light on the Hanford interferometer.

The technique could particularly improve the detection of waves created by merging binary neutron stars or of smaller black holes. That's because as lighter objects spiral into each other, they circle each other at up to 500 times per second right before they collide, and their waves become so high in pitch that they fall out of the interferometers' range. Higher sensitivity could enable the detectors to track the objects all the way to their fiery end.

Astronomers around the world are also preparing to follow up on detections of gravitational waves and to examine the same events using conventional techniques—including radio, optical and x-ray observatories—thanks to public alerts that will be sent out when a detection is made.

The astrophysics community had its first taste of this "multimessenger" astronomy when LIGO and Virgo detected the neutron-star merger, when observatories around the world made follow-up observations of the event. But in these previous runs, teams of astronomers that wanted to do such follow-ups had to sign memoranda of understanding with the LIGO-Virgo collaboration to receive confidential alerts; researchers also had to observe an embargo period. Starting with this run, that will no longer be the case. "If they follow it up and see a counterpart, they can do what they want. There is no restriction on what they publish, or when," Reitze says. "That's a big change."

Meanwhile, researchers at the newly built KAGRA gravitational-wave observatory in Japan are rushing to tune up their detector in time to join the network in early 2020. Having a fourth detector will be especially helpful to locate the position of an event in the sky with greater precision.

—Davide Castelvecchi

This article is reproduced with permission and was first published in Nature *on April 2, 2019.*

New "FarFarOut" World Is the Most Distant Solar System Object Known

Pinning down the object's orbit could reveal it to be a crucial clue in the search for undiscovered planets—or just another frozen space rock

THERE IS A NEW record holder for "most distant known object orbiting the sun"—an icy world nicknamed FarFarOut. The finding is preliminary, but researchers are now performing follow-up observations to nail down this object's exact distance and the details of its orbit. Like so many of its far-flung siblings in the sun's dark hinterlands, eventually FarFarOut could provide astronomers with vital new insights about our solar system's outer frontier.

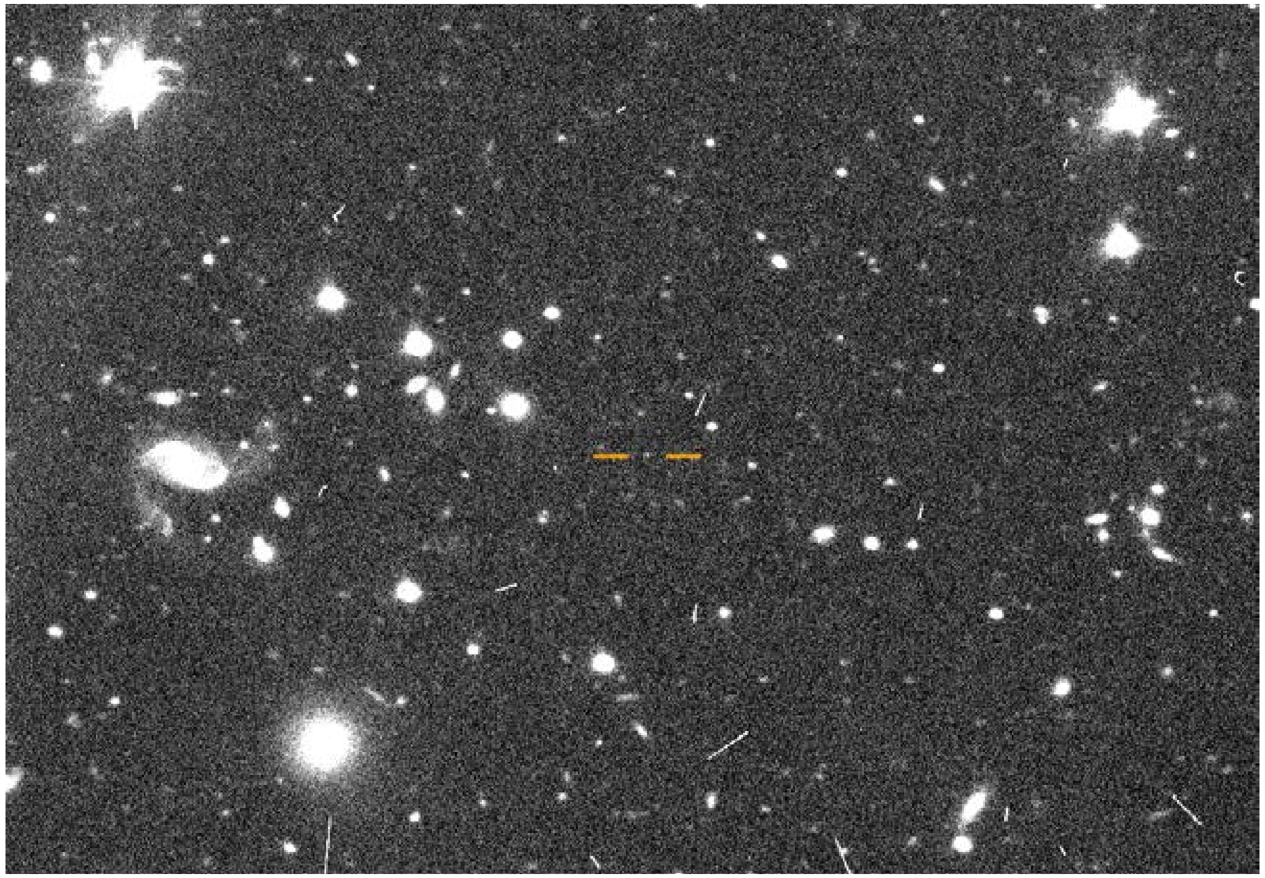
For the last six years, astronomers Scott Sheppard of the Carnegie Institution for Science and Chad Trujillo of Northern Arizona University, have been probing the heavens in the deepest all-sky survey ever performed for solar system bodies. They are on the hunt for Planet X, a small dwarf planet far beyond Pluto whose existence they proposed in 2014. So far, that search has yielded 62 distant objects, which make up about 80 percent of all those known beyond 60 astronomical units (AU). (One AU is equal to the Earth-sun distance, and Pluto's average distance is just shy of 40 AU.) Just last year, the pair made headlines with not one but two major discoveries—the dwarf planet 2015 TG387, nicknamed the Goblin, and 2018 VG18, nicknamed FarOut. The pair's dominance in the race to find ever-more distant denizens of the solar system is largely due to their dedication—they spend lots of time at telescopes, making observations at least every other month.

FarFarOut is the newest result from their single-minded search. While snowed in during a blizzard late last month, Sheppard decided to review some of the two terabytes of data he and Trujillo had captured last year during observations on the Subaru telescope in Hawaii. In two images of the sky taken one day apart during January 2018 he spied a dim, drifting object—its change in position a sign it was not a background star, but rather a newfound object in a distant orbit around the sun. "It's just barely detectable," Sheppard notes.

The pair's preliminary measurements, Sheppard says, suggest FarFarOut is between 130 and 150 AU from the sun, most likely around 140 AU. He estimates this newest-known member of the solar system is about 400 kilometers across, about half as wide as the dwarf planet Ceres. But that estimate is based on FarFarOut's brightness, which depends on its reflectivity—a property of the body that is as of yet unknown. "It could be as dark as coal or as bright as snow," he says, with either case generating substantially different size estimates.

Sheppard was in Chile in March, combing the sky as part of his scheduled survey. It will take some time to review the new data for signs of FarFarOut, but a new detection would provide one more data point for firming up the object's still-hazy route around the sun. Ideally, one last follow-up measurement could yield a final determination of its orbit.

Once FarFarOut's orbit is found, the fun can really begin. Astronomers' catch-all term for icy bodies beyond Neptune is "trans-Neptunian objects," which come in various flavors. Some circle the sun just beyond the giant planet's gravitational reach. Others are scattered farther out in orbits that never take them closer to the sun than the cusp of Neptune's influence, making them seem "detached" from the rest of the solar system that lies closer in. Knowing an orbit "ties into whether we can say anything interesting about what population of trans-Neptunian objects this belongs to," says Michele Bannister, a Queen's University Belfast astronomer who was not involved with Sheppard and Trujillo's work but also hunts for new objects in the solar backwaters.



The most distant solar system object known, informally named "FarFarOut," appears as a faint dot against background stars in this telescopic image. Further studies of FarFarOut could reveal hidden details of our solar system's outer frontier.

SCOTT SHEPPARD CARNEGIE INSTITUTION FOR SCIENCE AND DAVID THOLEN UNIVERSITY OF HAWAII

If, at 140 AUs, FarFarOut is at perihelion—its closest approach to the sun—that would be "amazingly interesting," says Konstantin Batygin, an astronomer at the California Institute of Technology who was not involved in the survey. In 2016, based in part on Sheppard and Trujillo's 2014 speculations about "Planet X," Batygin and his Caltech colleague, astronomer Mike Brown, announced their own search for a similar object, which they prefer to call "Planet Nine." Whatever one might call it, both teams—as well as many other astronomers—have been hunting for this elusive world ever since.

A perihelion of circa 140 AU would demand something weighty—something perhaps like Planet X or Planet Nine—had somehow wrested FarFarOut from the grip of Neptune's gravity. "If that's the case, they tell an extremely important story about Planet Nine," Batygin says. And there is, a priori, good reason to suspect FarFarOut's perihelion is just so: Most objects in the far reaches of the outer solar system are discovered near their closest approach, simply because that is when they reflect the most sunlight and are easiest to spot. But the case of FarFarOut may not be so simple, Batygin says, because Sheppard and Trujillo's survey is changing the rules of the game. "The types of observations Scott and Chad are doing push the boundary," he says. By staring at the sky on a regular basis for an extensive amount of time with state-of-the-art instruments on the world's largest telescopes, the pair is sensitive to dimmer, more distant objects than most other surveys could ever see. That means there is a chance FarFarOut is at a more distant point in its orbit, which, paradoxically, would make it less interesting as far as the search for Planet X or Planet Nine goes. If Sheppard and Trujillo did not catch FarFarOut close to perihelion, "it could be an object in a perfectly normal, highly interacting with Neptune orbit" that never crossed paths with any putative undiscovered planet lurking past Pluto, Bannister says.

Much like Sheppard and Batygin, Bannister also stresses more time and more data are unavoidably needed to know just how significant FarFarOut will be. "It's far too soon to be discussing any implications," she says. "There are no implications for the outer solar system until there's an orbit."

—Nola Taylor Redd

Soap-Bubble Pioneer Is First Woman to Win Prestigious Math Prize

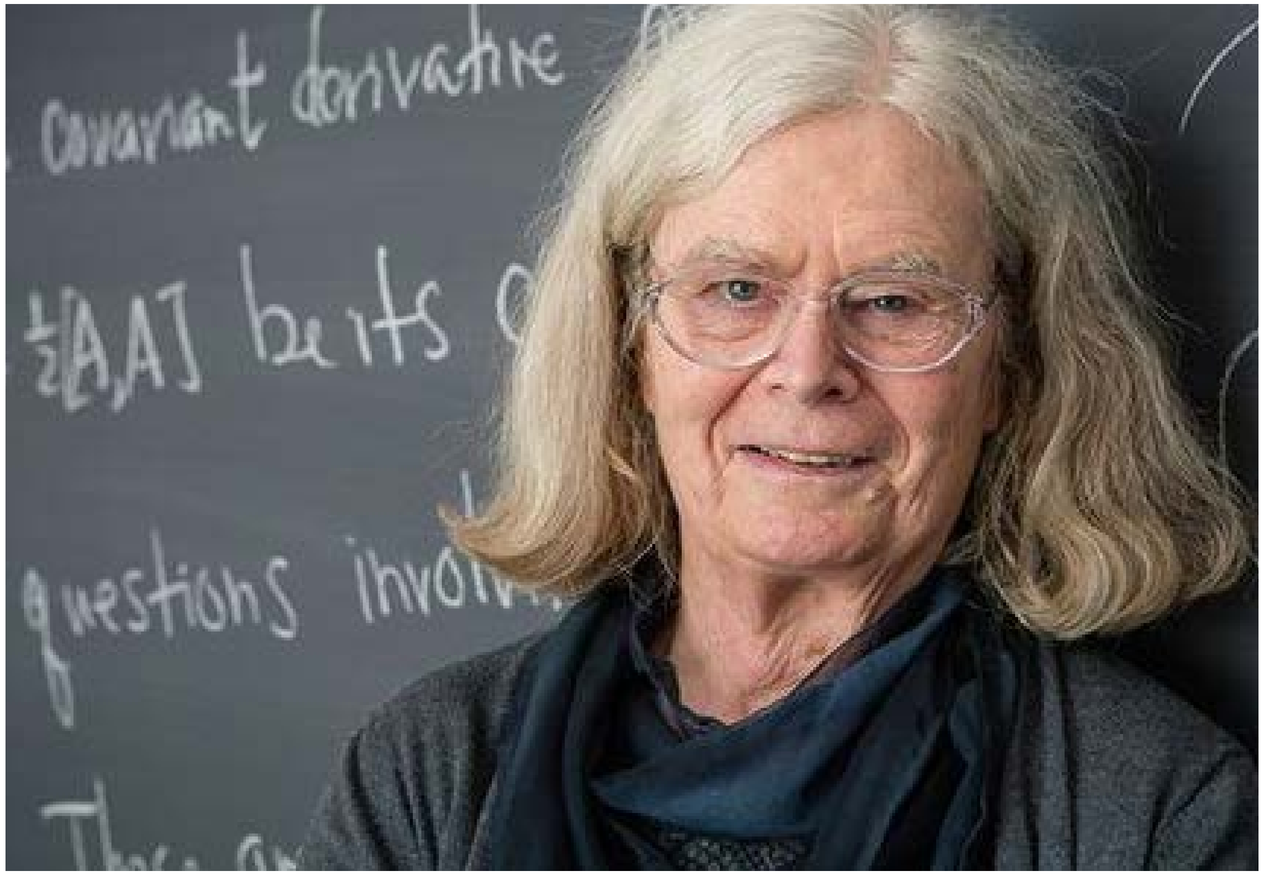
Abel Prize winner Karen Keskulla Uhlenbeck built bridges between analysis, geometry and physics

U.S. MATHEMATICIAN KAREN Keskulla Uhlenbeck has won the 2019 Abel Prize—one of the field's most prestigious awards for her wide-ranging work in analysis, geometry and mathematical physics. Uhlenbeck is the first woman to win the 6-million-kroner (U.S.$702,500) prize, which is given out by the Norwegian Academy of Science and Letters, since it was first awarded in 2003.

Uhlenbeck learned that she had won on March 17, after a friend called and told her that the academy was trying to contact her. "I was completely amazed," she told *Nature*. "It was totally out of the blue." The academy announced the award on March 19.

Uhlenbeck is legendary for her skill with partial differential equations, which link variable quantities and their rates of change, and are at the heart of most physical laws. But her long career has stretched across many fields, and she has used the equations to solve problems in geometry and topology.

One of her most influential results—and the one that she says she's most proud of—is the discovery of a phenomenon called bubbling, as part of seminal work she did with mathematician Jonathan Sacks. Sacks and Uhlenbeck were studying "minimal surfaces," the mathematical theory of how soap films arrange themselves into shapes that minimize their energy. But the theory had been marred by the appearance of points at which energy appeared to become infinitely concentrated. Uhlenbeck's insight was to "zoom in" on those points to show that this was caused by a new bubble



Karen Keskulla Uhlenbeck won the Abel Prize for the fundamental impact of her work on analysis, geometry and mathematical physics.

ANDREA KANE IAS

splitting off the surface.

She applied similar techniques to do foundational work in the mathematical theory of gauge fields, a generalization of the theory of classical electromagnetic fields, which underlies the Standard Model of particle physics.

DISPARATE FIELDS

Uhlenbeck did much of her work in the early 1980s, when research communities that had grown apart were starting to talk to each other again, she recalls. "There was a real flowering of this relationship between mathematics and physics," she says. Mathematicians proved that they had information useful to physicists, who "had great ideas of objects to study that mathematicians couldn't come up with by themselves."

The work of other prizewinning mathematicians has been rooted in techniques introduced by Uhlenbeck, says Mark Haskins, a mathematician at the University of Bath, U.K., who was one of Uhlenbeck's doctoral students. These include 1986 Fields Medal winner Simon Donaldson—who applied gauge theory to the topology of four-dimensional spaces—and 2009 Abel laureate Mikhail Gromov, who studied a mathematical analogue of the "strings" of string theory, in which he found the bubbling idea to be crucial.

Haskins says Uhlenbeck is one of those mathematicians who have "an innate sense of what should be true," even if they cannot always explain why. As a student, he recalls sometimes being baffled by her answers to his questions. "Your immediate reaction was that Karen had misheard you, because she had answered a different question," Haskins says. But "maybe weeks later, you would realize that you had not asked the correct question."

"LEGITIMATE REBELLION"

Karen Keskulla was born in Cleveland, Ohio, in 1942, and grew up in part in New Jersey, intensely interested in learning. "I read all of the books on science in the library and was frustrated when there was nothing left to read," she wrote in a 1996 autobiographical essay.

After an initial interest in physics, she earned her Ph.D. in mathematics in 1968 from Brandeis University in Waltham, Massachusetts. She was one of the few women in her department; some academics there recognized her unusual talent and encouraged her, but others did not. "We were told that we couldn't do math because we were women," she wrote in the 1996 essay. "I liked doing what I wasn't supposed to do, it was a sort of legitimate rebellion."

> **"I liked doing what I wasn't supposed to do, it was a sort of legitimate rebellion."**
> ***—Karen Keskulla Uhlenbeck***

Uhlenbeck held positions at several universities—initially ignored or marginalized by male colleagues, she says—before settling at the University of Texas at Austin in 1987, where she stayed until she retired in 2014.

RELENTLESS ADVOCATE

Uhlenbeck has been a relentless advocate for women in mathematics, and founded the Women and Mathematics program at the Institute for Advanced Study in Princeton, New Jersey. "She has been an enormous role model and mentor for many generations of women," says Caroline Series, a mathematician at the University of Warwick in Coventry, U.K., and the president of the London Mathematical Society.

In 1990, she gave a plenary speech at the International Congress of Mathematicians—the only woman to have done so apart from Emmy Noether, the founder of modern algebra, who spoke at the 1932 meeting. Uhlenbeck has earned several other top recognitions, including the U.S. National Medal of Science in 2000.

Uhlenbeck was at first a reluctant role model. But after a few successes by female mathematicians of her generation, she realized that the path toward fair representation would be harder than expected. "We all thought that once the legal barriers were down, women and minorities would walk through the doors of academia and take their rightful place." But fixing universities was easier than fixing the culture in which people grow up, says Uhlenbeck. She hopes that her prize will inspire new generations of girls to go into math, just as Noether and others inspired her.

—Davide Castelvecchi

This article is reproduced with permission and was first published in Nature *on March 19, 2019.*

How Long Do Neutrons Live? Physicists Close In on Decades-Old Puzzle

Researchers are narrowing down their measurements of how long the subatomic particle survives on its own

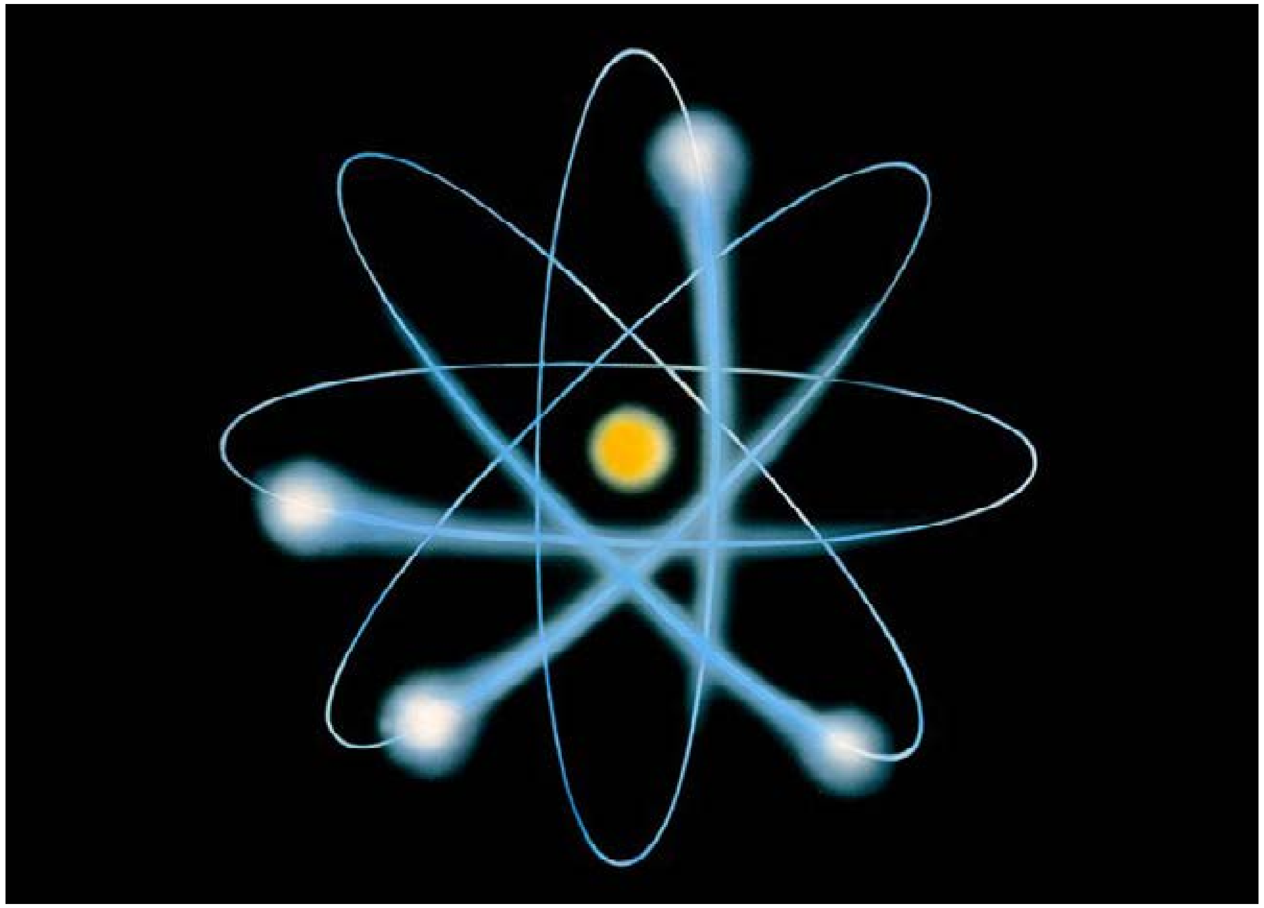
PHYSICISTS ARE DRAWING closer to answering a long-standing mystery of the universe: how long a neutron lives.

Neutrons are electrically neutral particles that usually combine with protons to make up atomic nuclei. Some neutrons are not bound up in atoms; these free-floating neutrons decay radioactively into other particles in a matter of minutes.

But physicists can't agree on precisely how long it takes a neutron to die. Using one laboratory approach, they measure the average neutron lifetime as 14 minutes 39 seconds. Using a different approach, they get eight seconds longer. The discrepancy has bedeviled researchers for nearly 15 years.

"We don't know why they're different," says Shannon Hoogerheide, a physicist at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. "We really need to understand and eliminate this discrepancy." She and other scientists debated new ways to solve the problem on April 13 and 14 at a meeting of the American Physical Society in Denver, Colorado.

Pinpointing the lifetime of a neutron is important for understanding how much hydrogen, helium and other light elements formed in the first few minutes after the universe was born in the big bang, 13.8 billion years ago. Scientists also think they can hunt for new types of physics if they can better pin down the neutron's lifetime, because that would help to constrain measurements of other subatomic particles.



MICHAEL GILBERT *GETTY IMAGES*

SUBATOMIC CLOCK

James Chadwick discovered the neutron in 1932, but it wasn't until 1951 that researchers first reported measuring the particle's lifetime, using nuclear reactors that manufactured free neutrons and tracked how they decayed. Physicists kept working their way closer to the answer—until 2005, when their measurements became precise enough to reveal the puzzling eight-second difference. Then scientists got worried.

One way of clocking the neutron's lifetime is to put some of the particles in a bottle and count how many are left after a period of time. This "bottle" method has been tried at several laboratories, including the Los Alamos National Laboratory in New Mexico and the Institut Laue–Langevin (ILL) in Grenoble, France. On average, they come up with a neutron lifetime of 14 minutes 39 seconds.

The other way is to feed neutrons into a detector that counts the protons created as the neutrons decay. This "beam" method has been used at NIST and the Japan Proton Accelerator Research Complex in Tokai. The Japanese work has just got under way, but the NIST collaboration reported in 2013 that their neutrons live eight seconds longer, on average, than seen in the bottle method.

That's a big problem, because the beam and bottle measurements are each so precise that they don't overlap, even when their margins of error are taken into account. So physicists have been looking for ways to explain why neutrons might be disappearing from bottles faster than from beams.

QUANTUM WEIRDNESS

One possibility is that one of the two methods is doing something wrong. In that case, researchers might want to combine beam and bottle in a single device. At the meeting, physicist Zhaowen Tang of the Los Alamos lab described how researchers could put a particle detector inside a bottle neutron trap and count neutrons using both methods. His team has acquired funding to start building the device.

Another possibility is that the beam and bottle approaches have been measuring the neutron lifetime correctly, but that some unseen factor accounts for the discrepancy between the two. A leading idea is that neutrons might occasionally decay into not just protons but also dark matter, the mysterious unseen material that makes up much of the universe's matter.

"It would be amazing if the good old neutron turns out to be the particle that opens the gates of the dark sector for us," says Bartosz Fornal, a theoretical physicist at the University of California, San Diego, who helped to propose the idea last year. But so far, experimentalists haven't been able to confirm whether this might be happening, several teams reported at the Denver meeting.

In the meantime, the NIST beam experiment has been gathering fresh data since last year, using sensitive detectors and other components that will make it more precise than previous runs—measuring the neutron lifetime to within one second rather than three to four seconds as has happened so far. "Everybody's waiting for the results from that," says Nadia Fomin, a physicist at the University of Tennessee in Knoxville. And the team is already designing its next-generation experiment, which aims to nail the neutron lifetime within 0.3 seconds.

"We're on the way to pinning this down," says Peter Geltenbort, a physicist at the ILL.

—Alexandra Witze

This article is reproduced with permission and was first published in Nature on April 15, 2019.

A Second Planet May Orbit Earth's Nearest Neighboring Star

Informally called "Proxima c," the candidate world appears to be six times the mass of Earth and orbits in the frigid outskirts of the Proxima Centauri system

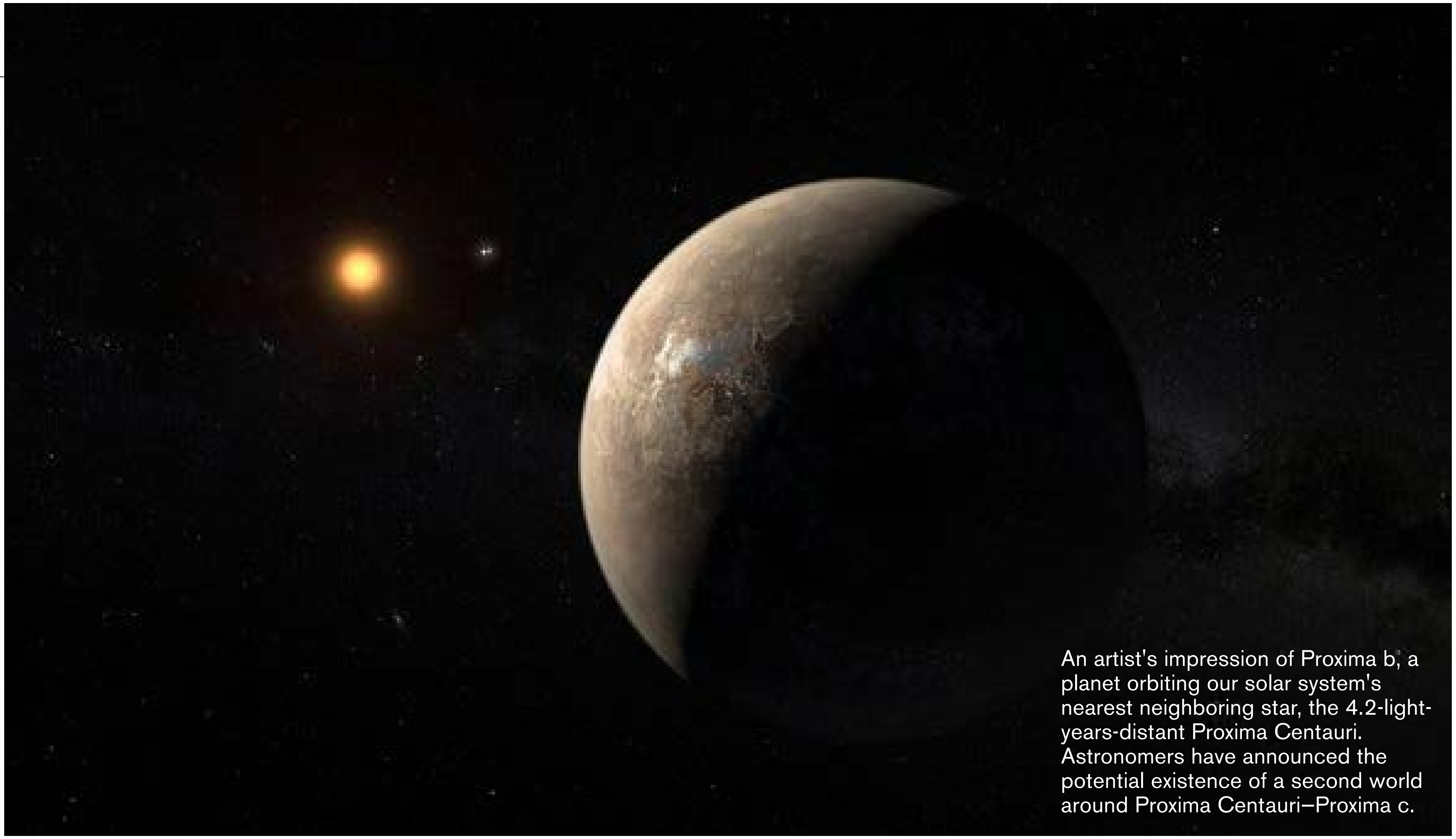
ASTRONOMERS SAY they may have detected a second planet around Proxima Centauri, our solar system's nearest neighboring star.

Announced at Breakthrough Discuss, an annual invitation-only interdisciplinary meeting held by the Breakthrough Initiatives (a scientific research organization primarily bankrolled by the Silicon Valley billionaire Yuri Milner), the planet's existence remains unconfirmed—for now. Dubbed Proxima c, it would be a so-called super-Earth, with a minimum mass roughly six times that of our planet's. Its approximately 1,900-day orbit would likely make it a frigid, inhospitable place, orbiting some 1.5 times the Earth-sun distance from Proxima Centauri—which is a red dwarf star some four light-years away that is much smaller and dimmer than our familiar yellow sun. If confirmed, the newfound world would join Proxima b, a roughly Earth-mass planet discovered in 2016 in a more clement orbit around Proxima Centauri.

According to the scientists making the presentation—Mario Damasso of the Astrophysical Observatory of Turin and Fabio Del Sordo of the University of Crete—the tentative detection is based upon the same expansive multiyear dataset that first revealed Proxima b, with the addition of more than 60 further measurements of the star taken in 2017. Primarily gathered through the European Southern Observatory's (ESO) HARPS instrument, the measurements look for planets by the telltale wobbling such worlds induce upon their host stars. The strength of such wobbles provides an estimate of a world's mass; the wobble's period yields a planet's orbit. Among other incidental evidence, the wobble of Proxima c—a subtle swerve in the position of Proxima Centauri by slightly more than a meter per second—appeared in earlier observations to be of borderline significance, but was pushed into firmer territory by the last few years of additional measurements. The search for Proxima Centauri's planets has been spearheaded by the international Pale Red Dot planet-hunting team. The results are summarized in a paper that has been submitted to a peer-reviewed journal.

"It is only a candidate," Damasso said during the presentation. "This is very important to underline." Del Sordo offered similar cautions in his remarks, comparing the candidate world to a "castle in the air," one that "we should keep working to put even stronger foundations under." (Neither Damasso nor Del Sordo would make further comments on the record outside of their presentation, citing concerns about the embargo policies of the journal to which they submitted their paper.)

Further measurements with HARPS, the pair said, could ultimately confirm the planetary nature of Proxima c, as could follow-up studies with other facilities on the ground and in space. ESO's next-generation planet-hunting ESPRESSO instrument on the Very Large Telescope in Chile, for example, would be able to detect the wobble caused by the candidate world with even higher fidelity. But most promising would be observations from the European Space Agency's Milky-Way-mapping Gaia satellite, which is monitoring the motions and positions of more than a billion stars in our galaxy—including, it turns out, Proxima Centauri. Gaia could detect the planet's presence by watching for wobbles, too. By the conclusion of its nominal five-year mission later this year, Del Sordo said, Gaia could provide "a decisive answer" as to whether or not Proxima c is real.



An artist's impression of Proxima b, a planet orbiting our solar system's nearest neighboring star, the 4.2-light-years-distant Proxima Centauri. Astronomers have announced the potential existence of a second world around Proxima Centauri–Proxima c.

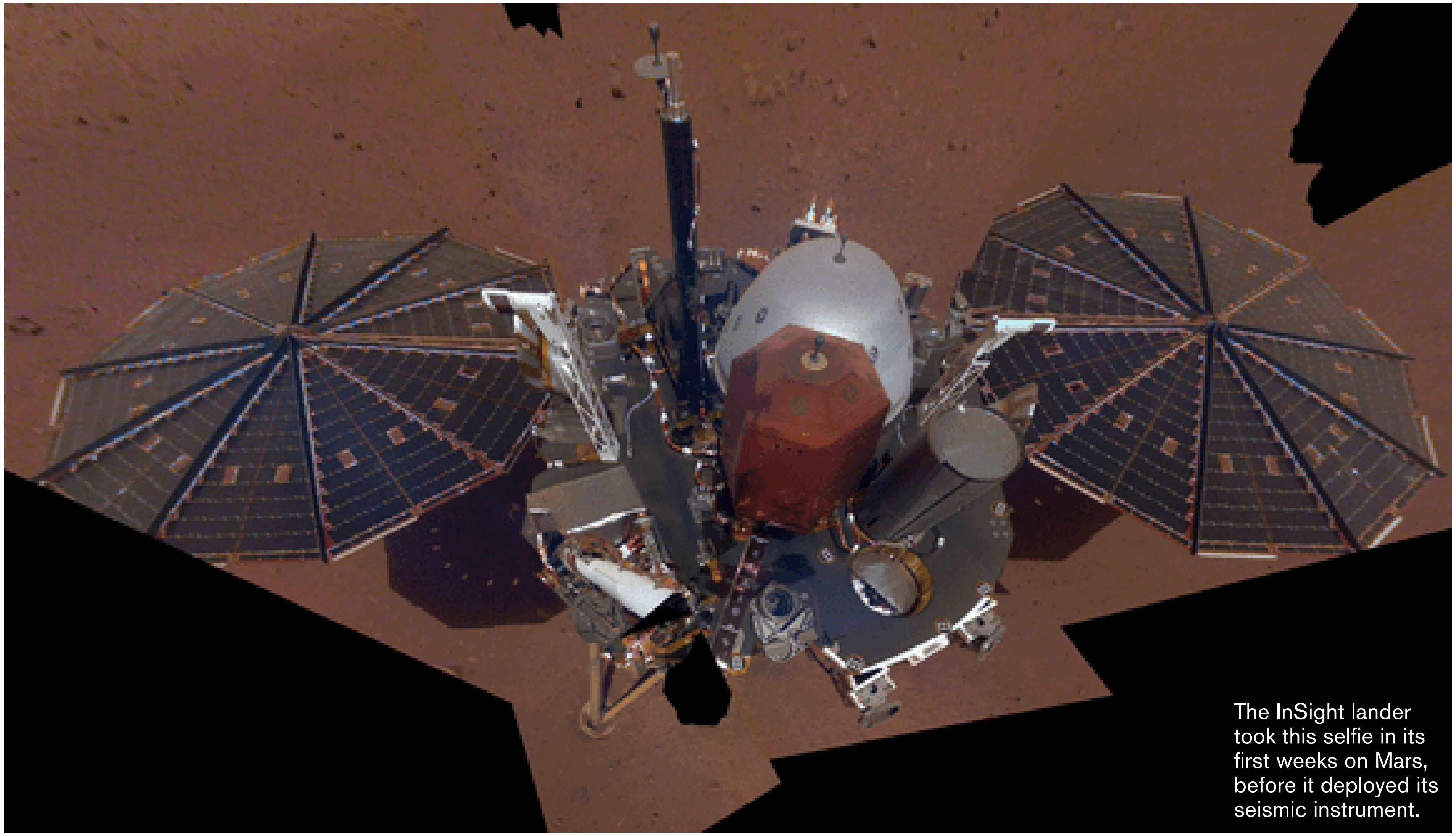
ESO/M. KORNMESSER

Beyond mere detection, the candidate planet would offer exciting opportunities for follow-up studies to characterize its nature, the presenting scientists said. According to Del Sordo, Proxima c would be "a spectacular laboratory for direct imaging"—astronomers' parlance for snapping a planet's picture across the vast gulfs of interstellar space. Proxima b has been discussed as a fruitful target for direct imaging as well. But because Proxima c is farther out from the star than b, it should be easier to see. Potentially within reach of future space observatories such as NASA's James Webb Space Telescope and Webb's planned successor, the Wide-Field Infrared Survey Telescope, the planet could become the first world beyond the solar system imaged in reflected light. (Previous direct images of planets have been in infrared light, where the glare of a planet's star is less overwhelming.)

Any image of Proxima c—presuming the planet proves genuine—would likely reveal a chilly, gas-dominated orb, but could still prove extremely useful for astronomers struggling to understand what super-Earths are actually like. Despite being the most common known variety of planet in the Milky Way, super-Earths are entirely absent from our own solar system. Midway in mass and size between Earth and Neptune, super-Earths may either be mostly gassy planets offering slim chances for life as we know it, or instead super-sized versions of our own habitable, rocky world.

Images of planets in the Proxima Centauri system might also help resolve lingering debates over the potential for red dwarf stars to harbor habitable planets; such stars are often more active than solar-type stars, blasting accompanying worlds with showers of high-speed particles and hard radiation that can strip away atmospheres like so much sand-blasted paint. Pictures could resolve the fates of such worlds—provided, that is, astronomers manage to secure time on Earth's most powerful telescopes to go look.

—Lee Billings



The InSight lander took this selfie in its first weeks on Mars, before it deployed its seismic instrument.

NASA AND JPL-CALTECH

First "Marsquake" Detected on Red Planet

NASA's InSight lander hears seismic energy rippling through Mars

NASA'S INSIGHT LANDER has detected the first known "marsquake."

The spacecraft picked up the faint trembling of Mars's surface on April 6, 128 days after landing on the planet last November. The quake is the first to be detected on a planetary body other than Earth or the moon.

The shaking was relatively weak, the French space agency CNES said on April 23. The seismic energy it produced was similar to that of the moonquakes that Apollo astronauts measured in the late 1960s and early 1970s.

"We thought Mars was probably going to be somewhere between

Earth and the moon" in terms of seismic activity, says Renee Weber, a planetary scientist at NASA's Marshall Space Flight Center in Huntsville, Alabama. "It's still very early in the mission, but it's looking a bit more moon-like than Earth-like," she says.

It's not yet clear whether the shaking originated within Mars or was caused by a meteorite crashing into the planet's surface.

David Mimoun, a scientist with the mission at the Institut Supérieur de l'Aéronautique et de l'Espace in Toulouse, France, says that the signal is so weak that it would not have been detected on Earth. "It's so small that at the beginning we were wondering if it was a quake or something else," he says.

EARS TO THE GROUND

InSight heard the marsquake using a French-built instrument that contains three extremely sensitive seismometers nestled inside a dome to protect them from the wind. Mission scientists had previously observed vibrations caused by the Martian wind blowing overhead. But the seismic characteristics of the April 6 event show that it came from within the planet.

> **"In my ideal universe, Mars would be having giant marsquakes all the time."**
> ***—Mark Panning***

"This signal was not like anything we'd seen before," says Mark Panning, a planetary seismologist at NASA's Jet Propulsion Laboratory in Pasadena, California.

Team scientists can't tell where the quake originated. Determining that would allow them to trace how seismic energy radiated through the planet, and to begin to understand the planet's interior structure—InSight's main goal. The spacecraft is meant to operate for one Martian year, or nearly two Earth years. "We've got time," says Panning. "In my ideal universe, Mars would be having giant marsquakes all the time."

InSight detected three other possible marsquakes, on March 14, April 10 and April 11. But they were even fainter than the April 6 event and their source is still unclear.

The spacecraft is working on Elysium Planitia, near Mars's equator. Mission controllers are still trying to figure out how to unstick its German-built heat probe. It became lodged on what is probably a buried rock in February, as it tried to hammer itself into the ground to measure temperatures there.

—Alexandra Witze

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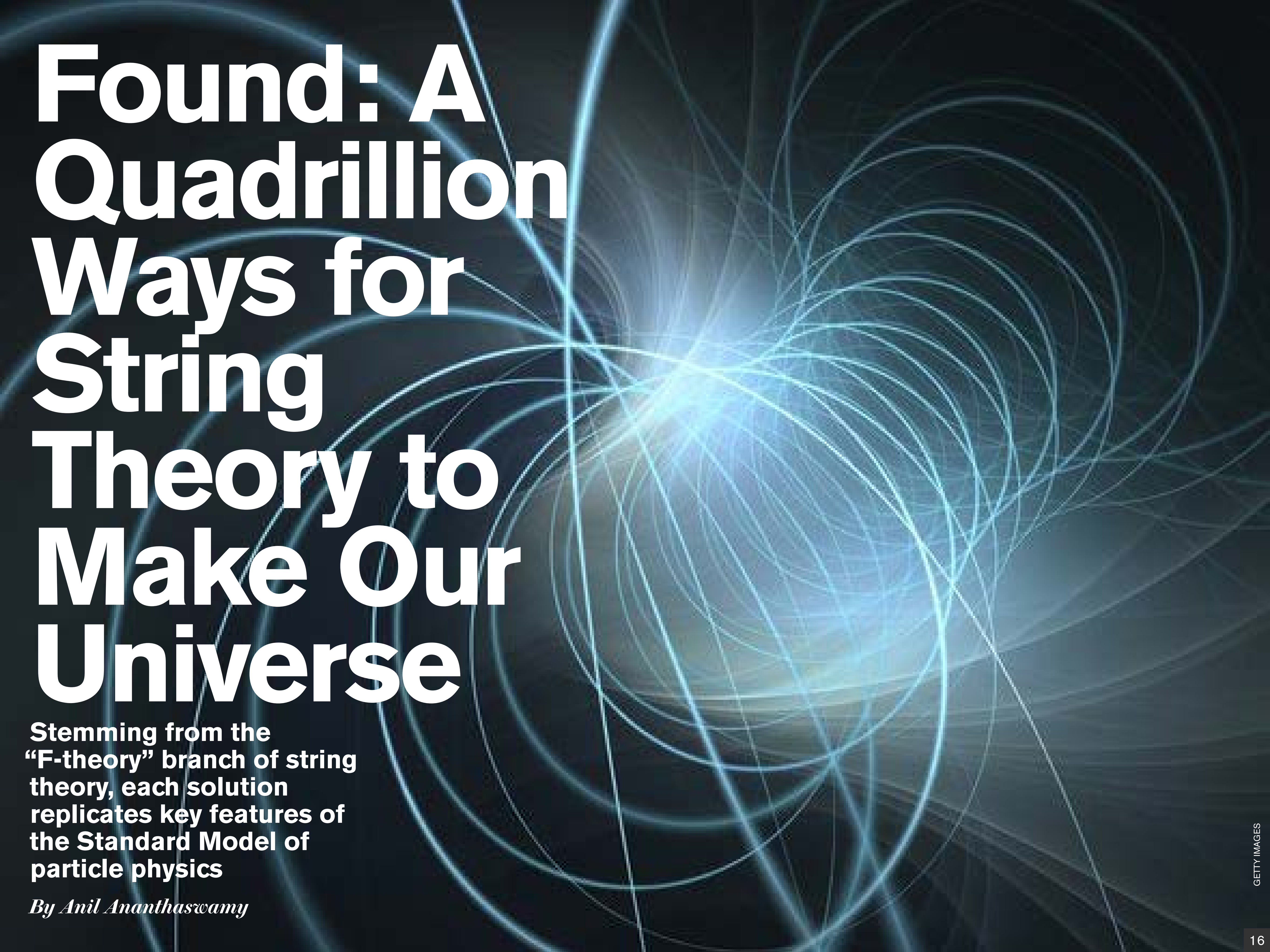


GETTY IMAGES

Found: A Quadrillion Ways for String Theory to Make Our Universe

Stemming from the "F-theory" branch of string theory, each solution replicates key features of the Standard Model of particle physics

By Anil Ananthaswamy

Anil Ananthaswamy is the author of *The Edge of Physics*, *The Man Who Wasn't There* and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality.*

PHYSICISTS WHO HAVE BEEN ROAMING THE “LANDSCAPE” of string theory—the space of zillions and zillions of mathematical solutions of the theory, where each solution provides the kinds of equations physicists need to describe reality—have stumbled upon a subset of such equations that have the same set of matter particles as exists in our universe.

But this is no small subset: there are at least a quadrillion such solutions, making it the largest such set ever found in string theory.

According to string theory, all particles and fundamental forces arise from the vibrational states of tiny strings. For mathematical consistency, these strings vibrate in 10-dimensional spacetime. And for consistency with our familiar everyday experience of the universe, with three spatial dimensions and the dimension of time, the additional six dimensions are “compactified” so as to be undetectable.

Different compactifications lead to different solutions. In string theory, a “solution” implies a vacuum of spacetime that is governed by Einstein’s theory of gravity coupled to a quantum field theory. Each solution describes a unique universe, with its own set of particles, fundamental forces and other such defining properties.

Some string theorists have focused their efforts on trying to find ways to connect string theory to properties of our known, observable universe—particularly the Standard Model of particle physics, which describes all known particles and all their mutual forces except gravity.

Much of this effort has involved a version of string theory in which the strings interact weakly. However, in the past two decades, a new branch of string theory called F-theory has allowed physicists to work with strongly interacting, or strongly coupled, strings.

“An intriguing, surprising result is that when the coupling is large, we can start describing the theory very geometrically,” says Mirjam Cvetic of the University of Pennsylvania in Philadelphia.

This means that string theorists can use algebraic geometry—which uses algebraic techniques to tackle geometric problems—to analyze the various ways of compactifying extra dimensions in F-theory and to find solutions. Mathematicians have been independently studying some of the geometric forms that appear in F-theory. “They provide us physicists a vast toolkit,” says Ling Lin, also of the University of Pennsylvania. “The geometry is really the key… it is the ‘language’ that makes F-theory such a powerful framework.”

Now, Cvetic, Lin, James Halverson of Northeastern University in Boston, and their colleagues have used such techniques to identify a class of solutions with string vibrational modes that lead to a similar spectrum of fermions (or, particles of matter) as is described by the Standard Model—including the property that all fermions come in three generations (for example, the electron, muon and tau are the three generations of one type of fermion).

The F-theory solutions found by Cvetic and colleagues have particles that also exhibit the handedness, or chirality, of the Standard Model particles. In particle physics lingo, the solutions reproduce the exact “chiral spectrum” of Standard Model particles. For example, the quarks and leptons in these solutions come in left and right-handed versions, as they do in our universe.

The new work shows that there are at least a quadrillion solutions in which particles have the same chiral spectrum as the Standard Model, which is 10 orders of magnitude more solutions than had been found within string theory until now. “This is by far the largest domain of Standard Model solutions,” Cvetic says. “It’s somehow surprising and actually also rewarding that it turns out to be in the strongly coupled string theory regime, where geometry helped us."

A quadrillion—while it's much, much smaller than the size of the landscape of solutions in F-theory (which at last count was shown to be of the order of $10^{272,000}$)—is a tremendously large number. "And because it's a tremendously large number, and it gets something nontrivial in real world particle physics correct, we should take it seriously and study it further," Halverson says.

Further study would involve uncovering stronger connections with the particle physics of the real world. The researchers still have to work out the couplings or interactions between particles in the F-theory solutions—which again depend on the geometric details of the compactifications of the extra dimensions.

It could be that within the space of the quadrillion solutions, there are some with couplings that could cause the proton to decay within observable timescales. This would clearly be at odds with the real world, as experiments have yet to see any sign of protons decaying. Alternatively, physicists could search for solutions that realize the spectrum of Standard Model particles that preserve a mathematical symmetry called R-parity. "This symmetry forbids certain proton decay processes and would be very attractive from a particle physics point of view, but is missing in our current models," Lin says.

Also, the work assumes supersymmetry, which means that all the Standard Model particles have partner particles. String theory needs this symmetry in order to ensure the mathematical consistency of solutions.

But in order for any supersymmetric theory to tally with the observable universe, the symmetry has to be broken (much like how a diner's selection of cutlery and drinking glass on her left or right side will "break" the symmetry of the table setting at a round dinner table). Else, the partner particles would have the same mass as Standard Model particles—and that is clearly not the case, since we don't observe any such partner particles in our experiments.

Crucially, experiments at the Large Hadron Collider (LHC) have also shown that supersymmetry—if it is the correct description of nature—is not broken even at the energy scales probed by the LHC, given that the LHC has yet to find any supersymmetric particles.

String theorists think that supersymmetry might be broken only at extremely high energies that are not within experimental reach anytime soon. "The expectation in string theory is that high-scale [supersymmetry] breaking, which is fully consistent with LHC data, is completely possible," Halverson says. "It requires further analysis to determine whether or not it happens in our case."

Despite these caveats, other string theorists are approving of the new work. "This is definitely a step forward in demonstrating that string theory gives rise to many solutions with features of the Standard Model," says string theorist Washington Taylor of MIT.

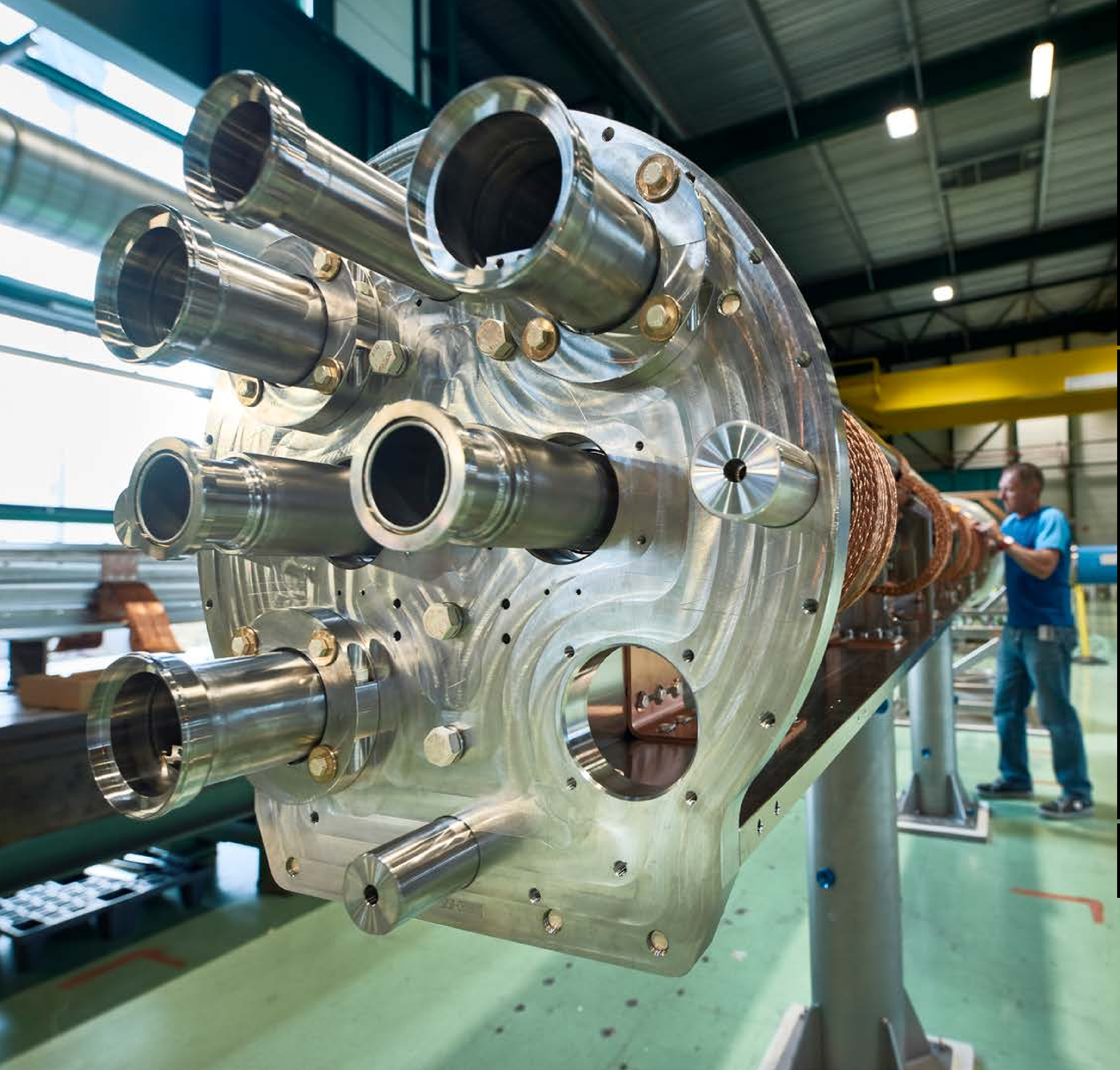
"It's very nice work," says Cumrun Vafa, one of the developers of F-theory, at Harvard University. "The fact you can arrange the geometry and topology to fit with not only Einstein's equations, but also with the [particle] spectrum that we want, is not trivial. It works out nicely here."

But Vafa and Taylor both caution that these solutions are far from matching perfectly with the Standard Model. Getting solutions to match exactly with the particle physics of our world is one of the ultimate goals of string theory. Vafa is among those who think that, despite the immensity of the landscape of solutions, there exists a unique solution that matches our universe. "I bet there is exactly one," he says. But, "to pinpoint this is not going to be easy."

CERN's Next Big Thing

After 10 years in operation, the largest particle accelerator in the world is undergoing major upgrades, and researchers are throwing their effort behind new future technologies

By Christine-Maria Horejs and Giulia Pacchioni



Close-up on new connection cryostat being built for the High-Luminosity LHC upgrade scheduled for 2026.

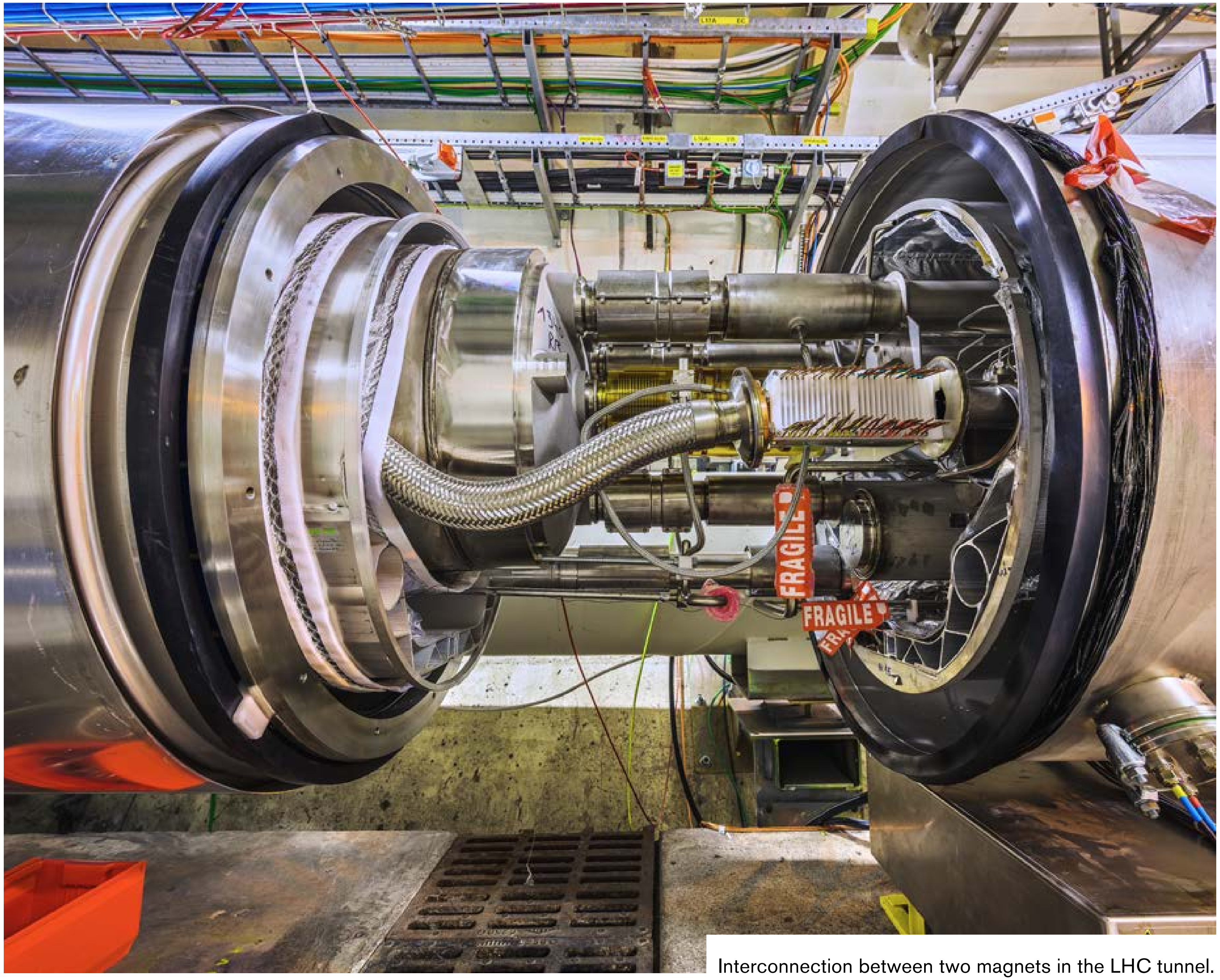
JULIEN MARIUS ORDAN

Christine-Maria Horejs is an associate editor and
Giulia Pacchioni is the senior editor at *Nature Reviews Materials.*

The Large Hadron Collider (LHC) is the largest particle accelerator in the world. But, after 10 years of operation, it's time to think about the next steps. With one approved upgrade—the High-Luminosity LHC—and design studies for possible future colliders on the table, intense efforts are being directed to the development of new technologies.

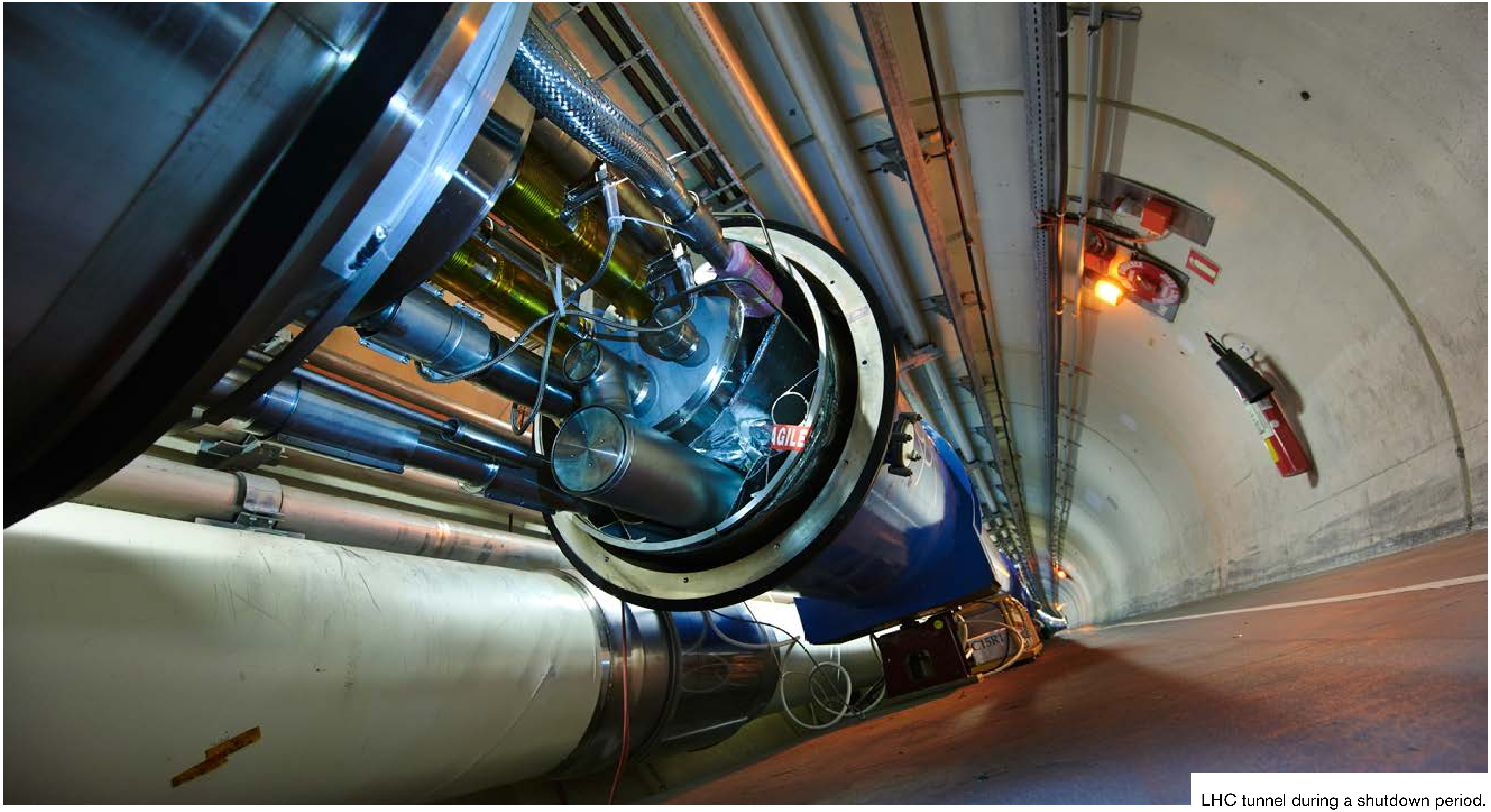
In September 2008, the champagne corks popped in the CERN control room as physicists and engineers celebrated the first beam in the Large Hadron Collider. It was the beginning of a decade of exciting science, the discovery of the Higgs boson being the highlight. The LHC confirmed many predictions of the Standard Model of particle physics, but it also raised unsettling questions—such as why the Higgs boson is so light, and why there is no sign of supersymmetry. Ten years on, physicists feel increasing pressure to find answers to these questions. A next-generation particle collider could be what's needed to reveal physics beyond the Standard Model.

CERN is on the case. One upgrade is already underway and will be operational in 2026: the High-Luminosity LHC (HL-LHC) will be housed in the LHC tunnel, but with innovative magnets



Interconnection between two magnets in the LHC tunnel.

MAXIMILLIEN BRICE AND JULIEN MARIUS ORDAN


LHC tunnel during a shutdown period.

MAXIMILLIEN BRICE AND JULIEN MARIUS ORDAN

and radiofrequency (RF) cavities that will substantially increase the luminosity (that is, the statistics of the measurements). The energy will be the same as that of the LHC (14 tera electron volts [TeV]), and the plan is to use the HL-LHC to extend the operational lifetime of the LHC until 2040.

But the community is already looking at the future of collider physics beyond 2040, and three proposals for building circular colliders at CERN are on the table. There are two options for a future circular collider (FCC) that would fit in a new 100-kilometer-long tunnel: a lepton-lepton collider or a hadron-hadron collider, with an energy of 100 TeV. Alternatively, on a smaller scale, a high-energy LHC could run in the existing LHC tunnel but use new magnets to reach an energy of 27 TeV. “It could be a long journey if things go well—a journey of several generations,” comments Günther Dissertori, chair of the FCC International Advisory Board and professor of physics at ETH.

A new big circular collider is the preferred option of many at CERN. The lepton and hadron colliders could be implemented one after the other, as it happened for CERN’s large electron-positron collider (LEP) from 1989 to 2000 and then the LHC from 2008. The lepton collider

Artistic 3-D view of the proposed new 100-km tunnel that could host different colliders.

PANAGIOTIS CHARITOS

would run for 15 years, performing precision measurements of known particles and possibly measuring deviations from the predictions of the Standard Model; over this period of time, the technology for the magnets needed for the hadron collider would mature, and the hadron machine could then be used to look for new particles at much higher energies than currently available. “This package is what makes the overall project so interesting; it is the combination that makes the physics,” adds Dissertori.

However, a lot of technological developments are needed, in particular for the RF cavities, which accelerate the particles, and for the magnets, which bend and focus the particle beam. Both will need to be made of high-performance superconducting materials: the cavities to withstand the very high electric fields that will be generated at their interior and the magnets to sustain electrical currents intense enough to generate the desired high magnetic fields, which determine the maximum energy of the beam.

THE APPROVED UPGRADE: HL-LHC

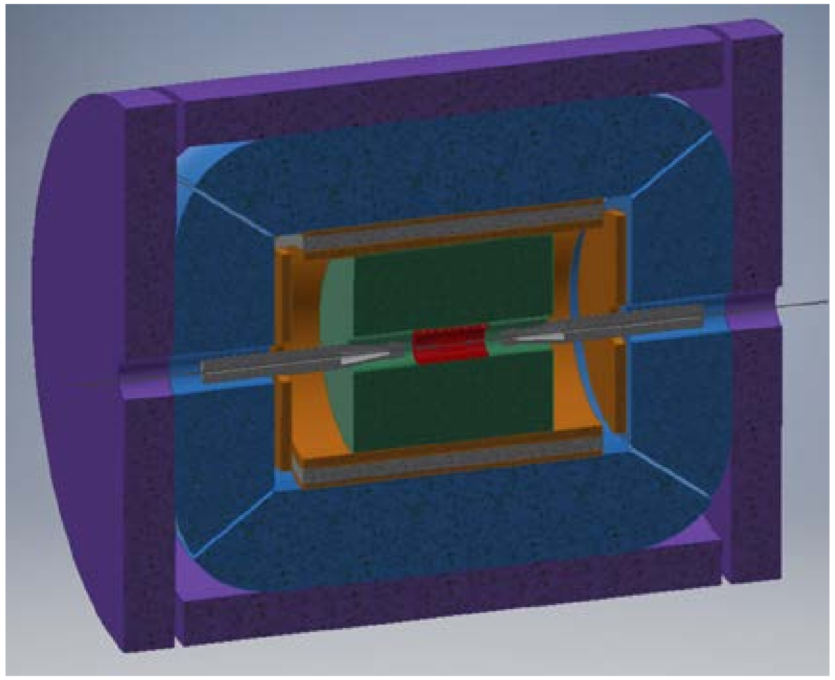
By “luminosity” particle physicists mean the number of collisions that can be produced in a detector per square centimeter per second. More collisions mean better statistics and thus a better chance to study very rare processes. The HL-LHC will have a luminosity 10 times higher than that of the LHC, so the hope is to observe subtle deviations from the predictions of the Standard Model.

At the heart of the high-luminosity upgrade are magnets made of Nb_3Sn—a superconducting material never used before in accelerators. These magnets can reach magnetic fields of up to 12 tesla (the LHC uses Nb-Ti magnets producing fields of 8 tesla). Different designs for the magnets are being tested at CERN and in collaborating laboratories in the U.S., and after two years of work, the performance is approaching the desired specifications. The HL-LHC Nb_3Sn magnets will be cooled by 1.9-kelvin superfluid helium but could also operate at 4.2 kelvin, whereas the Nb-Ti magnets of the LHC need to be cooled to 1.9 kelvin. It might seem like a small difference, but the energy savings would be substantial.

Nb_3Sn is the superconductor of choice for all future high-field magnets at CERN, but is not straightforward to use. In its superconducting form, Nb_3Sn is as brittle as glass and thus cannot withstand a cabling process. Therefore, nonsuperconducting wires composed of Nb and Sn, embedded in a copper matrix, must first be assembled into cables and then heat-treated for several days to react into the superconducting Nb_3Sn phase. For HL-LHC, all the cables will be manufactured at CERN or in collaborating labs in the U.S.

The other superconducting material that will have an important role in the HL-LHC is MgB_2, which has a critical temperature of 39 kelvin and therefore can be cooled with gaseous He. It will be used in the power lines transporting current from the power converters to the accelerator magnets. As a spinoff, researchers at CERN are currently working with companies to develop power lines that will reduce inefficiencies in power distribution.

Another key component that had to be developed for HL-LHC are new RF cavities, called crab cavities, that are made of bulk Nb. They are shaped in a special geometry that tilts the beams to maximize the overlap at the collision point, boosting the number of collisions. The crab cavities are currently being tested in the Super Proton Synchrotron (SPS), one of the older particle accelerators at CERN. Finally, the collimators, which absorb particles that stray from the beam, had to be improved for the HL-LHC to cope with the higher number of particles.



Preliminary design of a future detector for a precision-frontier lepton circular collider (FCC-ee).

Beyond its scientific mission, the HL-LHC also functions as a validator of new technologies that would be used in the FCC, such as the Nb_3Sn magnets. “We need to test the new material, otherwise, who would pay for a FCC that is based on an untested technology?” comments Lucio Rossi, leader of the HL-LHC project.

THE PROPOSED UPGRADE: FCC

If approved, the FCC will work at the energy frontier of particle accelerators and set the stage for the future of high-energy physics. More than 135 international institutions collaborate on the project. The building works would start in 2028 and be complete in 2040.

The FCC will comprise a 100-kilometer circular accelerator, 16 tesla magnets and next-generation superconducting RF cavities. The ring will be linked to the current accelerators, which will be used as injector machines—indeed, at CERN, every accelerator of the past feeds into the new ones.

A lepton collider could provide ultraprecise measurements of known particles of the Standard Model to determine their exact parameters. It would collide particles at energies ranging from 90 giga electron volts (GeV) to 365 GeV. These are low compared with the collision energies reached at the LHC, but are relevant for studying the W and Z bosons, Higgs boson and top quarks (which have masses of 80 GeV, 91 GeV, 125 GeV and 173 GeV, respectively). A lepton collider would also work as a Higgs factory, producing billions of Higgs bosons and allowing the detailed investigation of their coupling and interactions.

A hadron collider could produce particles with much higher mass (up to 20-30 TeV) that are beyond the energy limits of the LHC. Completely new energy scales would be probed. However, substantial technological developments are needed before the FCC can become reality. Major research and development programs are focused on high-field superconducting magnets and superconducting RF cavities, and, not to forget, a 100-kilometer-long circular tunnel will need to be built. For this, new civil engineering software has been developed to optimize the tunneling in the mountainous region between France and Switzerland. The tunnel would be the longest in the world (the Gott-hard tunnel, currently the longest, is 57 kilometers long), and tunneling and infrastructure costs would account for about 30 percent of the FCC budget.

MAGNETS—IT’S ALL ABOUT SUPERCONDUCTIVITY

Although Nb_3Sn magnets will be used in the HL-LHC, further improvements are needed to reach the 16-tesla fields that are required for the FCC. Therefore, a major research program at CERN focuses on different options to increase the performance of Nb_3Sn magnets, for example, by introducing new production processes and by optimizing the

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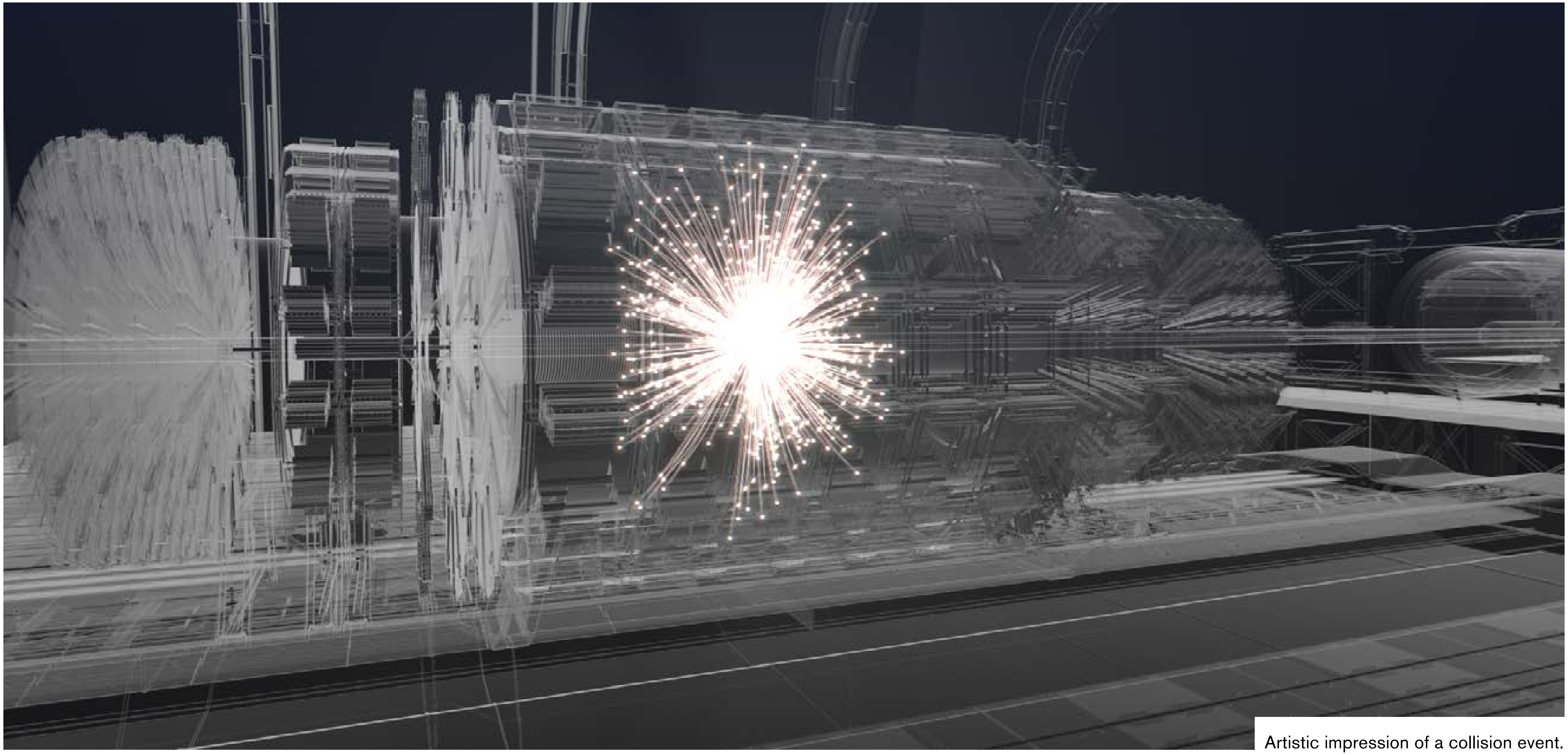

Artistic impression of a collision event.

PANAGIOTIS CHARITOS

critical current density of Nb_3Sn through grain refinement and artificial pinning. “The magnets for future higher-energy accelerators require fundamental research on superconductors to achieve the targets in performance and cost,” says Amalia Ballarino, from CERN.

A variety of other superconducting materials are also being developed and tested in labs all over the world, but can often be made only in the form of thin films and are difficult to produce on a large scale. The possibility of using high-temperature superconductors is also being discussed, but these materials are not yet mature enough (even though the design of a proposed big circular collider in China, which would also have a diameter of 100 kilometers, includes high-temperature superconductors for the magnets).

Once the magnets are ready, the interconnections between the different elements in the accelerator also need to be optimized. Therefore, it is important that scientists and engineers collaborate from the beginning. “It is not rocket science, but it is very complex,” says Rossi. “Getting older, I realized the importance of interfaces: if the welding does not work, nothing works.”

RF CAVITIES—MATERIAL CHALLENGES AHEAD

In the FCC, energy losses caused by synchrotron radiation will be as high as 100 megawatts. They will need to be compensated by superconducting RF cavities, which will need to accelerate the beam very efficiently; thus, a massive step forward is required in RF cavity research.

The electromagnetic field in the RF cavities oscillates at a specific frequency, providing the electromagnetic field needed to accelerate the particles. The shape and size of the cavities determine the resonance frequency. Various cavity architectures and material processing approaches are currently being tested at CERN. Pure Nb is the superconductor of choice here—there are not many other superconducting materials compatible with RF cavities. In addition, experimental prototype cavities with a Nb_3Sn coating have been produced; however, the brittleness of Nb_3Sn poses an even greater challenge when it comes to RF cavities, because to make the cavities resonant at a specific frequency (tuning), they have to be slightly deformed. Researchers at CERN are currently also looking at the possibility of coating copper cavities internally with Nb_3Sn, using an intermediate tantalum layer to avoid diffusion of copper into the superconducting layer. They are also testing alternative tuning methods to avoid cracking of Nb_3Sn.

THE FUTURE

The LHC is a marvel of engineering. Building an even bigger collider seems unthinkable but, in the words of Captain Jean Luc Picard, "things are only impossible until they're not." And it's not only CERN that is dreaming big: various options for future colliders are being discussed, including a linear collider in Japan and a circular collider in China. But no matter which future collider becomes a reality, beyond their potential for scientific discovery, these big machines will undoubtedly have a huge impact on the progress of material science and engineering.

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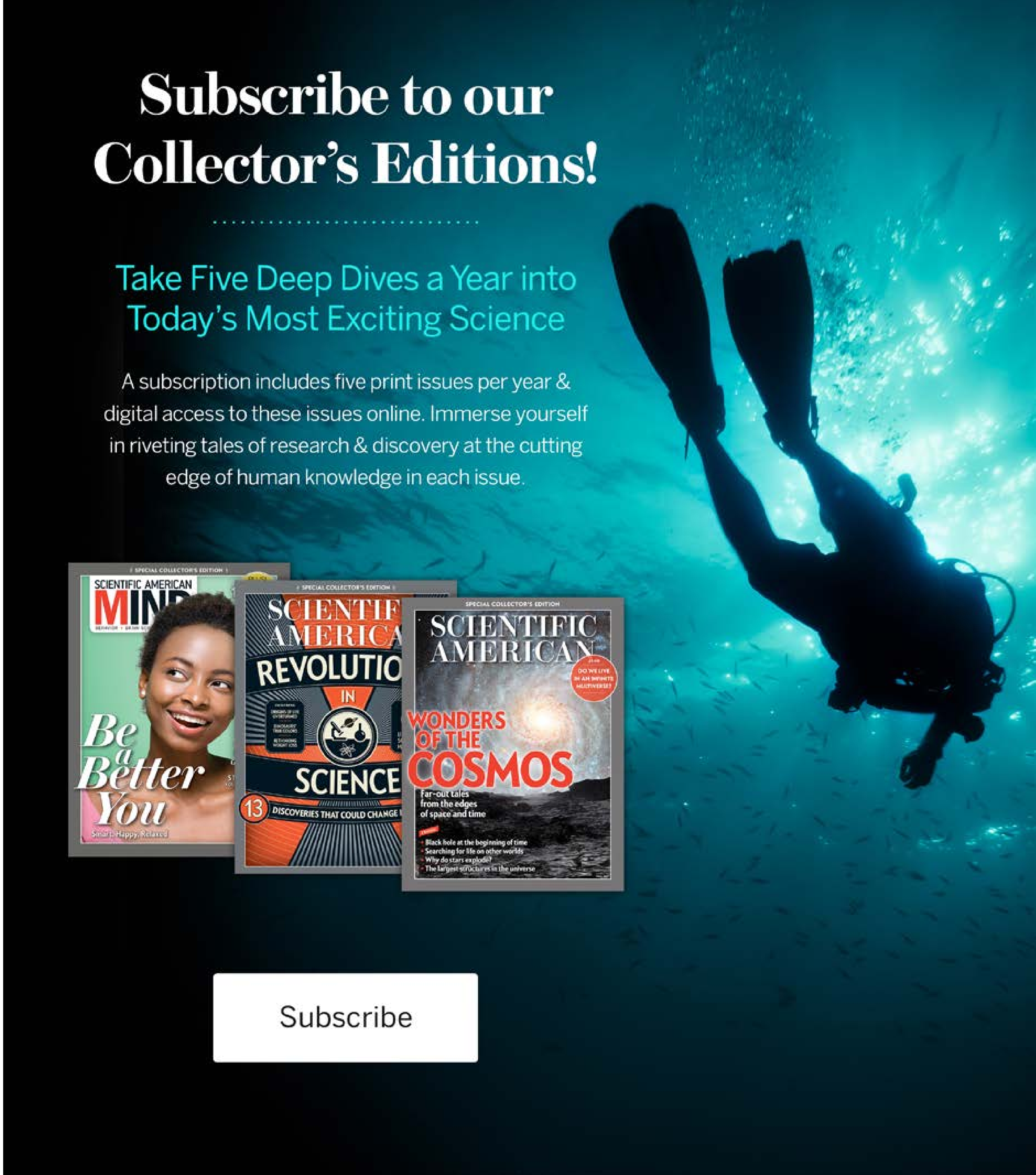
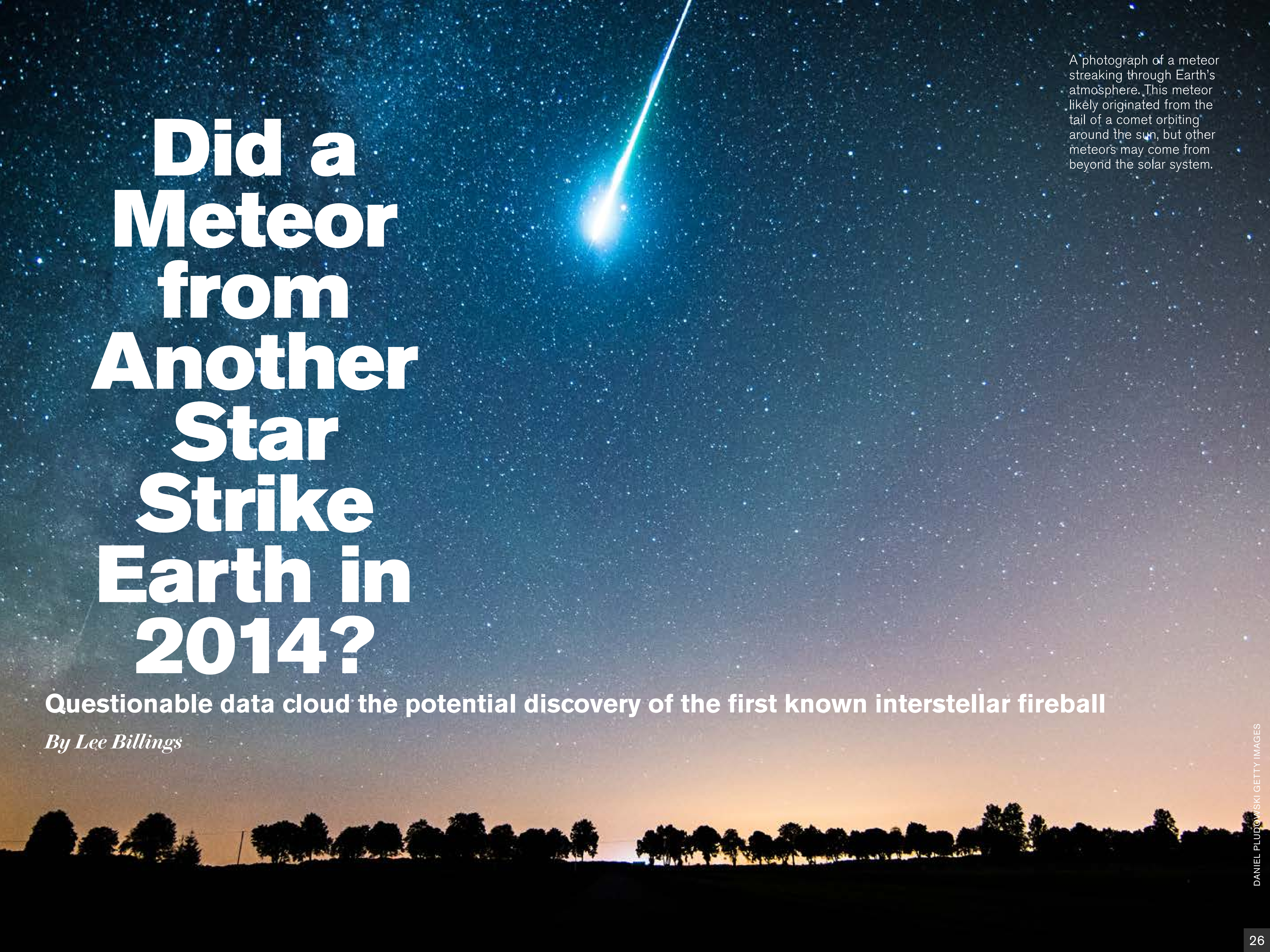


Did a Meteor from Another Star Strike Earth in 2014?

Questionable data cloud the potential discovery of the first known interstellar fireball

By Lee Billings



A photograph of a meteor streaking through Earth's atmosphere. This meteor likely originated from the tail of a comet orbiting around the sun, but other meteors may come from beyond the solar system.

DANIEL PLUDOWSKI GETTY IMAGES

Lee Billings is a senior editor at *Scientific American.* He covers space and physics.

By most standards, space is exceedingly empty, containing on average just one proton per four cubic meters of volume. In this cosmic ocean, so incomprehensibly desolate and vast, entire galaxies are akin to scattered spots of sea foam—not to mention the stars, planets and other lesser objects that fade to insignificance against the void. For random clumps of matter adrift in the deep to somehow find each other seems to border on the miraculous.

Yet find each other they do, and in surprising numbers. Stars and planets routinely hurl smaller objects into interstellar space as an inescapable consequence of orbital mechanics. And the recent discovery of ‘Oumuamua—a mysterious and first-of-its-kind interstellar object spied by chance when it passed close by our sun last year—confirms as much. Statistical extrapolations suggest that a quadrillion trillion similar objects may lurk as yet unseen in the dark spaces between the stars of the Milky Way, so many that there should always be one such far-flung passerby flying through the notional sphere bounded by Earth’s orbit around our star. With an estimated size of roughly half a kilometer, ‘Oumuamua in some respects represents the tip of the interstellar iceberg; just as grains of sand greatly outnumber large rocks on a beach, for every ‘Oumuamua-sized body wandering the galaxy there should be many, many more objects even smaller. Scientists already know of many microscopic interstellar immigrants—cosmic rays and micron-sized flecks of stardust that occasionally strike spacecraft—but other than ‘Oumuamua, nothing larger has ever definitively been found.

Now two researchers—Avi Loeb, chair of astronomy at Harvard University, and Harvard undergraduate Amir Siraj—say that has changed, arguing that a modest meteor observed in January 2014 was actually an outcast from another star. They detail their result in a preprint submitted for peer-reviewed publication in the *Astrophysical Journal Letters.* If confirmed, the finding could help open a new frontier in the detection and study of interstellar meteors.

A HYPERBOLIC CLAIM

“Previous approaches to this problem were like looking for your keys under a lamppost, where our sun is the lamp illuminating its surroundings and passing interstellar objects are the keys,” Loeb explains. “That’s a good technique—that’s how ‘Oumuamua was found—but it really limits you, particularly in trying to figure out an object’s composition.”

For their study, Loeb and Siraj used a different method, looking for evidence of interstellar objects in more than three decades of data from the Center for Near Earth Object Studies (CNEOS), a NASA-run global catalog of meteors detected by networks of U.S. government sensors.

Because there should be many more interstellar objects at smaller sizes, Loeb says, “there is a good chance those will appear to us as meteors, since the chances of their intersecting Earth are higher.” Monitoring a meteor’s bright trail as it burns up in our planet’s atmosphere can reveal not only the object’s size and composition but also its trajectory and velocity with respect to Earth and the sun. If a meteor’s inferred incoming speed exceeds about 42 kilometers per second—the solar system’s escape velocity in Earth’s vicinity—its trajectory could be considered “hyperbolic,” meaning it could have been an “unbound” interstellar passerby moving too fast to be captured by the sun’s gravity.

Only one event in the CNEOS database met Loeb and Siraj’s conservative criteria: a fireball off the coast of Papua New Guinea on January 8, 2014. According to the pair’s analysis of the CNEOS data, the meteor was half a meter in size and massed nearly 500 kilograms, entering the Earth’s atmosphere at nearly 44 kilometers per second before exploding high above the Pacific Ocean. Tellingly, the meteor’s trail showed it had not impacted Earth head-on, as one might expect of a fast-moving but native object in a retrograde orbit around our star. Instead it appeared to have swooped in from behind, overtaking our planet as the Earth moved around the sun—suggest-ing its actual velocity with respect to our solar system had been in blistering excess of 60 kilometers per second. Reconstructing the object's most probable path to Earth, Loeb and Siraj found no previous close encounters with Jupiter or other large bodies that could have boosted its speed.

The case for the meteor being a rock from another star seemed almost too good to be true, particularly since CNEOS data is best interpreted with caution. The catalog's primary sources are classified Earth-observing satellites operated by the U.S. military, which can record the brightness, orientation and duration of fireballs entering our planet's atmosphere. For reasons of national security, the government refuses to release information about potential sources of uncertainty in the satellites' secretive measurements.

"At first I didn't believe it," Siraj says. For a week, he and Loeb repeatedly checked their analysis of the CNEOS data, always arriving at the same conclusion: the meteor must have had an interstellar origin. Ultimately they chose to test their methods on a different, much more well-studied event—the 20-meter meteor that exploded over and wreaked havoc on the Russian city of Chelyabinsk in 2013. Using video recordings of the Chelyabinsk fireball, "we derived its orbit using our methods, and it was a very close match [to the CNEOS data]," Siraj says. "When I saw that, I thought, 'Oh, my God, this is real.'"

AN INTERSTELLAR ORIGIN OF LIFE?

The meteor's estimated extreme speed was not only much higher than that of objects orbiting the sun, but also well above what would be typical of other nearby systems swirling through the Milky Way's thin, star-studded disk. That, Loeb says, means its putative interstellar origins are decidedly exotic. "Either it came from a star in the galaxy's thick disk [a small and diffuse subset of speedy stars that surround the thin disk like a halo]," he says, "or it came from the galaxy's thin disk, from inner regions of a planetary system where objects orbit at higher speeds."

> **"Some of these objects could potentially transfer life between planetary systems."**
>
> **—Avi Loeb**

The pair's analysis also suggests interstellar objects of this scale strike Earth at least once per decade—meaning perhaps almost half a billion have rained down upon our planet throughout its 4.5-billion-year history. Stars near our own should eject anywhere between 0.2 and 20 Earth masses of such objects over the course of their lives, Loeb and Siraj estimate—and at any time, on the order of a million should be somewhere within Earth's orbit around the sun.

Such possibilities carry profound implications. "Some of these objects could potentially transfer life between planetary systems," Loeb says, referring to a broad theory known as panspermia (ancient Greek for "all seeds") that posits life first began in outer space and can readily migrate between planets. In principle, alien microbes sheltered within rocks blasted into space by a giant impact on some life-bearing world might survive an interstellar voyage and a fiery entry into a planet's atmosphere. Some researchers have posited this may even explain life's early emergence on Earth, which the fossil record suggests occurred with shocking rapidity more than four billion years ago, practically as soon as our planet became cool enough to harbor liquid water. "If this meteor is indeed interstellar, it shows a proof of concept," Loeb says. "Sure, it burned up, but bigger, rarer ones won't. And we don't need an impact every decade to seed the early Earth."

Even if Loeb and Siraj's meteor had managed to reach Earth's surface, however, other experts in the arcane topic of panspermia suggest it would not have brought anything living with it. "More likely, this object is not from a habitable (much less inhabited) body, but rather is a piece of a frozen, comet-like body," says Benjamin Weiss, a planetary scientist and meteorite expert at the Massachusetts Institute of Technology. More fundamentally, Weiss says, the claim that this particular space rock was interstellar is problematic. "The meteor catalog that [Loeb and Siraj] used does not report uncertainties on the incoming velocity," he notes. "These uncertainties need to be quantified before this meteor can be accepted as interstellar."

UNKNOWN UNCERTAINTIES

That is also the view of Paul Chodas, the CNEOS catalog's manager at NASA's Jet Propulsion Laboratory. "We at CNEOS simply post the fireball data that is reported to us; we have no information on the uncertainties," he says.

In March of this year, Chodas says, he and other CNEOS staffers flagged 2014's Papua New Guinea meteor as potentially interstellar based on their own calculations of its orbit—but did not publish that result due to concerns about the data's quality. Loeb and Siraj's "quite extraordinary" and "highly speculative" claim, he says, "is based on just a few numbers that are likely highly uncertain." (In their paper, Loeb and Siraj cite previous work reporting that the CNEOS catalog's typical uncertainty for the velocity of a meter-sized meteor is less than a kilometer per second—an insignificant offset in the enormous measured speed of their candidate interstellar fireball.)

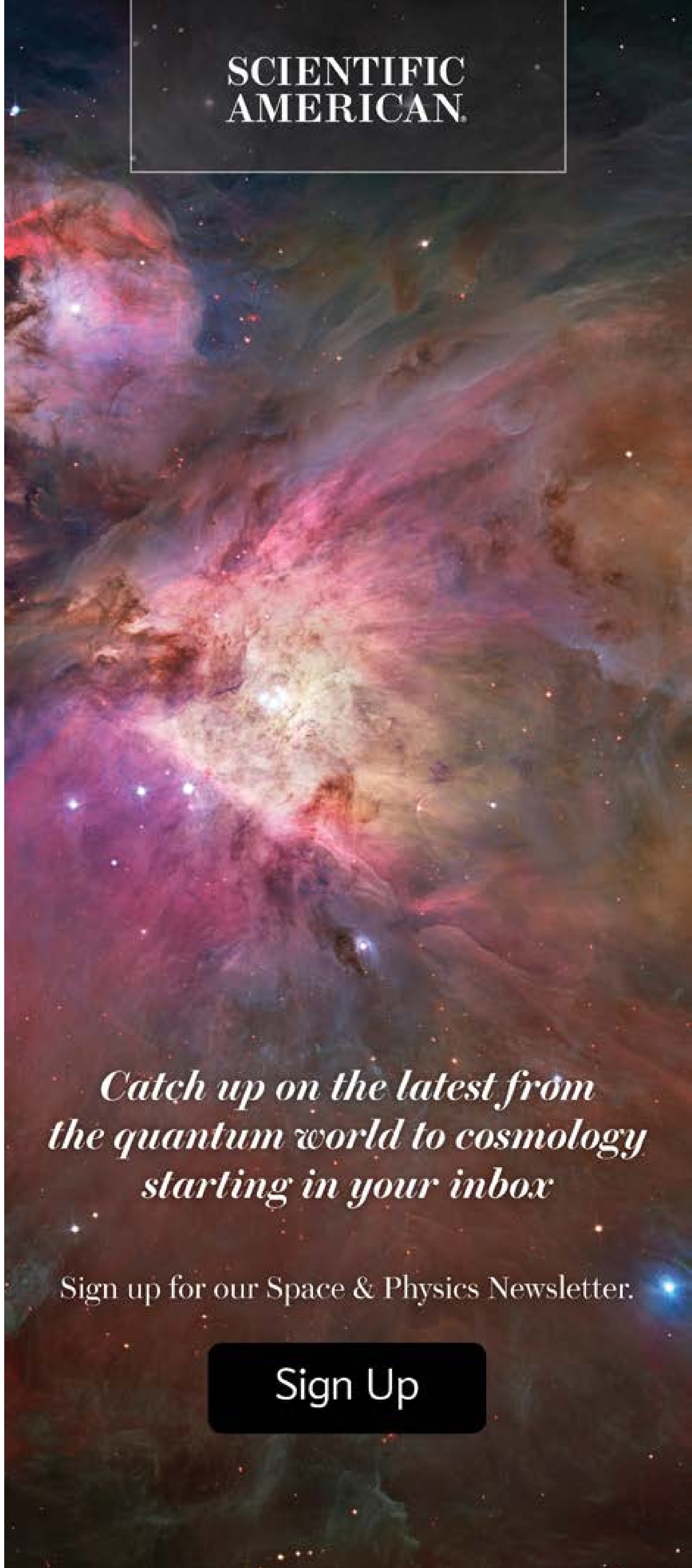
Asked about uncertainties in the CNEOS fireball catalog, Lindley Johnson, NASA's “planetary defense officer,” notes that its entries represent the use of data “in a way it was never, ever originally intended.” Although initially conceived as a simple list of fireball times, locations and energy levels, more than a decade ago the catalog also began incorporating estimates of speed and directionality for particularly data-rich events, in hopes that researchers could use those projections to track down meteorite debris fields from large fireballs that occurred over land. Soon, particularly bold analysts were using those projections to look back in time, piecing together the potential orbital histories of meteors to link them and any meteorites they produced to certain families of asteroids. That was “already stretching the credence in the data beyond anything really scientifically valid,” Johnson says. “Now [Loeb and Siraj] want to speculate based on such tenuous data that some could be interstellar objects? That really stretches the credibility past the breaking point for me.”

Peter Brown, a planetary astronomer and leading meteor expert at Canada's Western University, says that even though the CNEOS catalog is on average of very high quality, the validity of any single data point—particularly for smaller meteors—remains questionable. “Statistically, I think the catalog's derived orbits and velocities and trajectories are fine,” he says. “But we simply don't know which ones are good and which ones are bad.” Furthermore, Brown says, of the thousands of small fireballs previously detected by other, independent surveys using ground-based cameras and radar stations, not one has clearly exhibited a hyperbolic trajectory. “If a tenth or a twentieth of a percent of the population was hyperbolic as Loeb and Siraj claim, you'd expect to have a fair number of hyperbolics in the data from ground-based networks—but we don't see that.”

Even so, Brown adds, “it is a fantastic thing that others are coming from different disciplines and applying their own approaches to this rich data set.... Interstellar meteorites must be hitting Earth's atmosphere, and fireballs are the natural way to look for them. We just have to find them convincingly, in ways that can't be dismissed as measurement uncertainties.”

This, naturally, is part of Loeb and Siraj's grand plan. The next step in the quest for interstellar meteors, they say, is to ensure that potentially hyperbolic fireballs can be not only detected but also characterized. Observed with the right equipment, a fireball's light can be broken up into a multicolored spectrum which acts as a “barcode” to reveal the object's chemical composition—a critical clue as to whether or not it formed around our sun.

“Every few years we should have one of these hyperbolic meteors,” Loeb says. “If we just ensure observers are flagging fireballs with excess velocities, we should be able to set up spectroscopic surveys to get each one's spectrum as it burns up in the atmosphere and indeed demonstrate an origin beyond our solar system. Surely this is something worth investing in!”



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SPACE

Quantum Monism Could Save the Soul of Physics

The multiverse may be an artifact of a deeper reality that is comprehensible and unique

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“The most incomprehensible thing about the universe is that it is comprehensible,” Albert Einstein famously once said. These days, however, it is far from being a matter of consensus that the universe is comprehensible, or even that it is unique. Fundamental physics is facing a crisis, related to two popular concepts that are frequently invoked, summarized tellingly by the buzzwords “multiverse” and “uglyverse.”

Multiverse proponents advocate the idea that there may exist innumerable other universes, some of them with totally different physics and numbers of spatial dimensions; and that you, I and everything else may exist in countless copies. “The multiverse may be the most dangerous idea in physics,” argues the South African cosmologist George Ellis.

Ever since the early days of science, finding an unlikely coincidence prompted an urge to explain, a motivation to search for the hidden reason behind it. One modern example: the laws of physics appear to be finely tuned to permit the existence of intelligent beings who can discover those laws—a coincidence that demands explanation.

With the advent of the multiverse, this has changed. As unlikely as a coincidence may appear, in the zillions of universes that compose the multiverse, it will exist somewhere. And if the coincidence seems to favor the emergence of complex structures, life or consciousness, we shouldn’t even be surprised to find ourselves in a universe that allows us to exist in the first place.

But this “anthropic reasoning” in turn implies that we can't predict anything anymore. There is no obvious guiding principle for the CERN physicists searching for new particles. And there is no fundamental law to be discovered behind the accidental properties of the universe.

Quite different but not less dangerous is the other challenge—the “uglyverse.” According to theoretical physicist Sabine Hossenfelder, modern physics has been led astray by its bias for “beauty,” giving rise to mathematically elegant, speculative fantasies without any contact to experiment. Physics has been “lost in math,” she argues. But then, what physicists call “beauty” are structures and symmetries. If we can’t rely on such concepts anymore, the difference between comprehension and a mere fit to experimental data will be blurred.

Both challenges have some justification. “Why should the laws of nature care what I find beautiful?” Hossenfelder righteously asks, and the answer is: They shouldn’t. Of course, nature could be complicated, messy and incomprehensible—if it were classical. But nature isn’t. Nature is quantum mechanical. And while classical physics is the science of our daily life where objects are separable, individual things, quantum mechanics is different. The condition of your car, for example, is not related to the color of your wife’s dress. In quantum mechanics, though, things that were in causal contact once remain correlated, described by Einstein as “spooky action at a distance.” Such correlations constitute structure, and structure is beauty.

In contrast, the multiverse appears difficult to deny. Quantum mechanics in particular seems to be enamored with it. Firing individual electrons at a screen with two slits results in an interference pattern on a detector behind the screen. In each case, it appears that the electron went through *both* slits each time.

Quantum physics is the science behind nuclear explosions, smart phones and particle collisions—and it is infamous for its weirdness such as Schrödinger’s cat existing in a limbo of being half dead and half alive. In quantum mechanics, different realities (such as “particle here” and “particle there” or “cat alive” and “cat dead”) can be superimposed such as waves on the surface of a lake. The particle can be in a “half here and half there” state. This is called a “superposition,” and for particles or waves it gives rise to interference patterns.

Originally devised to describe the microscopic world, quantum mechanics in recent years has been shown to govern increasingly large objects—if they are sufficiently isolated from their environment. Somehow, however, our daily life seems to be protected from experiencing too much quantum weirdness. Nobody has ever seen an undead cat, and whenever you measure the position of a particle you get a definite result.

A straightforward interpretation assumes that all possible options are realized, albeit in different, parallel realities or “Everett branches”—named after Hugh Everett, who first advocated this view known as the “many worlds interpretation” of quantum mechanics. Everett’s “many worlds” are in fact one example of a multiverse—one out of four, if you follow Max Tegmark’s *Scientific American* feature from May 2003. Two of the others are not that interesting, since one is not really a multiverse but rather different regions in our own universe, and the other one is based on the highly speculative idea that matter is nothing but math. The remaining multiverse is the “string theory landscape” to which we will return later.

By appealing to quantum mechanics in order to justify the beauty of physics, it seems that we sacrificed the uniqueness of the universe. But this conclusion results from a superficial consideration. What is typically overlooked in this picture is that Everett’s multiverse is not fundamental. It is only apparent or “emergent,” as philosopher David Wallace at the University of Southern California insists.

To appreciate this point one needs to understand the principle behind both quantum measurements and “spooky action at a distance.” Instrumental for both phenomena is a concept known as “entanglement,” pointed out in 1935 by Einstein, Boris Podolsky and Nathaniel Rosen. In quantum mechanics, a system of two entangled spins adding up to zero can be composed of a superposition of pairs of spins with opposite directions while it is absolutely undetermined in which direction the individual spin points. Entanglement is nature’s way of integrating parts into a whole; individual properties of constituents cease to exist for the benefit of a strongly correlated total system.

Whenever a quantum system is measured or coupled to its environment, entanglement plays a crucial role. Quantum system, observer and the rest of the universe become interwoven with each other. From the perspective of the local observer, information is dispersed into the unknown environment and a process called "decoherence"—first discovered by H. Dieter Zeh in 1970—sets in. Decoherence is the agent of classicality. It describes the loss of quantum properties when a quantum system interacts with its surroundings. Decoherence acts if it would open a zipper between quantum physics' parallel realities. From the observer's perspective, the universe and she herself seem to "split" into separated Everett branches. The observer observes a live cat or a dead cat but nothing in between. The world looks classical to her, while from a global perspective it is still quantum mechanical. In fact, in this view the entire universe is a quantum object.

This is where "quantum monism," as championed by Rutgers University philosopher Jonathan Schaffer, enters the stage. Schaffer has mused over the question of what the universe is made of. According to quantum monism, the fundamental layer of reality is not made of particles or strings but the universe itself—understood not as the sum of things making it up but rather as a single, entangled quantum state.

Similar thoughts have been expressed earlier, for example, by the physicist and philosopher Carl Friedrich von Weizsäcker. Taking quantum mechanics seriously predicts a unique, single quantum reality underlying the multiverse. The homogeneity and the tiny temperature fluctuations of the cosmic microwave background, which indicate that our observable universe can be traced back to a single quantum state, usually identified with the quantum field that fuels primordial inflation, support this view.

Moreover, this conclusion extends to other multiverse concepts such as different laws of physics in the various valleys of the "string theory landscape" or other "baby universes" popping up in eternal cosmological inflation. Since entanglement is universal, it doesn't stop at the boundary of our cosmic patch. Whatever multiverse you have, when you adopt quantum monism they are all part of an integrated whole. There always is a more fundamental layer of reality underlying the many universes within the multiverse, and that layer is unique.

Both quantum monism and Everett's many worlds are predictions of quantum mechanics taken seriously. What distinguishes these views is only the perspective. What looks like "many worlds" from the perspective of a local observer is indeed a single, unique universe from a global perspective (such as that of someone who would be able to look from outside onto the entire universe).

In other words, many worlds is how quantum monism looks like for an observer who has only limited information about the universe. In fact, Everett's original motivation was to develop a quantum description of the entire universe in terms of a "universal wave function." It is as if you look out through a muntin window. Nature looks divided into separate pieces but this is an artifact of your perspective.

Both monism and many worlds can be avoided, but only when one either changes the formalism of quantum mechanics—typically in ways that are in conflict with Einstein's theory of special relativity—or if one understands quantum mechanics not as a theory about nature but as a theory about knowledge: a humanities concept rather than science.

As it stands, quantum monism should be considered as a key concept in modern physics. It explains why "beauty," understood as structure, correlation and symmetry among apparently independent realms of nature, isn't an "ill-conceived aesthetic ideal" but a consequence of nature descending from a single quantum state. In addition, quantum monism also removes the thorn of the multiverse as it predicts correlations realized not only in a specific baby universe but in any single branch of the multiverse—such as the opposite directions of entangled spins in the Einstein-Podolsky-Rosen state.

Finally, quantum monism soothes the crisis in experimental fundamental physics relying on increasingly large colliders to study smaller and smaller constituents of nature, simply since the smallest constituents are not the fundamental layer of reality. Studying the foundations of quantum mechanics, new realms in quantum field theory or the largest structures in cosmology may turn out to be equally useful.

This doesn't mean that every observed coincidence points to the foundations of physics or that any notion of beauty should be realized in nature—but it tells us we shouldn't stop seeking. As such, quantum monism has the potential to save the soul of science: the conviction that there is a unique, comprehensible and fundamental reality.

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

Living Near a Supermassive Black Hole

It would pose some dangers, of course—but it could also be fun!

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We have known since the 1990s that planets exist around pulsars, which are extraordinarily dense objects born out of the violent explosions of stars. It is therefore reasonable to assume that planets might also exist around black holes, which, perhaps surprisingly to many people, have a much weaker impact on their environment than pulsars. It's even possible that life may form on some of these planets, given that organisms on Earth have adapted to extreme conditions, including boiling heat, freezing cold, and acidic, highly salty and even radioactive environments.

Inhabited planets could exist near the supermassive black holes that lie at the cores of most galaxies. Our own galaxy, the Milky Way, harbors a black hole whose mass is as great as four million stars put together. Known as Sgr A* (Sgr stands for Sagittarius), its innermost stable circular orbit (ISCO) has roughly the size of the orbit of Mercury around our sun.

So, what would life be like on such a planet?

Before addressing the many health hazards for life near a black hole, we should consider the benefits. If civilizations form in, or migrate to, the vicinity of black holes, what could they do for fun and profit? The following top 10 activities come to mind:

- Using the black hole as a source of clean energy by dumping trash through the accretion disk of matter that swirls around it. Up to 42 percent of the rest mass of this trash can be converted to radiation at the ISCO of a maximally spinning black hole.
- Coupling some engineered device to the spin of the black hole, as a giant flywheel from which spin energy can be harnessed.

- Surfing with light sails on relativistic jets at speeds approaching that of light.
- Prolonging youth by visiting beauty salons near the horizon of the black hole, where time is ticking more slowly as a result of gravitational redshift.
- Viewing the spectacle of the entire universe reflected and distorted as gravitationally lensed images around the black hole.
- Establishing an amusement park at the so-called photon sphere, where one could enjoy relativistic effects for fun, such as seeing oneself from behind by looking straight ahead as light circles around the black hole.
- Taking advantage of new opportunities for space travel. For example, when the Milky Way and its sister galaxy Andromeda merge billions of years from now, the two black holes at their centers will pair into a tight binary, which should act as a gravitational slingshot and eject stars or planets at up to the speed of light, as described in two papers that the author wrote with James Guillochon. Travel agencies may offer tickets to exceptional rides on ejected planets that traverse the entire universe.
- Sending criminals into the black hole as the ultimate prison with a death sentence at the singularity. The mass of the black hole will determine how much time is left for the prisoners to live. The lesser their crime, the more massive the black hole would be, extending their remaining life span after crossing the "prison walls" associated with the black hole horizon.
- Using gravitational waves from small objects orbiting the black hole for communication. Such signals cannot be blocked by any known form of matter.
- Testing fundamental aspects of quantum gravity through organized trips for string physics experimentalists.

The main danger for astronauts attempting to execute these activities stems from gravitational tides. As Albert Einstein noted in his famous thought experiment, being inside a free-falling elevator or spacecraft feels like having no gravity at all. But any difference in gravitational acceleration between your head and toes, which measures the curvature of spacetime, could potentially rip your body apart. Such tides would impose a death sentence near a stellar-mass black hole but are of no threat to the human body in the much more expansive environment around a supermassive black hole, like Sgr A*.

Correspondingly, the density of matter required to make a black hole scales linearly with its spacetime curvature. Low-mass black holes are formed through the collapse of the core of a massive star to densities far greater than that of an atomic nucleus. But to make a supermassive black hole, which is much more rarefied, it is sufficient to fill the orbit of Jupiter with liquid water. As simple as this engineering project might sound, it is by no means practical since it requires about 100 million solar masses of water. And the heat generated while pouring the water in would burn any associated facilities.

Indeed, the heat released by accreting supermassive black holes poses an existential threat to civilizations residing near the centers of galaxies. In a paper with John Forbes, we showed that a significant fraction of all planets in the universe are vulnerable to their atmospheres being stripped or their oceans being boiled off as a result of having been close to an active galactic nucleus sometime during their lives.

For the first time in human history, we now have the technology to image the silhouettes of the supermassive black holes at the centers of the Milky Way and the giant elliptical galaxy M87 on the background of the glowing gas behind them. The first such images are scheduled to be released later this year.

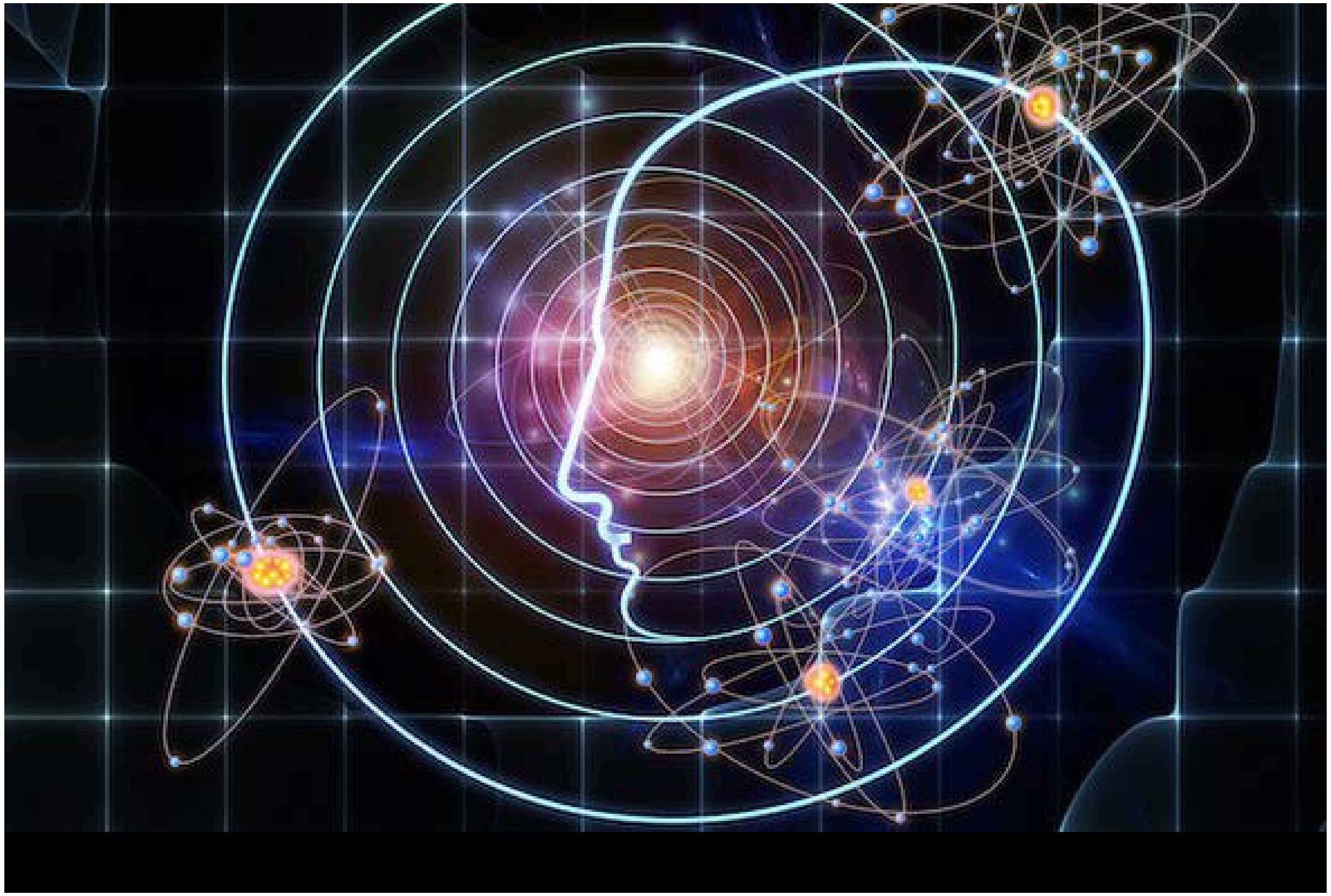
In the summary lecture of the 2018 conference of Harvard's Black Hole Initiative, an interdisciplinary center that focuses on the study of black holes, I suggested that future advances in space propulsion might allow us to organize a field trip to a nearby black hole. This will provide a great opportunity to pursue some of the aforementioned activities—and perhaps even exchange notes on quantum gravity with any backpackers from other civilizations who might have already camped out there.

Bernardo Kastrup has a Ph.D. in philosophy (ontology, philosophy of mind) and another in computer engineering (reconfigurable computing, artificial intelligence). He has worked as a scientist in some of the world's foremost research laboratories, including CERN. His most recent book is *The Idea of the World: A Multi-Disciplinary Argument for the Mental Nature of Reality.*

PHYSICS

Physics Is Pointing Inexorably to Mind

So-called information realism has some surprising implications



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In his 2014 book, *Our Mathematical Universe*, physicist Max Tegmark boldly claims that “protons, atoms, molecules, cells and stars” are all redundant “baggage.” Only the mathematical apparatus used to describe the behavior of matter is supposedly real, not matter itself. For Tegmark, the universe is a “set of abstract entities with relations between them,” which “can be described in a baggage-independent way”—i.e., without matter. He attributes existence solely to descriptions, while incongruously denying the very thing that is described in the first place. Matter is done away with, and only information itself is taken to be ultimately real.

This abstract notion, called information realism, is philosophical in character, but it has been associated with physics from its very inception. Most famously, information realism is a popular philosophical underpinning for digital physics. The motivation for this association is not hard to fathom.

Indeed, according to the Greek atomists, if we kept on dividing things into ever-smaller bits, at the end there would remain solid, indivisible particles called atoms, imagined to be so concrete as to have even particular shapes. Yet, as our understanding of physics has progressed, we’ve realized that atoms themselves can be further divided into smaller bits, and those into yet smaller ones, and so on, until what is left lacks shape and solidity altogether. At the bottom of the chain of physical reduction there are only elusive, phantasmal entities we label as "energy" and "fields"—abstract conceptual tools for describing nature, which themselves seem to lack any real, concrete essence.

To some physicists, this indicates that what we call "matter," with its solidity and concreteness—is an illusion; that only the mathematical apparatus they devise in their theories is truly real, not the perceived world the apparatus was created to describe in the first place. From their point of view, such a counterintuitive conclusion is an implication of theory, not a conspicuously narcissistic and self-defeating proposition.

Indeed, according to information realists, matter arises from information processing, not the other way around. Even mind—psyche, soul—is supposedly a derivative phenomenon of purely abstract information manipulation. But in such a case, what exactly is meant by the word "information," since there is no physical or mental substrate to ground it?

You see, it is one thing to state in language that information is primary and can, therefore, exist independently of mind and matter. But it is another thing entirely to explicitly and coherently conceive of what—if anything—this may mean. By way of analogy, it is possible to write—as Lewis Carroll did—that the Cheshire Cat's grin remains after the cat disappears, but it is another thing entirely to conceive explicitly and coherently of what this means.

Our intuitive understanding of the concept of information—as cogently captured by Claude Shannon in 1948—is that it is merely a measure of the number of possible states of an independently existing system. As such, information is a property of an underlying substrate associated with the substrate's possible configurations—not an entity unto itself.

To say that information exists in and of itself is akin to speaking of spin without the top, of ripples without water, of a dance without the dancer, or of the Cheshire Cat's grin without the cat. It is a grammatically valid statement devoid of sense; a word game less meaningful than fantasy, for internally consistent fantasy can at least be explicitly and coherently conceived of as such.

One assumes that serious proponents of information realism are well aware of this line of criticism. How do they then reconcile their position with it? A passage by Luciano Floridi may provide a clue. In a section entitled "The nature of information," he states:

"Information is notoriously a polymorphic phenomenon and a polysemantic concept so, as an explicandum, it can be associated with several explanations, depending on the level of abstraction adopted and the cluster of requirements and desiderata orientating a theory.... *Information remains an elusive concept.*" (Emphasis added.)

Such obscure ambiguity lends information realism a conceptual fluidity that makes it unfalsifiable. After all, if the choice of primitive is given by "an elusive concept," how can one definitely establish that it is wrong? In admitting the possibility that information may be "a network of logically interdependent but mutually irreducible concepts," Floridi seems to suggest even that such elusiveness is inherent and unresolvable.

Whereas vagueness may be defensible in regard to natural entities conceivably beyond the human ability to apprehend, it is difficult to justify when it comes to a human concept, such as information. We invented the concept, so we either specify clearly what we mean by it or our conceptualization remains too vague to be meaningful. In the latter case, there is literally no sense in attributing primary existence to information.

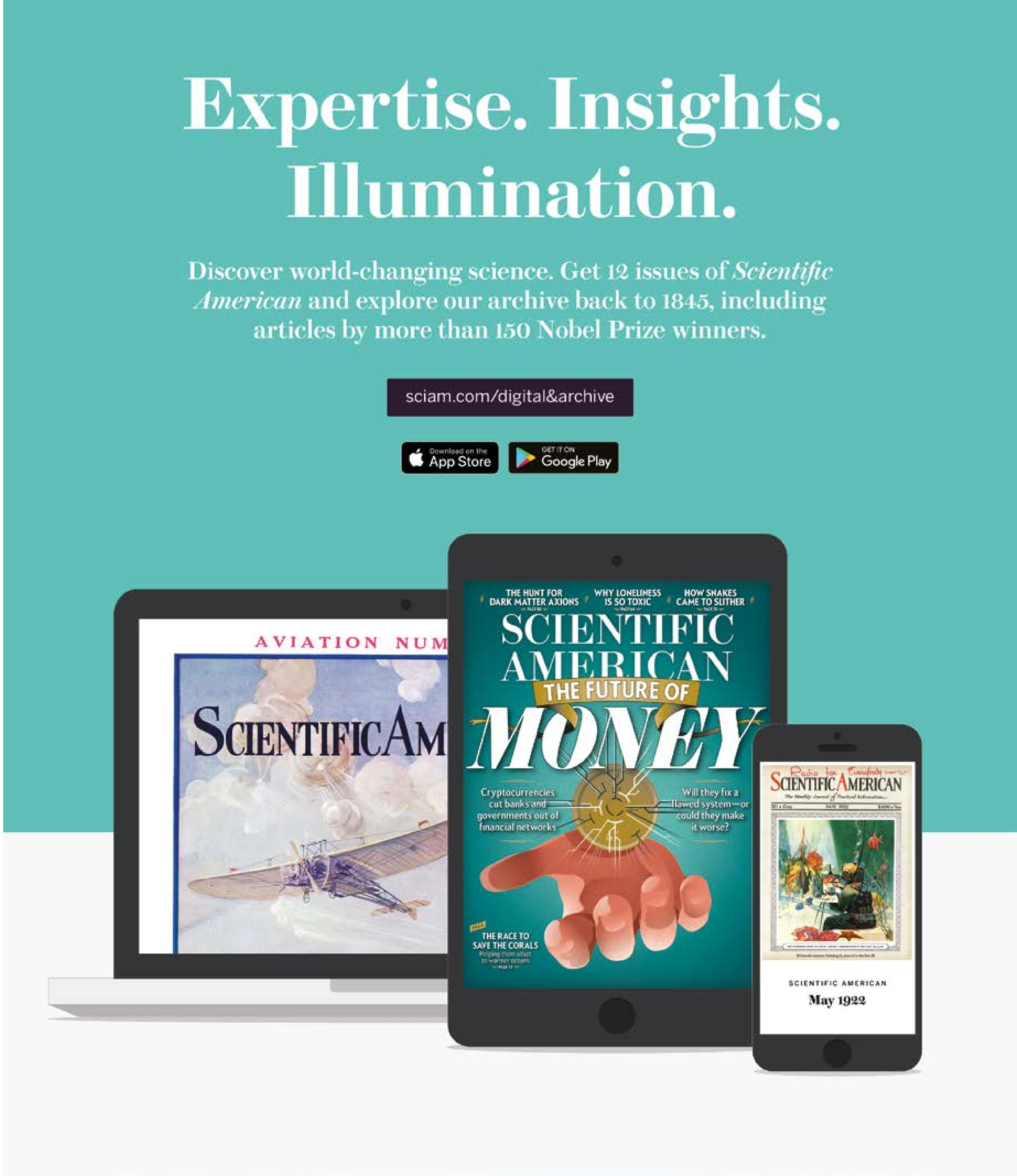
The untenability of information realism, however, does not erase the problem that motivated it to begin with: the realization that, at bottom, what we call "matter" becomes pure abstraction, a phantasm. How can the felt concreteness and solidity of the perceived world evaporate out of existence when we look closely at matter?

To make sense of this conundrum, we don't need the word games of information realism. Instead, we must stick to what is most immediately present to us: solidity and concreteness are qualities of our experience. The world measured, modeled and ultimately predicted by physics is the world of perceptions, a category of mentation. The phantasms and abstractions reside merely in our descriptions of the behavior of that world, not in the world itself.

Where we get lost and confused is in imagining that what we are describing is a nonmental reality underlying our perceptions, as opposed to the perceptions themselves. We then try to find the solidity and concreteness of the perceived world in that postulated underlying reality. However, a nonmental world is inevitably abstract. And since solidity and concreteness are felt qualities of experience—what else?—we cannot find them there. The problem we face is thus merely an artifact of thought, something we conjure up out of thin air because of our theoretical habits and prejudices.

Tegmark is correct in considering matter—defined as something outside and independent of mind—to be unnecessary baggage. But the implication of this fine and indeed brave conclusion is that the universe is a mental construct displayed on the screen of perception. Tegmark's "mathematical universe" is inherently a mental one, for where does mathematics—numbers, sets, equations—exist if not in mentation?

As I elaborate extensively in my new book, *The Idea of the World,* none of this implies solipsism. The mental universe exists in mind but not in your personal mind alone. Instead, it is a transpersonal field of mentation that presents itself to us as physicality—with its concreteness, solidity and definiteness—once our personal mental processes interact with it through observation. This mental universe is what physics is leading us to, not the hand-waving word games of information realism.



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*

Astronomical Events
June-July 2019

June	Event
1	**Dawn: waning crescent moon right of Venus 30 minutes before sunrise**
3	**New moon**
4	**After sunset: waxing crescent moon between Mercury and Mars, low in west-northwest**
5	**Moon reaches northernmost declination (22.4°)**
7	**Moon at perigee (368,504 km), apparent diameter 32′ 43″**
9	**Moon near Regulus in constellation Leo**
10	**Moon: first quarter**
	Jupiter at opposition
15	**Evening sky: moon to the right of Jupiter**
16	**Evening sky: moon to the left of Jupiter**
17	**Full moon**
	After sunset: Mercury and Mars form a close pair low in west-northwest
18	**After sunset: Mercury and Mars form a close pair low in west-northwest**
	Moon reaches southernmost declination (–22.4°), close to Saturn
21	**Solstice; summer begins in the Northern Hemisphere**
22	**Neptune stationary**
23	**Moon at apogee (404,548 km), apparent diameter 30′ 04″**
	Mercury in greatest elongation east (25°)
25	**Moon: last quarter**
30	**Morning sky: moon close to Aldebaran in constellation Taurus**

June-July 2019: Visibility of the planets

In the evening twilight, Mercury and Mars make an impressive sight low in the west in June. Jupiter and Saturn dominate the night sky throughout June and July. Venus is now ending its apparition as morning star.

Mercury was in superior conjunction (behind the sun) on May 21 and is now moving eastwards away from the sun. In early June the innermost planet becomes visible low in the west-northwest sky about 30 minutes after sunset, when civil twilight ends. Mercury reaches its greatest elongation 25° east of the sun on June 23. The planet puts on a fine evening showing during June, but it is brighter at the beginning of the month and much fainter at the end. The use of binoculars is highly recommended to spot the planet. (But wait until the sun is completely below the horizon before you start looking in this direction to avoid eye damage.) If you are unsure where to look, you can easily locate the planet on the evening of June 4, when Mercury is 6° right of the thin crescent moon. Two weeks later, Mercury passes Mars. Although Mars itself is somewhat fainter than Mercury, the close conjunction will make an impressive sight through binoculars on the evenings of June 17 and 18.

Venus rises about one hour before the sun at the beginning of June and keeps up this lead through the end of the month, although the elongation decreases from 20° to 12° during this period. However, the planet will not be higher than 5 degrees above the eastern horizon by the time when twilight begins. But Venus is brilliant enough to withstand the brightening daylight for quite some time. Throughout the first half of July Venus sinks deeper in the glow of dawn and vanishes from sight.

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Astronomical Events

June-July 2019

July • Event

2	**Moon reaches northernmost declination (22.4°)**
	New moon
	Total solar eclipse (visible from South Pacific Ocean and South America)
4	**Earth at aphelion (152.1 million km)**
5	**Moon at perigee (363,726 km), apparent diameter 33′ 26″**
7	**Mercury stationary**
9	**Moon: first quarter**
	Saturn at opposition
12	**Evening sky: moon to the right of Jupiter**
13	**Evening sky: Moon to the left of Jupiter**
14	**Pluto at opposition**
15	**Moon reaches southernmost declination (–22.4°), close to Saturn**
16	**Full moon**
	Partial lunar eclipse (visible from Australia, most of Asia, Europe, Africa, South America)
21	**Moon at apogee (405,481 km), apparent diameter 29′ 56″**
	Mercury in inferior conjunction
25	**Moon: last quarter**
30	**Moon reaches northernmost declination (22.4°)**
31	**Mercury stationary**

June-July 2019: Visibility of the planets

In the evening twilight, Mercury and Mars make an impressive sight low in the west in June. Jupiter and Saturn dominate the night sky throughout June and July. Venus is now ending its apparition as morning star.

Saturn rises about two hours after Jupiter. The planet is the brightest object in constellation Sagittarius and its motion is retrograde (westward among the stars) during June and July as it reaches opposition on July 9. When the waning gibbous moon rises on the evening of June 18, Saturn is just 1° above. During the night, you can watch how fast the distance between the two celestial bodies increases due to the moon's eastward motion. One month later, on the evening of July 15, you can see Saturn just left of the nearly full moon, and you can watch how the moon passes the ringed planet during the course of the night.

Mars moves eastward through the constellation Gemini, which can be seen in the evening twilight low above the western horizon in June. The Red Planet sets about two hours after sunset. Use binoculars to observe the conjunction with Mercury on the evenings of June 17 and 18. One hour after sunset, the planetary duo is about 7° above the horizon. By the end of June, both planets are ending their apparitions, becoming lost in the sunset. They remain hidden in the sun's light during July.

Jupiter reaches opposition (opposite the sun in Earth's sky) on June 10. Therefore, it can be seen throughout the whole night, from evening twilight, when it shines low in the east through morning twilight, when it is about to set in the west. The giant planet moves slowly westwards in southern Ophiuchus (the Serpent-bearer). The bright full moon is right of Jupiter on the evening of June 15, and left of Jupiter on the next evening. Both celestial bodies repeat this configuration on the nights of July 12 and 13, respectively, but then the phase of the moon is waxing gibbous.

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SKY REPORT

June

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

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

●	●	●	•	•	•	·
−1	0	1	2	3	4	5

Apparent magnitudes

- ⁙ Open cluster
- ⁙ Globular cluster
- ෴ Galaxy
- 🟥 Nebula

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SKY REPORT

July

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

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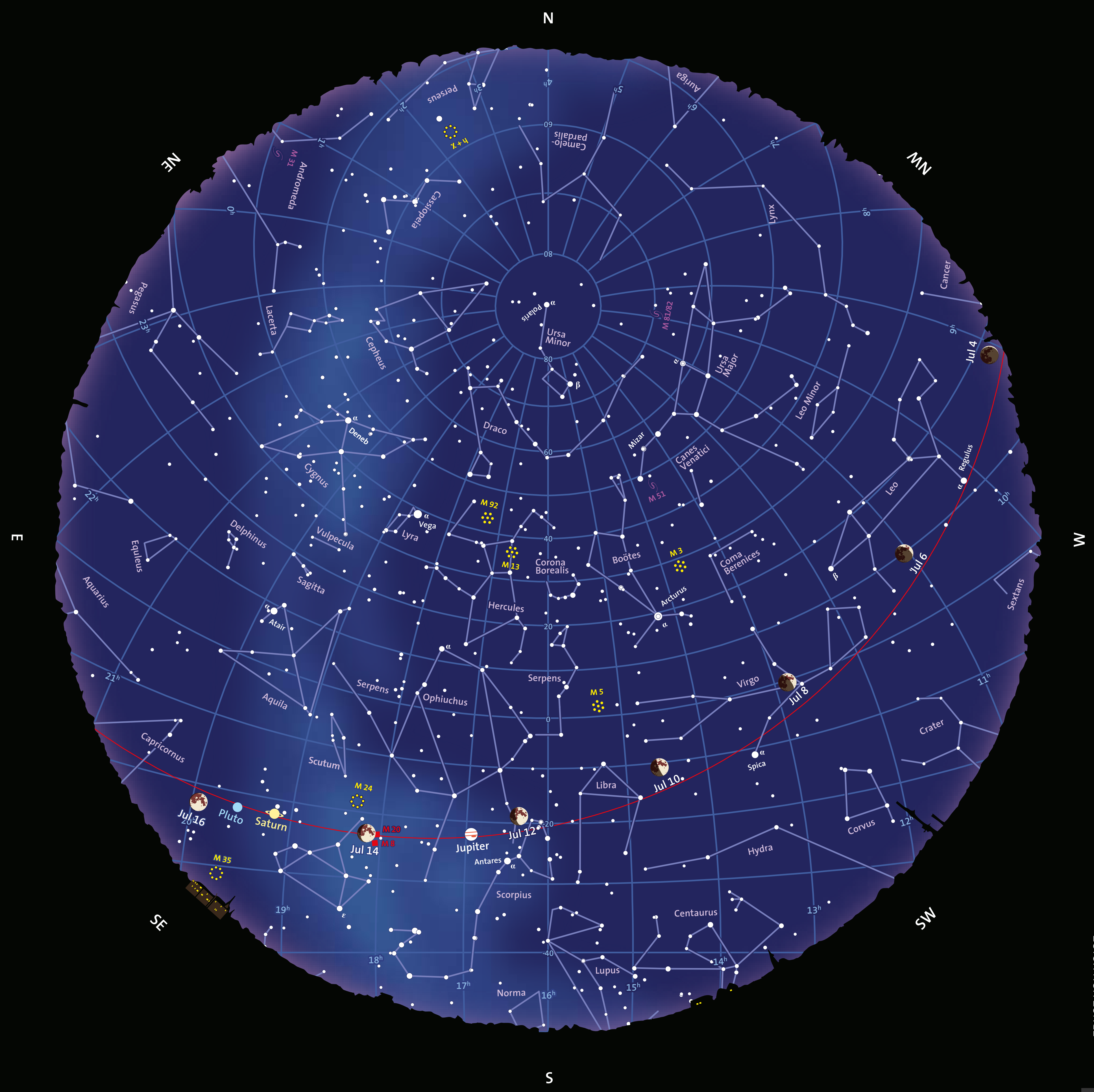

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