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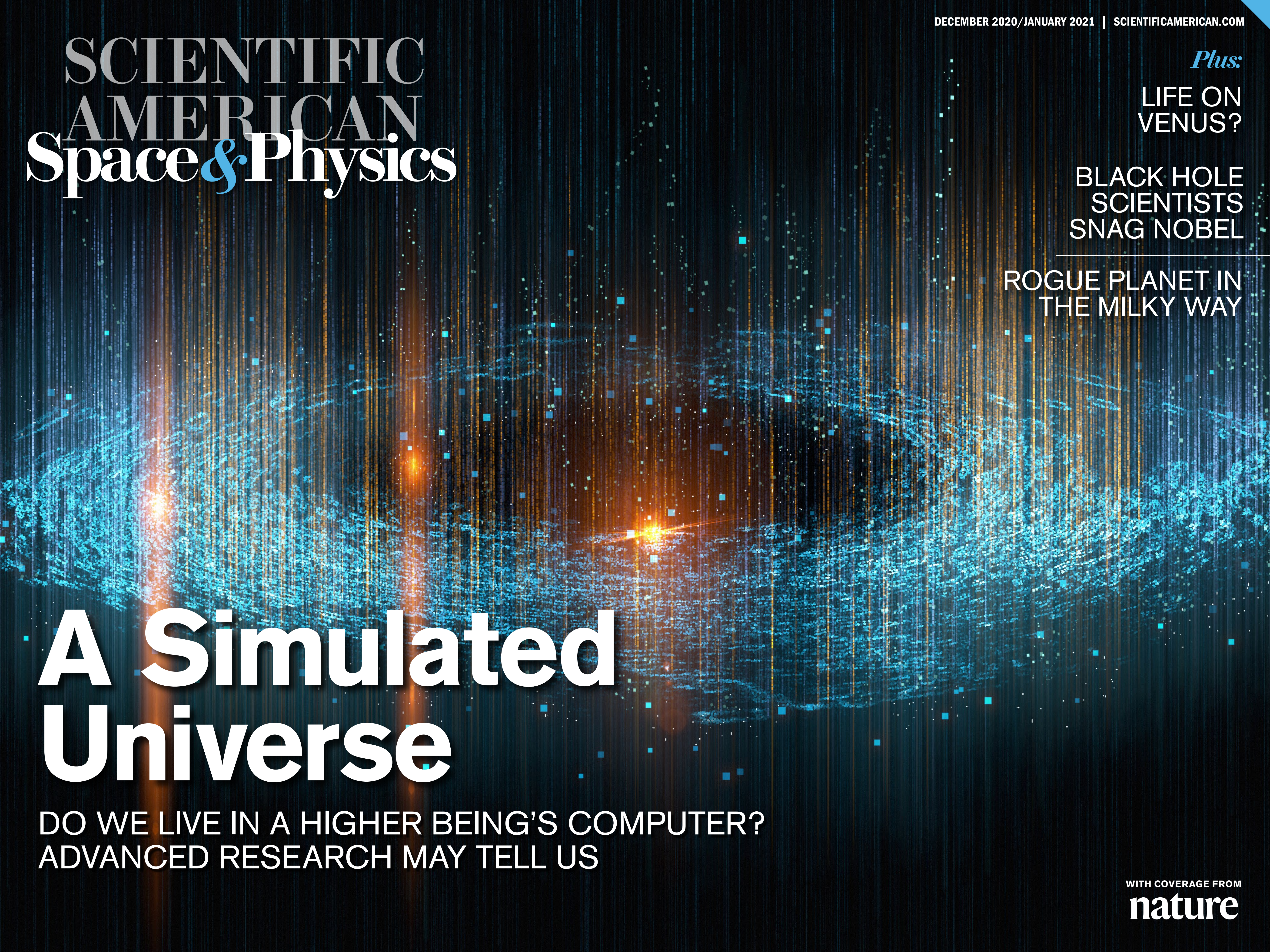

Plus:

LIFE ON VENUS?

BLACK HOLE SCIENTISTS SNAG NOBEL

ROGUE PLANET IN THE MILKY WAY

A Simulated Universe

DO WE LIVE IN A HIGHER BEING'S COMPUTER? ADVANCED RESEARCH MAY TELL US

WITH COVERAGE FROM
nature

LIZ TORMES

Are We Real? And Other Questions of Physics

What if this life is just a computer simulation running on some intellectually superior alien's console? Something about this idea is tantalizing to people (evidenced by the success of *The Matrix* films) and has special appeal for our readers. It's hooked physicists, philosophers, computer scientists and engineers, too, as author Anil Ananthaswamy writes in this edition's cover feature ["Do We Live in a Simulation? Chances Are about 50–50"]. What is it, exactly, that is so enticing about this possibility? The fear that we are mere puppets of a more advanced species? Or perhaps it's the calm that comes from the idea that none of this is real anyway. Examining the nature of our own reality, indeed whether we have a reality, is the most "meta" branch of physics.

In more satisfying endeavors, journalist Daniel Garisto reviews the long history of the search for black holes, whose champions were awarded this year's Nobel Prize in Physics ["Nobel Prize Work Took Black Holes from Fantasy to Fact"]. One recipient, physicist Andrea Ghez, pushed her fellow astronomers and technicians tirelessly, despite doubt from the field, as her colleague Hilton Lewis describes in this issue's opinion section ["How Andrea Ghez Won the Nobel for an Experiment Nobody Thought Would Work"]. Sometimes we have to fight for the realities we believe in.

Andrea Gawrylewski
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Your Opinion Matters!

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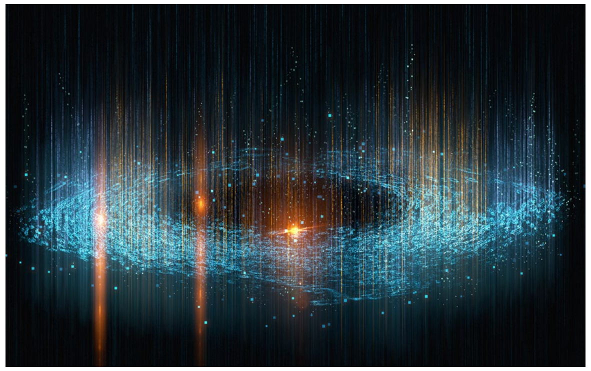

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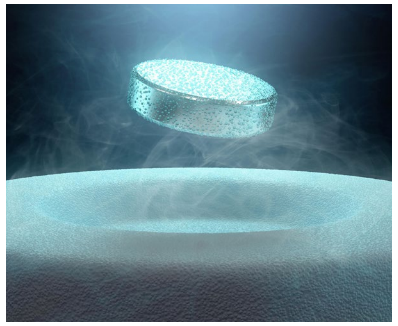

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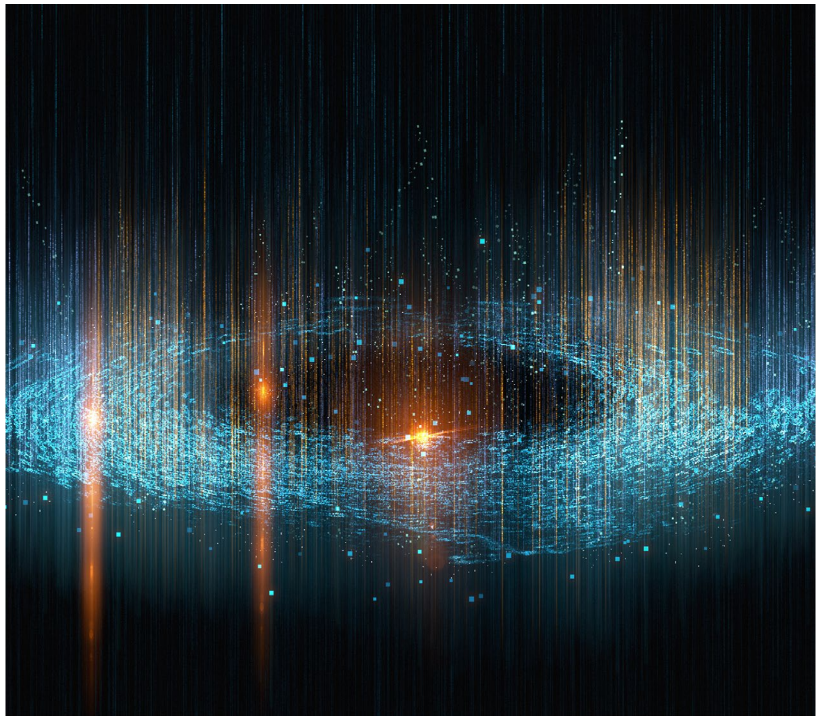

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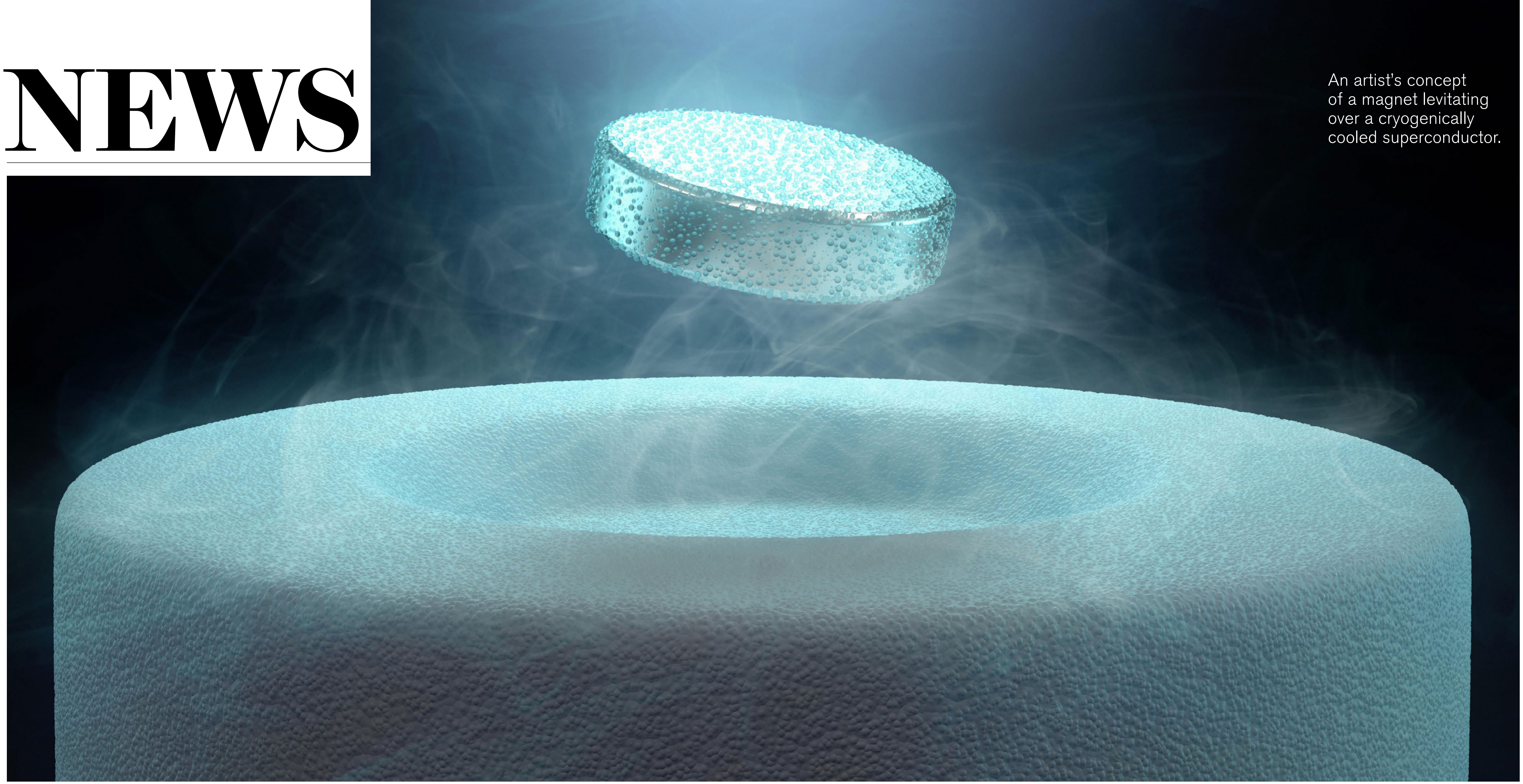

An artist's concept of a magnet levitating over a cryogenically cooled superconductor.

ALAMY

First Room-Temperature Superconductor Excites and Baffles Scientists

A compound of hydrogen, carbon and sulfur has broken a symbolic barrier—but its high-pressure conditions make it difficult to analyze

Scientists have created a mystery material that seems to conduct electricity without any resistance at temperatures of up to about 15 degrees Celsius. That's a new record for superconductivity, a phenomenon usually associated with very cold temperatures. The material itself is poorly understood, but it shows the potential of a class of superconductors discovered in 2015.

The superconductor has one serious limitation, however: it survives only under extremely high pressures, approaching those at the center of Earth, meaning that it will not have any immediate practical applications. Still, physicists hope it could pave the way for the development of zero-resistance materials that can function at lower pressures.

Superconductors have a number of technological applications, from magnetic resonance imaging machines to mobile-phone towers, and researchers are beginning to experiment with them in high-performance generators for wind turbines. But their usefulness is still limited by the need for bulky cryogenics. Common superconductors work at atmospheric pressures, but only if they are kept very cold. Even the most sophisticated ones—copper oxide–based ceramic materials—work only below 133 kelvins (–140 degrees Celsius). Superconductors that work at room temperature could have a big technological impact, for example, in electronics that run faster without overheating.

The latest study, published in *Nature* on October 14, seems to provide convincing evidence of high-temperature conductivity, says physicist Mikhail Eremets of the Max Planck Institute for Chemistry in Mainz, Germany—although he adds that he would like to see more raw data from the experiment. He says that it vindicates a line of work that he started in 2015, when his group reported the first high-pressure, high-temperature superconductor—a compound of hydrogen and sulfur that had zero resistance up to –70 degrees C.

In 2018 a high-pressure compound of hydrogen and lanthanum was shown to be superconductive at –13 degrees C. But the latest result marks the first time this kind of superconductivity has been seen in a compound of three elements rather than two—the material is made of carbon, sulfur and hydrogen. Adding a third element greatly broadens the combinations that can be included in future experiments searching for new superconductors, says study co-author Ashkan Salamat, a physicist at the University of Nevada, Las Vegas. "We've opened a whole new region" of exploration, he notes.

Materials that superconduct at high but not extreme pressures could already be put to use, says Maddury Somayazulu, a high-pressure materials scientist at Argonne National Laboratory. The study shows that by "judiciously choosing the third and fourth element" in a superconductor, he says, you could in principle bring down its operational pressure.

The work also validates decades-old predictions by theoretical physicist Neil Ashcroft of Cornell University that hydrogen-rich materials might superconduct at temperatures much higher than was thought possible. "I think there were very few people outside of the high-pressure community who took him seriously," Somayazulu says.

MYSTERY MATERIAL

Physicist Ranga Dias of the University of Rochester, along with Salamat and other collaborators, placed a mixture of carbon, hydrogen and sulfur in a microscopic niche they had carved between the tips of two diamonds. They then triggered chemical reactions in the sample with laser light and watched as a crystal formed. As they lowered the experimental temperature, resistance to a current passed through the material dropped to zero, indicating that the sample had become superconductive. Then they increased the pressure and found that this transition occurred at higher and higher temperatures. Their best result was a transition temperature of 287.7 kelvins at 267 gigapascals—2.6 million times atmospheric pressure at sea level.

> **"I am sure, after this manuscript is published, many theoretical and experimental groups will jump on this problem."**
> —*Eva Zurek*

The researchers also found some evidence that the crystal expelled its magnetic field at the transition temperature, a crucial test of superconductivity. But much about the material remains unknown, researchers warn. "There are a lot of things to do," Eremets says. Even the crystal's exact structure and chemical formula are not yet understood. "As you go to higher pressures, the sample size gets smaller," Salamat says. "That's what makes these types of measurements really challenging."

High-pressure superconductors made of hydrogen and one other element are well understood. And researchers have made computer simulations of high-pressure mixtures of carbon, hydrogen and sulfur, says Eva Zurek, a computational chemist at the State University of New York at Buffalo. But she adds those studies cannot explain the exceptionally high superconducting temperatures seen by Dias's group. "I am sure, after this manuscript is published, many theoretical and experimental groups will jump on this problem," she says.

—Davide Castelvecchi

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Rogue Rocky Planet Found Adrift in the Milky Way

The diminutive world and others like it could help astronomers probe the mysteries of planet formation

Not all planets orbit stars. Some are instead "free-floating" rogues adrift in interstellar space after being ejected from their home systems. For decades astronomers have sought to study such elusive outcasts, hoping to find patterns in their size and number that could reveal otherwise hidden details of how planetary systems emerge and evolve.

Of the handful known so far, most free floaters have been massive gas giants, but now researchers may have found one small enough to be rocky—smaller even than Earth. If its rogue status is confirmed, the roughly Mars- to Earth-mass object would be the most diminutive free-floating planet ever seen. Yet finding such small worlds could soon become routine, thanks to NASA's upcoming Nancy Grace Roman Space Telescope, set to launch in the mid-2020s.

Most planet-hunting methods rely on observing subtle changes in a star's light to discern any orbiting companions. But free-floating worlds, of course, have no star. Instead astronomers use a quirk of Einstein's general theory of relativity to locate these lost planets: All massive objects warp spacetime around themselves, similar to how a bowling ball stretches a rubber sheet and can act as lenses to magnify far-distant sources. When a "lensing" foreground planet is properly aligned with a background star, it amplifies that star's light, causing a slight brightening. This technique is known as microlensing, and astronomers first pioneered it to find black holes.

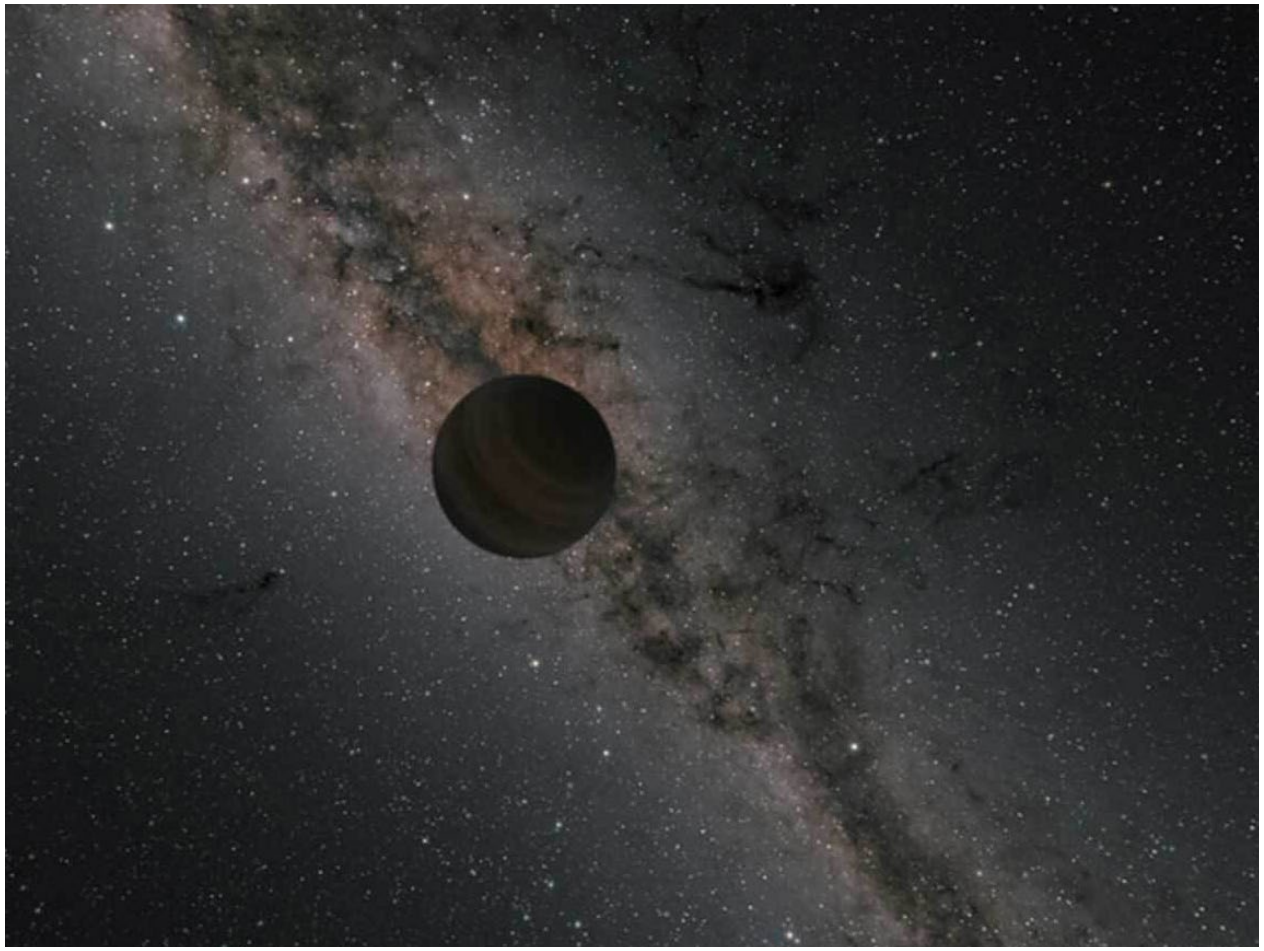


Illustration of a rogue planet drifting through interstellar space.

NASA, JPL-CALTECH AND R. HURT (CALTECH-IPAC)

Of the approximately 100 worlds found to date by microlensing, only four have been identified as free-floating. All the rest are planets that spin around their stars on orbits that are stretched out so long that they typically elude detection through other standard planet-hunting techniques. It is possible that the newfound wee world known as OGLE-2016-BLG-1928 could be attached to a star. But if so, its orbit would place it at least eight times as far from its stellar host as the Earth is from the sun. Confirming the planet's likely free-floating status will require a few more years—time enough for any potential parent star, should it exist, to shift its position so that its light can be separated from that of the background star.

"It's really a very exciting result," says Andrew Gould, an astronomer at the Ohio State University and an author of the preprint paper describing the result. That study, which was led by Przemek Mróz of the California Institute of Technology, has been submitted to *Astrophysical Journal Letters*, where it is currently under review. "It's a huge milestone to get this planet," Gould adds.

"This is a very robust result and

almost certainly a low-mass planet," says astronomer Scott Gaudi of Ohio State, who is leading the team working to determine the best observing strategy for NASA's Roman telescope and was not part of the group that found the new world. "This gives us the first little peek at the likely distribution of a population of Earth-mass planets in the galaxy," he says.

AT THE "HAIRY EDGE"

Most planets form from the gas and dust left over after a star is born. Under the leading planetary formation model, called core accretion, the gas and dust gradually and incrementally combine to form larger and larger pieces that eventually coalesce into planets. A competing theory, disk instability, instead proposes that small segments of the disk rapidly collapse to form planets, and it favors the creation of larger worlds over smaller rocky ones.

Not all planets in a family get along. Gas giants can act as bullies, flinging their smaller siblings into elongated orbits or tossing them out of their system completely. These ejected worlds may continue to fly through space on their own as free-floating planets.

The Optical Gravitational Lensing Experiment (OGLE) has been scanning the skies for the faint stellar flickers caused by microlensing events since 1992. But the new world was not spotted until Mróz and his colleagues reviewed some of OGLE's archival data. By combining OGLE's results with contemporaneous observations from the Korea Microlensing Telescope Network, as well as data from the European Space Agency's Milky Way–mapping Gaia satellite, the team was able to better estimate properties useful for gauging the putative free-floating planet's mass, such as the distance between the world and the background star. Mróz and his colleagues ultimately pegged the world's mass at somewhere between that of Mars and Earth—making it one of the smallest objects ever found by microlensing.

"It's really at the hairy edge of what we can do," Gaudi says.

PROBING PLANETARY FORMATION

This discovery hints that rocky worlds are common in the space between stars. Detecting something like this at the limits of astronomers' current capabilities suggests OGLE was either incredibly lucky or that small free-floating planets wander the Milky Way in astronomical abundance.

The discovery of a single free-floating terrestrial planet demonstrates that such objects do, in fact, exist, whereas before they were only theorized. And as more low-mass drifters are found, they can help scientists narrow down how worlds are born. Core accretion models suggest planets should form in bunches, while a star might form a single world under disk instability. Because of their isolation, single-world systems would have no planets to eject. If astronomers find very few free-floating worlds as technology improves, disk instability might gain stronger support as the dominant mode of planet formation. At the same time, finding terrestrial worlds drifting through deep space provides more support for the core accretion model.

"It's very difficult to form such low-mass planets" under disk instability says Wei Zhu, a research associate at the Canadian Institute for Theoretical Astrophysics, who was not part of the new discovery. The newfound drifter instead provides strong support for the core accretion model. "That's a good sign," he says.

But ejection caused by planetary interactions is not the only way to wind up with worlds flying through stars, which theorists will have to take into account in their studies. Most stars form in clusters, surrounded by their own stellar siblings, and they might be much better at sharing than planets are. Worlds in the outskirts of their system could be pulled away completely by the gravity of a passing star, either joining that other star's collection of planets or being tossed aside into space. Some castaway worlds may even find themselves bouncing from star to star, attaching to and being stripped from one sun after another. "They're basically Ping-Pong planets," says Susanne Pfalzner, an astronomer at the Jülich Research Center in Germany, who was not part of Mróz's team.

Beyond its potential implications for planet-formation models, the newfound rogue planet is already having an effect on astronomers' plans for future missions. According to Gaudi, it strengthens the case for changing Roman's survey strategy. The OGLE observations utilized only a single light filter, but two different filters can help to disentangle the source star more easily, making stronger measurements of the stellar properties that help determine the mass of the free-floating planet. Roman originally planned to focus most of its observations on a single filter, only occasionally switching to a second, but Gaudi says the new study is making the planning team reinvestigate whether more two-filter observations would be worth the reduction in data quality that would occur.

Regardless, current best-guess projections suggest Roman should reveal more than 200 free-floating Mars-sized planets—enough to potentially determine whether most are products of planetary interactions or of stellar encounters in clusters, Zhu says. In contrast, Gould is skeptical that Roman will detect sufficient numbers of small worlds to robustly discern between these two possibilities, but he remains sanguine about the future observatory's transformative effects.

"Roman will find more free-floating planets at a higher rate than we are finding today," he says. "It's going to be a huge leap."

—Nola Taylor Redd

Google's Quantum Computer Achieves Chemistry Milestone

A downsized version of the company's Sycamore chip performed a record-breaking simulation of a chemical reaction

When researchers at Google announced last fall that they had achieved "quantum superiority"—a point at which a quantum computer can perform a task beyond the reach of regular computers—some people wondered what the big deal was. The program, which checked the output of a random number generator, was of limited practical value and did not prove that the company's machine could do anything useful, critics said.

Now, however, Google's quantum computer has achieved something that could have real-world applications: successfully simulating a simple chemical reaction. The feat points the way toward quantum chemistry, which could expand scientists' understanding of molecular reactions and lead to useful discoveries, such as better batteries, new ways to make fertilizer and improved methods of removing carbon dioxide from the air.

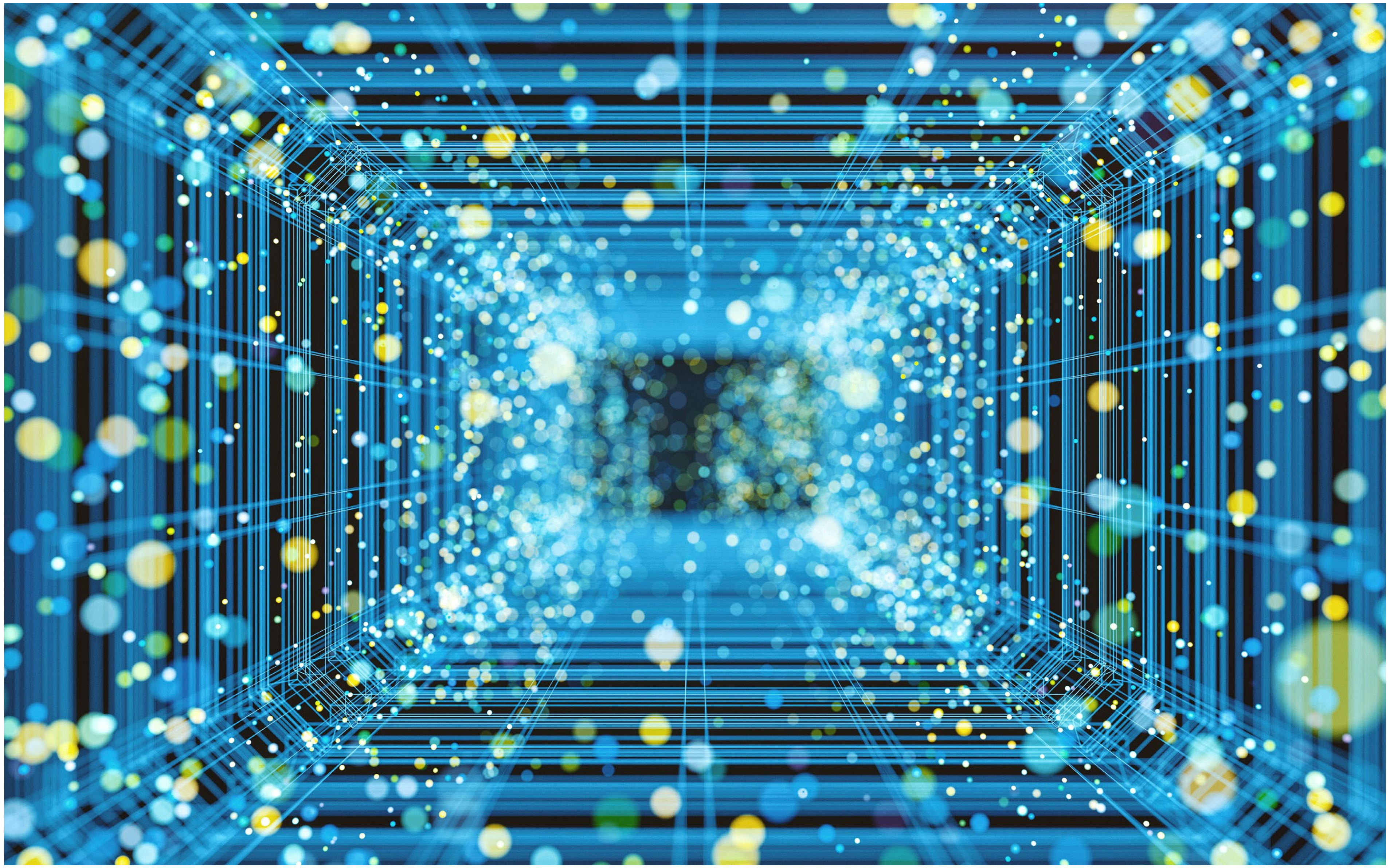
Last year's quantum-superiority experiment was run on a chip dubbed Sycamore, which contained 53 superconducting quantum bits, or qubits. Chilled to near absolute zero, the qubits take on quantum-mechanical properties, allowing scientists to manipulate them in more complicated and useful ways than the simple "on/off" flows of current that make up the bits of classical computers. The hope is that one day, quantum computers will become powerful enough to quickly perform calculations that would take the lifetime of the universe for a classical computer to complete.

This quantum-chemistry experiment, which was described in the August 28 issue of the journal *Science*, relied on the same basic Sycamore design, although it only used 12 qubits. But it demonstrates the system's versatility, says Ryan Babbush, the researcher in charge of developing algorithms for the Google project. "It shows that, in fact, this device is a completely programmable digital quantum computer that can be used for really any task you might attempt," he says.

The team first simulated a simplified version of the energy state of a molecule consisting of 12 hydrogen atoms, with each of the 12 qubits representing one atom's single electron. The researchers then modeled a chemical reaction in a molecule containing hydrogen and nitrogen atoms, including how that molecule's electronic structure would change when its hydrogen atoms shifted from one side to the other. Because the energy of electrons dictates how fast a reaction occurs at a given temperature or concentration of different molecules, such simulations could help chemists understand exactly how that reaction works—and how it would change if they altered the temperature or the chemical cocktail.

The simulation the researchers ran, known as the Hartree-Fock procedure, can also be performed on a classical computer, so it did not, by itself, demonstrate the superiority of a quantum computer. And it was run with help from a classical computer, which used machine learning to evaluate each calculation and then refine new rounds of quantum simulation. But the feat validates the project's underlying methods, which will be integral to future quantum-chemistry simulations, says Nicholas Rubin, a research scientist on the Google quantum team. And it was twice as large as the previous record-holding chemistry calculation made on a quantum computer.

In 2017 IBM performed a quantum-chemistry simulation using six qubits. Rubin says that result described a molecular system with a level of complexity that scientists in the 1920s could calculate by hand. In doubling that figure to 12 qubits, Google's project tackled a system that could be calculated with a 1940s-era computer. "If we double it again, we'll probably go to something like 1980," Babbush adds. "And if we double it again, then we'll probably be beyond what you could do classically today."



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So far no quantum computer has achieved what a classical computer could not, says Xiao Yuan, a postdoctoral research fellow at Stanford University's Institute for Theoretical Physics, who wrote a commentary accompanying Google's paper in *Science*. Even the company's achievement of quantum superiority in 2019 was called into question by IBM researchers, who showed a way to achieve the same results on a supercomputer in two and a half days, although Google's version took just more than three minutes. But, Yuan says, the quantum-chemistry experiment is an important step toward a major goal. "If we can use a quantum computer to solve a classically hard and meaningful question, that would be really the most exciting news," he adds.

There is no theoretical reason scientists could not achieve that goal, Yuan says, but the technical challenge of moving from a few qubits to several hundred—and eventually many more—will require a lot of complicated engineering. A general-purpose quantum computer with millions of qubits will require the development of error-correction protocols, a particularly arduous problem that may take a decade or more to solve. But so-called noisy intermediate-scale quantum computers, which do not have full error correction, might still prove useful in the meantime.

Chemistry is well matched with quantum computing because a chemical reaction is inherently quantum, says Alán Aspuru-Guzik, a pioneer of quantum chemistry at the University of Toronto. To fully model such a reaction, one must know the quantum states of all the electrons involved. And what better way is there to model a quantum system than to use another quantum system? Long before engineers develop a generally programmable quantum computer, devices with a handful of qubits should be able to outperform classical computers on a subset of interesting problems in chemistry, Aspuru-Guzik says. “So this is a big deal, but it’s not the end of the story,” he adds.

For instance, Aspuru-Guzik is seeking better battery materials to store energy produced by wind turbines and solar cells. Such materials have properties that can be in conflict: they need to be reactive enough to charge and discharge quickly but still stable enough to avoid exploding or catching fire. Computer models of the reactions could help identify ideal materials for that tricky task. Such models could also be important in developing new drugs.

Even so, quantum computers may not be the only revolutionary new way to model chemical reactions, Aspuru-Guzik says. It is possible that artificial intelligence could develop algorithms efficient enough to run usable simulations on classical computers. To hedge its bets, his lab works on both possibilities: it is developing new algorithms to run on midrange quantum computers and creating AI-driven robots to discover new types of materials.

But Google’s work makes Aspuru-Guzik optimistic that quantum computing can solve interesting problems in the not too distant future. “This is the best that a quantum computer can do today,” he says. “But there is a lot of work, both in the hardware and the software, to get there.”

—Neil Savage

Want to Talk to Aliens? Try Changing the Technological Channel beyond Radio

Finding cosmic civilizations might require a more innovative approach than listening for radio transmissions

The endeavor known as the search for extraterrestrial intelligence (SETI) has long relied on radio telescopes to listen for broadcasts from potential alien callers. Yet in an expansive galaxy such as ours, how can we ever be sure that we have tuned in to the right station?

A new model simulating contact across the Milky Way suggests—perhaps unsurprisingly—that unless our galaxy is dense with long-lived intelligent species, the odds of stumbling across a signal are low. Yet the findings, which were published in the *International Journal of Astrobiology,* also point out that the probability of interaction could be greatest at the moment when a novel communication technology first comes online.

Along with providing fodder for imaginative scenarios—we flip the switch on some new listening device and, voilà, receive a transmission from E.T.—the results might encourage would-be alien hunters to innovate. Research efforts dedicated to discovering and developing new methods to communicate across cosmic distances may ultimately offer greater chances of making contact than long programs using a single technology.

For Marcelo Lares, the research began with a challenge. An astronomer at the National University of Córdoba in Argentina, Lares ordinarily works on data-rich statistical analyses involving stellar populations, the large-scale structure of the universe and gravitational-wave events.

Thinking about aliens offers no such informational abundance. “We have just one observation, which is that Earth is the only known planet with life,” Lares says.

Scientific speculations about otherworldly life, intelligence and technology often rely on the Drake equation. This mathematical framework was first written down by astronomer Frank Drake in 1961. It estimates the number of communicating species by looking at the fraction of stars in the galaxy with planets, the percentage of those planets that develop life and the odds that such living creatures will grow curious about, and capable of, making interstellar contact with other beings.

Lares and his collaborators wanted something simpler. Rather than hazarding guesses about the unknowns involved in life's genesis and the development of intelligence and technology, they created a model with essentially three parameters: the moment when communicating species "awaken" and begin broadcasting evidence of their presence, the reach of such signals and the lifetime of any given transmission.

The resulting arrangement places a bunch of nodes—or intelligent message creators—at random throughout the Milky Way, where they sometimes broadcast and sometimes do not. "It's like a Christmas tree," says astronomer José Funes of the Catholic University of Córdoba, who was Lares's co-author. "You have lights going on and off."

The team ran more than 150,000

Aerial photograph taken on August 27, 2019, shows the Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) in China's southwestern province of Guizhou.

OU DONGQU *ALAMY*

simulations, each time with a different set of assumptions about these basic parameters, to see which scenarios favored interstellar contact. A galaxy full of technological aliens announcing themselves produced far more interactions than one where species were separated by vast distances or great amounts of time.

Such conclusions might not necessarily be shocking. "It's just a statistical way of saying, 'If you want to increase your chances of contact, you need greater numbers [of communicators] or have them last a long time,'" says planetary scientist Ravi Kopparapu of NASA's Goddard Spaceflight Center, who was not involved in the work.

But Lares counters that quantifying our intuitive conceptions with mathematical models can be valuable, if only to serve as a reality check on our basic understanding. The findings set a kind of upper limit on the probability of contact under different circumstances, he adds.

In each case, the simulations showed that the odds of interstellar interaction are by far the largest just at the moment when a species "awakens" and figures out the right way to communicate. That result is because other nodes will have already come online and presumably found one another, essentially creating a large branch of "lit up" Christmas tree lights and increasing the chances of stumbling across this broadcasting network. But if the lights are flashing out of sync with one another or at vastly different times—a situation analogous to using the wrong contact technology or being separated by large time spans—intelligent species might never find one another.

After SETI's historically preferred contact technology, radio waves, became commonly available in the early part of the 20th century, some discoveries were even initially thought to be alien transmissions. And in the 1960s British astronomers Jocelyn Bell Burnell and Antony Hewish originally called the first detection of a pulsar, a rapidly spinning stellar corpse, LGM-1 for "little green men," because the source's pulses seemed too regular to be natural. Yet humanity has slowly been sending out fewer radio emissions over the decades as we have upgraded our technology to wired and fiber-optic cables, which has lessened the chances that aliens might stumble across our leaking transmissions.

The new study's authors see their findings as one possible answer to the Fermi paradox, which asks why we have not found evidence of intelligent aliens, given that in the long history of our galaxy, some technological species could have arisen and sent dispatches of its existence across space by now. The work suggests this absence is not very meaningful—perhaps E.T. is too far away from us in space and time or is just using some calling card that is unknown to us.

At the heart of the research is also an attempt to step away from some of the human-centric biases that tend to plague speculations about alien others. "It's very difficult to imagine extraterrestrial communication without our anthropomorphic way of thinking," Funes says. "We need to make an effort to exit from ourselves."

Kopparapu concurs with this assessment. "Unexpected discoveries come from unexpected sources," he says. "In our common knowledge thinking, we are in a box. It is hard for us to accept that there could be something else outside it."

SETI's focus on radio waves developed under particular circumstances during a small slice of human history. Although the undertaking has sometimes tried other means to discover intelligent aliens, such as looking for high-powered laser beams or evidence of massive star-encircling artificial structures called Dyson spheres, any search still seemingly remains just as limited by the human imagination as it is by fundamental physics.

Yet looking for something as potentially fantastical as another cosmic culture requires the convergence of many disciplines, including physics, biology and even philosophy, Lares says. The effort to consider more creative messages, such as ones made by neutrinos, gravitational waves or phenomena that science has yet to discover, can help break down our parochial conceptions and give us a fuller understanding of ourselves.

Despite the small odds of contact, Lares is hopeful that attacking the problem in many ways will one day pay off. "I think that a SETI search is a high-risk bet," he says. "The probability of success is actually very low. But the prize is really very high."

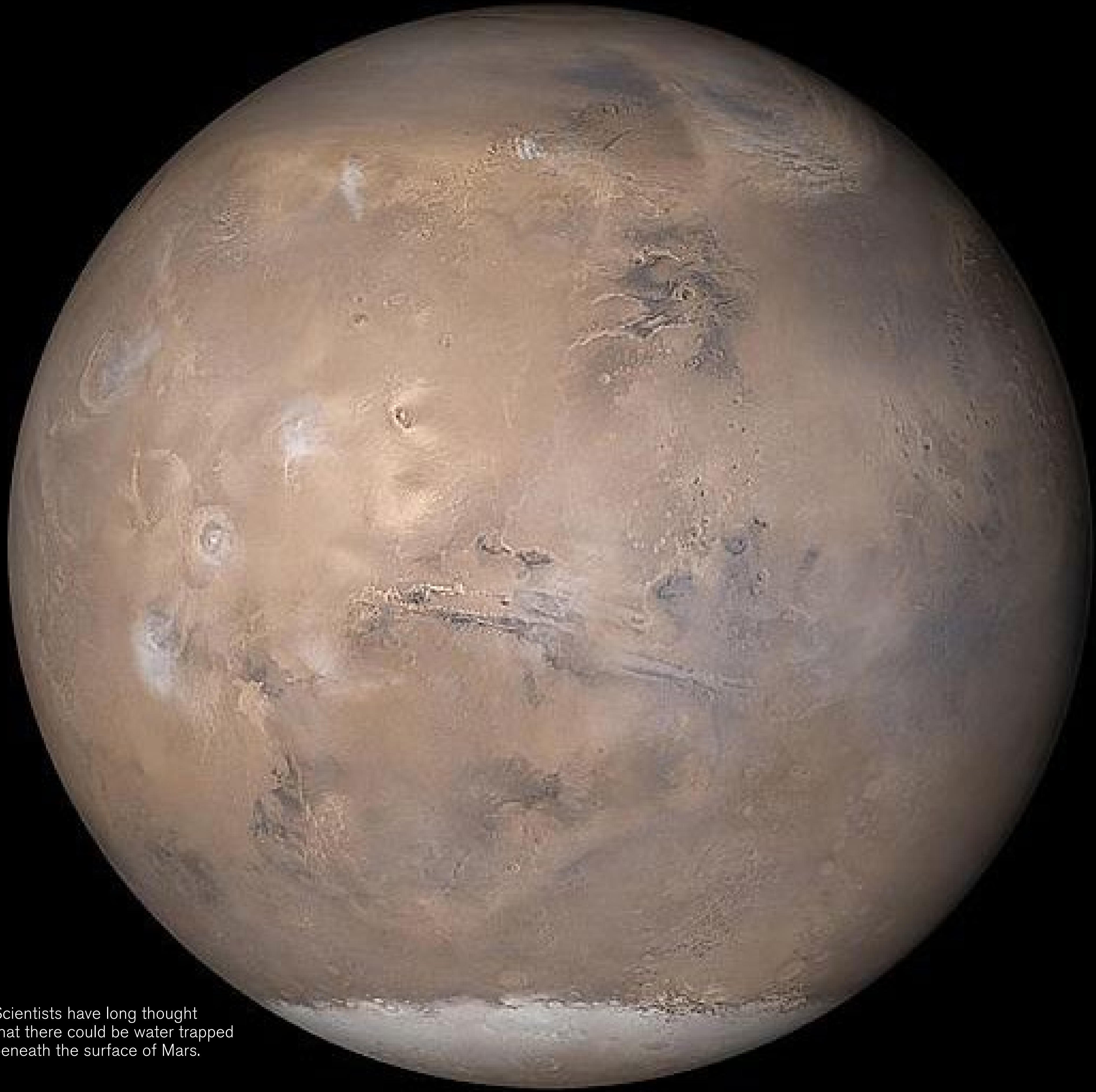
—Adam Mann

Water on Mars: Discovery of Three Buried Lakes Intrigues Scientists

Researchers say they have detected a group of lakes hidden under the Red Planet's icy surface

Two years ago planetary scientists reported the discovery of a large saltwater lake under the ice at Mars's south pole, a finding that was met with excitement and some skepticism. Now researchers say they have confirmed the presence of that lake—and found three more.

The discovery, reported on September 28 in *Nature Astronomy*, was made using radar data from the European Space Agency's (ESA) orbiting Mars Express spacecraft. It follows the detection of a single subsurface lake in the same region in 2018—which, if confirmed, would be the first body of liquid water ever detected on the Red Planet and a possible habitat for life. But that finding was based on just 29 observations made from 2012 to 2015, and many researchers said



Scientists have long thought that there could be water trapped beneath the surface of Mars.

NASA, JPL AND MALIN SPACE SCIENCE SYSTEMS

they needed more evidence to support the claim. The latest study used a broader data set comprising 134 observations from between 2012 and 2019.

"We identified the same body of water, but we also found three other bodies of water around the main one," says planetary scientist Elena Pettinelli of the University of Rome, who is one of the paper's co-authors. "It's a complex system."

The team used a radar instrument on Mars Express called the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) to probe the planet's southern polar region. MARSIS sends out radio waves that bounce off layers of material in the planet's surface and subsurface. The way the signal is reflected back indicates the kind of material that is present at a particular location—rock, ice or water, for example. A similar method is used to identify subsurface glacial lakes on Earth. The team detected some areas of high reflectivity that they say indicate bodies of liquid water trapped under more than one kilometer of Martian ice.

The lakes are spread over about 75,000 square kilometers—an area roughly one-fifth the size of Germany. The largest, central lake measures 30 kilometers across and is surrounded by three smaller lakes, each a few kilometers wide.

SALTY LAKES

On the surface of Mars, the low pressure that results from the planet's lack of a substantial atmosphere makes liquid water impossible. But scientists have long thought that there could be water trapped under Mars's surface, perhaps a remnant of when the planet once had seas and lakes billions of years ago. If such reservoirs exist, they could be potential habitats for Martian life. On Earth, life is able to survive in subglacial lakes in places such as Antarctica.

But the amount of salt present could pose problems. It is thought that any underground lakes on Mars must have a reasonably high salt content for the water to remain liquid. Although this far beneath the surface there may be a small amount of heat from the interior of Mars, this alone would not be enough to melt the ice into water. "From a thermal point of view it has to be salty," Pettinelli says.

Lakes with a salt content about five times that of seawater can support life, but as you approach 20 times that of seawater, life is no longer present, says John Priscu, an environmental scientist at Montana State University.

"There's not much active life in these briny pools in Antarctica," says Priscu, whose group studies microbiology in icy environments. "They're just pickled. And that might be the case [on Mars]."

HEATED DEBATE

The presence of the Martian lakes themselves is also still debated. After the 2018 discovery, researchers raised concerns such as the lack of an adequate heat source to turn the ice into water. And although the latest finding supports the 2018 observation and involves much more data, not everyone is yet convinced that the regions identified are liquid water.

"If the bright material really is liquid water, I think it's more likely to represent some sort of slush or sludge," says Mike Sori, a planetary geophysicist at Purdue University.

Jack Holt, a planetarty scientist at the University of Arizona, says that while he thinks the latest data are fine, he is not sure about the interpretation. "I do not think there are lakes," says Holt, who is on the science team for the Mars Shallow Radar sounder (SHARAD) on NASA's Mars Reconnaissance Orbiter (MRO). "There is not enough heat flow to support a brine here, even under the ice cap."

A Chinese mission that is on its way to Mars might offer one way to check the claims. The Tianwen-1 mission will enter orbit in February 2021, and in addition to deploying a rover onto the surface, the orbiter will carry a suite of scientific instruments. These include radar equipment that could be used to make similar observations. "Its capabilities are similar to MARSIS and SHARAD," says David Flannery of the Queensland University of Technology.

For the time being, the prospect that these lakes are remnants of Mars's wet past remains an exciting possibility. "There may have been a lot of water on Mars," Pettinelli says. "And if there was water, there was the possibility of life."

—Jonathan O'Callaghan

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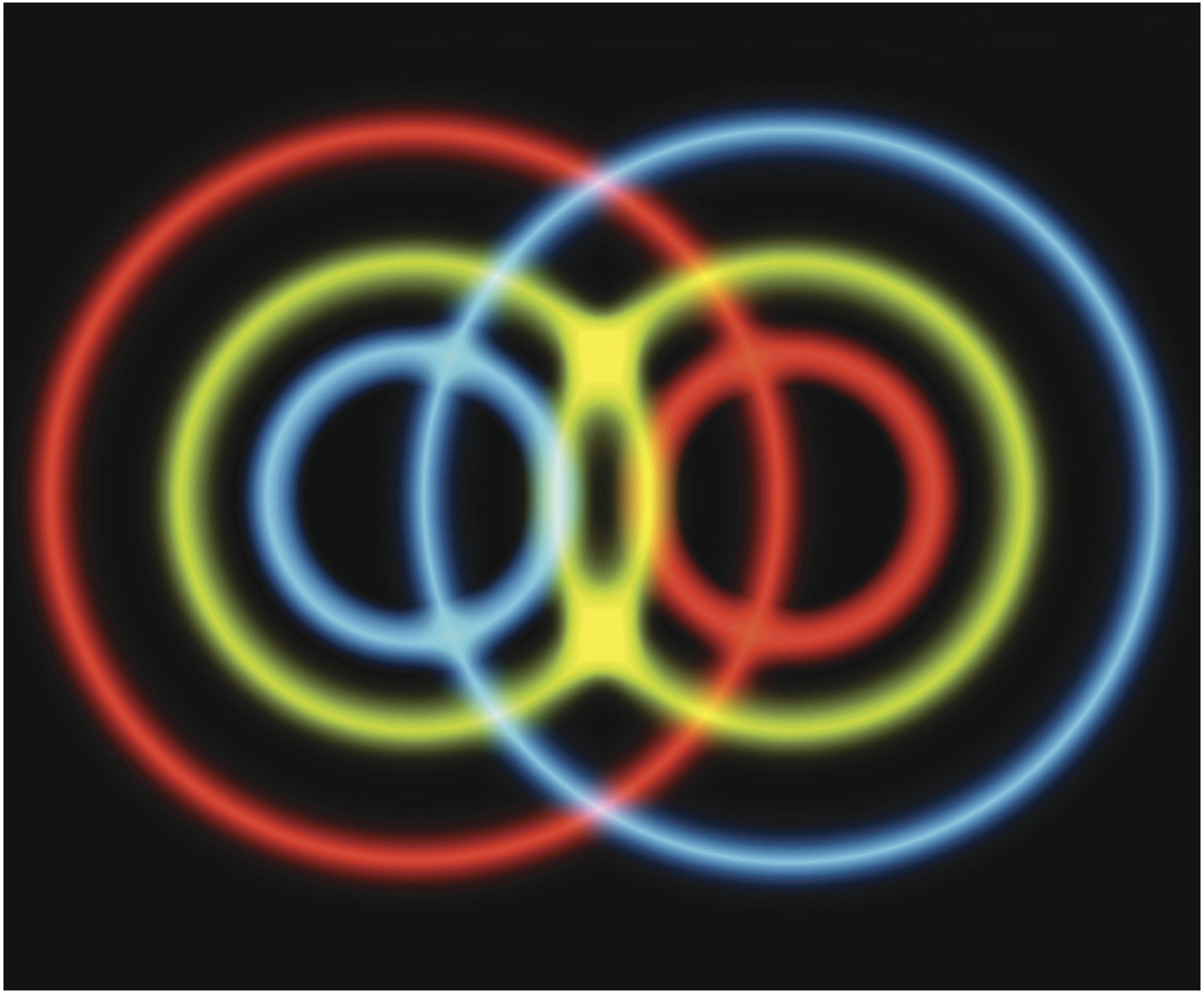
Identical Quantum Particles Pass Practicality Test

A new study proves that far from being mere mathematical artifacts, particles that are indistinguishable from one another can be a potent resource in real-world experiments

Quantum particles are known to be strange or even “spooky.” But can those properties ever be useful? A new study proves that one type of wackiness—entanglement between identical particles—has practical value.

Ordinarily, two objects are never exactly alike. They can only seem that way because scientists use imperfect instruments to try and tell them apart. In quantum physics, however, true indistinguishability is possible. For example, while two distinguishable electrons may seem to be the same, they can often be differentiated by measuring their respective spins. For identical quantum particles, there is neither an analogous quantity that could be measured nor a more perfect measuring device that could discern some other difference between them.



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Quantum particles can also be entangled. This type of connection is so strong that nothing about one of the entangled particles can be described without having to reference the other. Albert Einstein famously called quantum entanglement “spooky action at a distance” because it somehow allows particles to always be “in touch,” no matter how far apart researchers locate them. Combining these two properties that are specific to quantum mechanics—true indistinguishability and entanglement—has so far only resulted in confusion among physicists.

Now researchers have mathematically quantified just how useful fully indistinguishable entangled particles can be. Their preprint study, which in August was accepted for publication in *Physical Review X,* shows that identical-particle entanglement can be the secret ingredient for improving today’s best recipes for quantum-information processing. The finding could prove crucial for developing better materials, computers and telecommunications systems.

REAL OR IMAGINARY?

“There’s been a long discussion about the nature of identical-particle entanglement,” says Benjamin Morris, a physicist at the University of Nottingham in England and co-lead author of the study. In fact, some physicists have argued that such entanglement is nothing more than a quirk of mathematics. According to the rules of quantum mechanics, Morris explains, particles that are exactly the same are only allowed to make up very specific states. These states have a mathematical form equivalent to the one describing entangled particles that can be told apart through some measurement. But unlike such distinguishable particles, truly identical particles are assigned labels that do not reflect any physical difference between them. “You could argue that these labels have no meaning,” Morris admits.

Maciej Lewenstein, a physicist at the Institute of Photonic Sciences in Spain, who was not involved with the study, illustrates this point with an extreme example: a system consisting of two identical quantum particles—one inside your body and the other on the moon. A mathematical description of their shared state suggests that they are entangled. This result is automatic—essentially given “for free” because of quantum rules for indistinguishability rather than arising from some entangling protocol carried out by a researcher. But the implied connection between the particles has no obvious practical value. More commonly, physicists would take two particles that they know they can differentiate and purposefully entangle the pair. Only then would the scientists take one particle to the moon, allowing Einstein’s spookiness to guarantee that measuring some physical property of the other particle on Earth would instantaneously reveal the value of the same measurement for its lunar partner.

> **“Let’s say you baked a loaf of bread, and you want to know ‘What was it that made the bread rise?’ We showed that particle entanglement was the ‘yeast.’ ”**
>
> ***—Benjamin Morris***

But performing a measurement on one entangled identical particle does not reveal anything physically new about the other—the two are, after all, indistinguishable, on the moon or anywhere else.

Nevertheless, experimental physicists had noticed that systems of such particles could produce better results in certain experiments than their unentangled counterparts, notes Gerardo Adesso, a mathematical physicist at the University of Nottingham and a co-author of the new paper. “It seemed that this property was at least something useful,” he says. For example, using identical entangled particles led to better accuracy in quantum metrology, the quantum science of very precise measurements. In the study, Adesso, Morris and their collaborators determined that such improvements were made explicitly because of entangled identical particles rather than some other property of quantum mechanics. Morris offers an analogy: “Let’s say you baked a loaf of bread, and you want to know ‘What was it that made the bread rise?’ ” he says. “We showed that particle entanglement was the ‘yeast.’ ” The team’s result is the strongest evidence yet of identical-article entanglement being a feature of physical reality and not just a mathematical oddity.

A QUANTUM TEST KITCHEN

The researchers' study relies on quantum-resource theory. This idea involves selecting some specific quantum property of a system—such as identical-particle entanglement—then measuring how that property enhances the system's performance in some task, says Eric Chitambar, a quantum-information researcher at the University of Illinois at Urbana-Champaign, who was not involved with the paper. Accordingly, the team first identified a set of states that exhibit identical-particle entanglement (states containing "yeast" in Morris's metaphor) and a set of operations for manipulating them (actions involved in "bread making"). An important constraint, Chitambar notes, is that any operation generating additional identical-particle entanglement is forbidden. In the bread analogy, the researchers avoided operations akin to adding baking powder so that they could make clear statements about the importance of yeast already being in their dough. By working out just how much yeast produces a certain amount of "rise" in the system, they were able to quantify the effects of identical-particle entanglement. In a final step, they checked the validity of their bread-making analysis by using it on the results from a previously conducted investigation that relied on identical particles, finding good agreement between their theory and the actual experiment.

The team also proved that systems with entangled identical particles can be coaxed into having other forms of entanglement that are already widely used in quantum computing. Jayne Thompson, a physicist at Singapore-based company Horizon Quantum Computing, who was not affiliated with the study, explains this finding by likening identical-particle entanglement to "a valid currency" that can be exchanged for other operationally useful physical properties. As with any currency exchange, the precise exchange rate is important. Adesso offers one example: "The figure of merit that people use to quantify the advantages in metrology applications can actually be interpreted as a measure of the amount of [identical]-particle entanglement," he says.

Because Adesso and his collaborators were able to produce concrete measures of the usefulness of identical-particle entanglement, they are optimistic their approach can be used to more rigorously quantify the varying performance of myriad quantum-information-processing systems—an important development to combat hype in this rapidly expanding field.

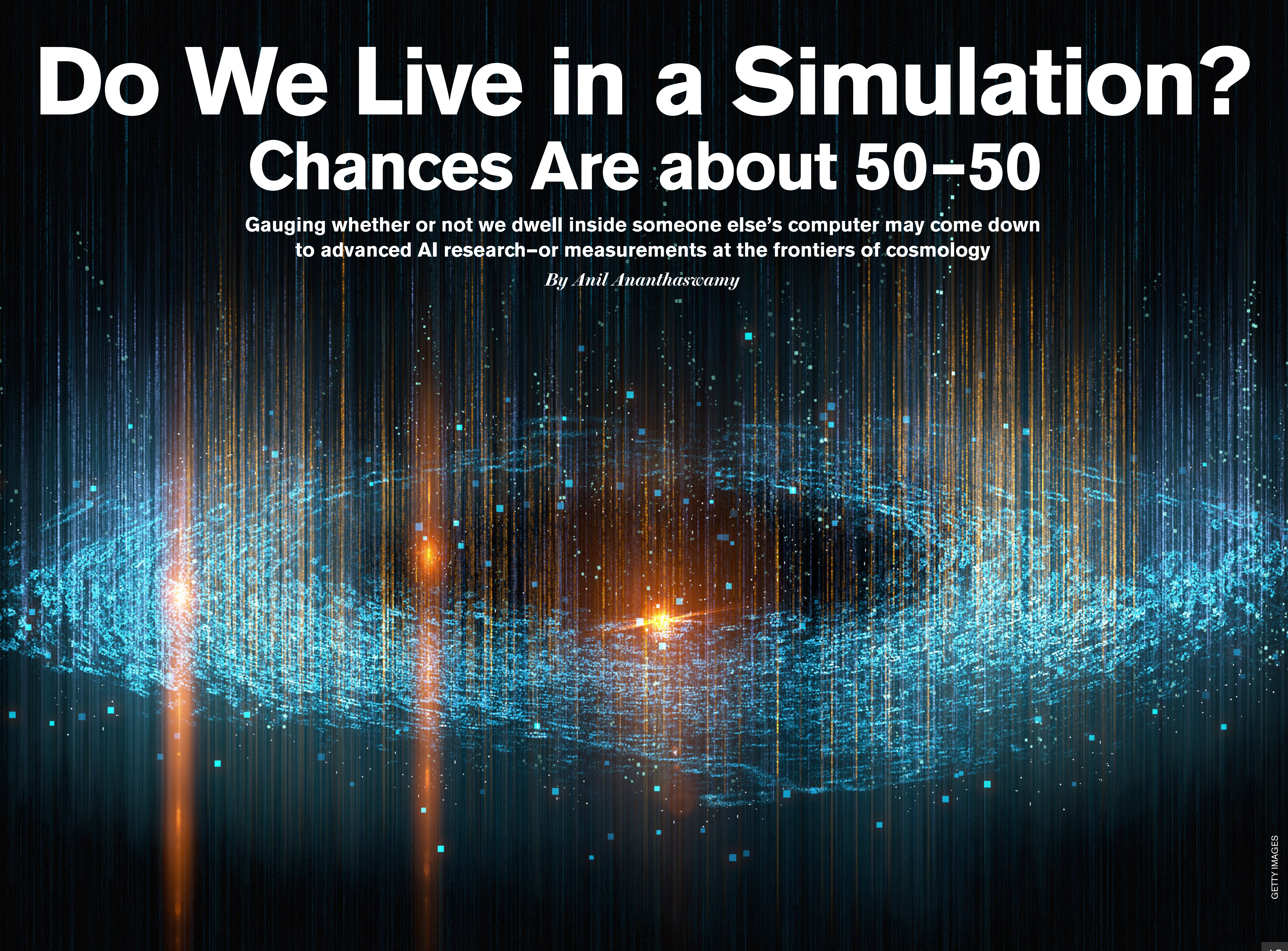
Far from being mere artifacts of wacky math, identical quantum particles are proving to be real, valuable assets for the future of quantum technology. "We hope the impact of this paper is to make the [physics] community reassess the value of identical particles in quantum mechanics more generally," Adesso says.

—*Karmela Padavic-Callaghan*

Do We Live in a Simulation? Chances Are about 50–50

Gauging whether or not we dwell inside someone else’s computer may come down to advanced AI research—or measurements at the frontiers of cosmology

By Anil Ananthaswamy



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Anil Ananthaswamy is 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.*

IT IS NOT OFTEN THAT A COMEDIAN GIVES AN ASTROPHYSICIST GOOSE BUMPS when discussing the laws of physics. But comic Chuck Nice managed to do just that in a recent episode of the podcast StarTalk. The show's host Neil deGrasse Tyson had just explained the simulation argument—the idea that we could be virtual beings living in a computer simulation. If so, the simulation would most likely create perceptions of reality on demand rather than simulate all of reality all the time—much like a video game optimized to render only the parts of a scene visible to a player. "Maybe that's why we can't travel faster than the speed of light because if we could, we'd be able to get to another galaxy," said Nice, the show's co-host, prompting Tyson to gleefully interrupt. "Before they can program it," the astrophysicist said, delighting at the thought. "So the programmer put in that limit."

Such conversations may seem flippant. But ever since Nick Bostrom of the University of Oxford wrote a seminal paper about the simulation argument in 2003, philosophers, physicists, technologists and, yes, comedians have been grappling with the idea of our reality being a simulacrum. Some have tried to identify ways in which we can discern if we are simulated beings. Others have attempted to calculate the chance of us being virtual entities. Now a new analysis shows that the odds that we are living in base reality—meaning an existence that is not simulated—are pretty much even. But the study also demonstrates that if humans were to ever develop the ability to simulate conscious beings, the chances would overwhelmingly tilt in favor of us, too, being virtual denizens inside someone else's computer. (A caveat to that conclusion is that there is little agreement about what the term "consciousness" means, let alone how one might go about simulating it.)

In 2003 Bostrom imagined a technologically adept civilization that possesses immense computing power and needs a fraction of that power to simulate new realities with conscious beings in them. Given this scenario, his simulation argument showed that at least one proposition in the following trilemma must be true: First, humans almost always go extinct before reaching the simulation-savvy stage. Second, even if humans make it to that stage, they are unlikely to be interested in simulating their own ancestral past. And third, the probability that we are living in a simulation is close to one.

Before Bostrom, the 1999 movie *The Matrix* had already done its part to popularize the notion of simulated realities. And the idea has deep roots in Western and Eastern philosophical traditions, from Plato's cave allegory to Zhuang Zhou's butterfly dream. More recently, Elon Musk gave further fuel to the concept that our reality is a simulation: "The odds that we are in base reality is one in billions," he said at a 2016 conference.

"Musk is right if you assume [propositions] one and two of the trilemma are false," says astronomer David Kipping of Columbia University. "How can you assume that?"

To get a better handle on Bostrom's simulation argument, Kipping decided to resort to Bayesian reasoning. This type of analysis uses Bayes's theorem, named after Thomas Bayes, an 18th-century English statistician and minister. Bayesian analysis allows one to calculate the odds of something happening (called the "posterior" probability) by first making assumptions about the thing being analyzed (assigning it a "prior" probability).

Kipping began by turning the trilemma into a dilemma. He collapsed propositions one and two into a single statement because in both cases, the final outcome is that there are no simulations. Thus, the dilemma pits a physical hypothesis (there are no simulations) against the simulation hypothesis (there is a base reality—and there are simulations, too). "You just assign a prior probability to each of these models," Kipping says. "We just assume the principle of indifference, which is the default assumption when you don't have any data or leanings either way."

So each hypothesis gets a prior probability of one half, much as if one were to flip a coin to decide a wager.

The next stage of the analysis required thinking about "parous" realities—those that can generate other realities—and "nulliparous" realities—those that cannot simulate offspring realities. If the physical hypothesis was true, then the probability that we were living in a nulliparous universe would be easy to calculate: it would be 100 percent. Kipping then showed that even in the simulation hypothesis, most of the simulated realities would be nulliparous. That is because as simulations spawn more simulations, the computing resources available to each subsequent generation dwindles to the point where the vast majority of realities will be those that do not have the computing power necessary to simulate offspring realities that are capable of hosting conscious beings.

Plug all these into a Bayesian formula, and out comes the answer: the posterior probability that we are living in base reality is almost the same as the posterior probability that we are a simulation—with the odds tilting in favor of base reality by just a smidgen.

These probabilities would change dramatically if humans created a simulation with conscious beings inside it because such an event would change the chances that we previously assigned to the physical hypothesis. "You can just exclude that [hypothesis] right off the bat. Then you are only left with the simulation hypothesis," Kipping says. "The day we invent that technology, it flips the odds from a little bit better than 50–50 that we are real to almost certainly we are not real, according to these calculations. It'd be a very strange celebration of our genius that day."

The upshot of Kipping's analysis is that, given current evidence, Musk is wrong about the one-in-billions odds that he ascribes to us living in base reality. Bostrom agrees with the result—with some caveats. "This does not conflict with the simulation argument, which only asserts something about the disjunction," the idea that one of the three propositions of the trilemma is true, he says.

"If the simulation has infinite computing power, there is no way you're going to see that you're living in a virtual reality, because it could compute whatever you want to the degree of realism you want."
—Houman Owhadi

But Bostrom takes issue with Kipping's choice to assign equal prior probabilities to the physical and simulation hypothesis at the start of the analysis. "The invocation of the principle of indifference here is rather shaky," he says. "One could equally well invoke it over my original three alternatives, which would then give them one-third chance each. Or one could carve up the possibility space in some other manner and get any result one wishes."

Such quibbles are valid because there is no evidence to back one claim over the others. That situation would change if we can find evidence of a simulation. So could you detect a glitch in the Matrix?

Houman Owhadi, an expert on computational mathematics at the California Institute of Technology, has thought about the question. "If the simulation has infinite computing power, there is no way you're going to see that you're living in a virtual reality, because it could compute whatever you want to the degree of realism you want," he says. "If this thing can be detected, you have to start from the principle that [it has] limited computational resources." Think again of video games, many of which rely on clever programming to minimize the computation required to construct a virtual world.

For Owhadi, the most promising way to look for potential paradoxes created by such computing shortcuts is through quantum-physics experiments. Quantum systems can exist in a superposition of states, and this superposition is described by a mathematical abstraction called the wave function. In standard quantum mechanics, the act of observation causes this wave function to randomly collapse to one of many possible states. Physicists are divided over whether the process of collapse is something real or just reflects a change in our knowledge about the system. "If it is just a pure simulation, there is no collapse," Owhadi says. "Everything is decided when you look at it. The rest is just simulation, like when you're playing these video games."

To this end, Owhadi and his colleagues have worked on five conceptual variations of the double-slit experiment, each designed to trip up a simulation. But he acknowledges that it is impossible to know, at this stage, if such experiments could work. "Those five experiments are just conjectures," Owhadi says.

Zohreh Davoudi, a physicist at the University of Maryland, College Park, has also entertained the idea that a simulation with finite computing resources could reveal itself. Her work focuses on strong interactions, or the strong nuclear force—one of nature's four fundamental forces. The equations describing strong interactions, which hold together quarks to form protons and neutrons, are so complex that they cannot be solved analytically. To understand strong interactions, physicists are forced to do numerical simulations. And unlike any putative supercivilizations possessing limitless comput-

> **“It’s arguably not testable as to whether we live in a simulation or not. If it’s not falsifiable, then how can you claim it’s really science?”**
> ***—David Kipping***

ing power, they must rely on shortcuts to make those simulations computationally viable—usually by considering spacetime to be discrete rather than continuous. The most advanced result researchers have managed to coax from this approach so far is the simulation of a single nucleus of helium that is composed of two protons and two neutrons.

“Naturally, you start to ask, if you simulated an atomic nucleus today, maybe in 10 years, we could do a larger nucleus; maybe in 20 or 30 years, we could do a molecule,” Davoudi says. “In 50 years, who knows, maybe you can do something the size of a few inches of matter. Maybe in 100 years or so, we can do the [human] brain.”

Davoudi thinks that classical computers will soon hit a wall, however. “In the next maybe 10 to 20 years, we will actually see the limits of our classical simulations of the physical systems,” she says. Thus, she is turning her sights to quantum computation, which relies on superpositions and other quantum effects to make tractable certain computational problems that would be impossible through classical approaches. “If quantum computing actually materializes, in the sense that it’s a large-scale, reliable computing option for us, then we’re going to enter a completely different era of simulation,” Davoudi says. “I am starting to think about how to perform my simulations of strong interaction physics and atomic nuclei if I had a quantum computer that was viable.”

All of these factors have led Davoudi to speculate about the simulation hypothesis. If our reality is a simulation, then the simulator is likely also discretizing spacetime to save on computing resources (assuming, of course, that it is using the same mechanisms as our physicists for that simulation). Signatures of such discrete spacetime could potentially be seen in the directions high-energy cosmic rays arrive from: they would have a preferred direction in the sky because of the breaking of so-called rotational symmetry.

Telescopes “haven’t observed any deviation from that rotational invariance yet,” Davoudi says. And even if such an effect were to be seen, it would not constitute unequivocal evidence that we live in a simulation. Base reality itself could have similar properties.

Kipping, despite his own study, worries that further work on the simulation hypothesis is on thin ice. “It’s arguably not testable as to whether we live in a simulation or not,” he says. “If it’s not falsifiable, then how can you claim it’s really science?”

For him, there is a more obvious answer: Occam’s razor, which says that in the absence of other evidence, the simplest explanation is more likely to be correct. The simulation hypothesis is elaborate, presuming realities nested upon realities, as well as simulated entities that can never tell that they are inside a simulation. “Because it is such an overly complicated, elaborate model in the first place, by Occam’s razor it really should be disfavored, compared to the simple natural explanation,” Kipping says.

And maybe we are living in base reality after all—*The Matrix*, Elon Musk and weird quantum physics notwithstanding.

Venus's swirling cloud tops, as seen by the Akatsuki probe's ultraviolet imager.

ISAS AND JAXA WIKIMEDIA (CC BY 4.0)

Venus Might Host Life, New Discovery Suggests

The unexpected atmospheric detection of phosphine, a smelly gas made by microbes on Earth, could spark a revolution in astrobiology

By Adam Mann

Adam Mann is a journalist specializing in astronomy and physics. His work has appeared in *National Geographic*, the *Wall Street Journal*, *Wired* and elsewhere.

There is something funky going on in the clouds of Venus. Telescopes have detected unusually high concentrations of the molecule phosphine—a stinky, flammable chemical typically associated with feces, farts and rotting microbial activity—in an atmospheric layer far above the planet's scorching surface.

The finding is curious because here on Earth, phosphine is essentially always associated with living creatures, either as a by-product of metabolic processes or of human technology such as industrial fumigants and methamphetamine labs. Although it is toxic to many organisms, the molecule has been singled out as a potentially unambiguous signature of life because it is so difficult to make through ordinary geological or atmospheric action.

Swathed in sulfuric acid clouds and possessing oppressive surface pressures and temperatures hot enough to melt lead, Venus is a hellish world. But the particular cloud layer where the phosphine is present happens to be relatively balmy, with ample sunlight and Earth-like atmospheric pressure and temperature. The results will have to be carefully vetted by the scientific community. Yet they seem likely to spark renewed interest in exploring our sister planet next door.

A MOLECULAR MYSTERY

"It's a really puzzling discovery because phosphine doesn't fit in our conception of what kinds of chemicals should be in Venus's atmosphere," says Michael Wong, an astrobiologist at the University of Washington. Planetary scientist Sanjay Limaye of the University of Wisconsin–Madison agrees. "The bottom line is that we don't know what's going on," he says. (Neither Wong nor Sanjay was involved in the work.)

After the sun and moon, Venus is the brightest object visible to the naked eye in Earth's sky. For thousands of years, people told stories about the glittering jewel that appeared around sunrise and sunset. Venus's brilliance is what made it attractive to Jane Greaves, a radio astronomer at Cardiff University in Wales. She typically focuses her attention on distant newborn planetary systems but wanted to test her molecular identification abilities on worlds within our cosmic backyard.

In 2017 Greaves observed Venus with the James Clerk Maxwell Telescope (JCMT) on Mauna Kea in Hawaii, searching for bar code–like patterns of lines in the planet's spectrum that would indicate the presence of different chemicals. While doing so, she noticed a line associated with phosphine. The data suggested the molecule was present at around 20 parts per billion in the planet's atmosphere, a concentration between 1,000 and a million times greater than that in Earth's atmosphere. "I was stunned," Greaves says.

Phosphine is a relatively simple molecule containing one phosphorus atom and three hydrogen atoms. It is known to reek of garlic or rotting fish, although by the time it reaches concentrations where humans can smell it, it is likely to cause lung damage. In the pilot episode of the series *Breaking Bad,* the character Walter White prepares phosphine gas to knock out two assailants who are threatening him.

Yet making the substance is not as easy as seen on TV. Phosphorus and hydrogen "hate each other," says Clara Sousa-Silva, a molecular astrophysicist at the Massachusetts Institute of Technology and a co-author of a study reporting the phosphine finding. "Hydrogen has much better stuff to do, and phosphorus would rather bond with oxygen. But if you throw enough energy at them, they can come together and be stable in some environments."

The gas giants Jupiter and Saturn contain phosphine because they have hot interiors where it can be energetically favorable to produce the molecule. Venus's runaway greenhouse atmosphere, in contrast, is full of oxygen-containing chemicals such as carbon dioxide that would normally soak up phosphine's phosphorus. For the molecule to be present at any level, let alone the amounts Greaves was seeing, was a genuine head-scratcher.

Meanwhile Sousa-Silva has built her career around studying phosphine—she goes by the handle @DrPhosphine on Twitter—predicting how it might appear in the atmosphere of a distant alien exoplanet. "I was considering these exotic worlds light-years away—super-Earths, tropical planets, sewage planets," she says. "And the whole time, it was just here next door."

The researchers and their colleagues made follow-up observations of Venus with the more powerful Atacama Large Millimeter/submillimeter Array (ALMA) in Chile last year, again detecting the atmospheric signature of phosphine. They then tried to come up with every possible reason for the strange molecule's existence, including volcanic activity, lightning strikes and even meteorites breaking up in the planet's atmosphere. "I think the best routes we could find fell short by a factor of about 10,000," Greaves says.

Of course, there might be additional pathways to making phosphine the team has not yet considered. But after exhausting their imaginations seeking out abiotic explanations, the researchers felt forced to acknowledge one other possibility in their paper, which appeared in September in *Nature Astronomy*: the molecule could be made by life on Venus, just as life is the main way it manifests on Earth.

LIFE IN THE CLOUDS

Astrobiologists have long been enamored with Mars, a dry, rocky planet with conditions not all that dissimilar to those of Earth. More recently, they have become moonstruck by icy, potentially habitable worlds in the outer solar system, such as Saturn's geyser-spewing satellite Enceladus and Jupiter's oceanic moon Europa. But despite its drawbacks, Venus has not been entirely neglected by scientists speculating about life's extraterrestrial abodes.

"I've always thought it's as plausible to have life in the clouds of Venus as to find it in the subsurface of Mars. Each is an environment that could be habitable but isn't guaranteed to be."
—David Grinspoon

From 50 to 60 kilometers above the Venusian surface, there is an atmospheric layer with pressure equal to that of sea level on Earth and temperatures between zero and 50 degrees Celsius. If not for the sulfuric acid clouds, one might call this layer "hospitable." Even so, there are terrestrial organisms that will happily tolerate such extremely acidic conditions in hot springs or other environments. This relatively clement region is precisely the place where the phosphine has been found.

Since the 1960s astronomers have also noticed that Venus's clouds are not reflecting as much of the sun's ultraviolet light as they should be: an unknown something in the atmosphere seems to be preferentially absorbing that light instead. This observation led the late astrobiologists Harold Morowitz and Carl Sagan to propose that energy-hungry photosynthetic organisms might be the culprit. Meanwhile there are other researchers who have never stopped searching for alternative abiotic explanations.

Recent evidence suggests that the planet is still geologically active. And a model that was released earlier this year showed that Venus might have had an ocean for nearly three billion years—one that only disappeared a few hundred million years ago. Conceivably, life could have arisen on Venus when our sister world was much more Earth-like, only becoming airborne as the runaway greenhouse effect rendered the planet's surface uninhabitable.

"I've always thought it's as plausible to have life in the clouds of Venus as to find it in the subsurface of Mars," says David Grinspoon, an astrobiologist at the Planetary Science Institute, who was not involved with the study. "Each is an environment that could be habitable but isn't guaranteed to be."

Yet an almost equally good case can be made for Venus's clouds being inimical to life as we know it. Microbes have been found floating around in Earth's atmosphere, but none are known to exclusively spend their entire life cycle there. All of them have to land eventually, and Venus's surface seems too inhospitable a place to make for a good reservoir.

The Venusian area under consideration is also 50 times more arid than Chile's Atacama Desert, the driest place on our planet. And although it is true that living things have found good ways to thrive in aqueous environments tinged with traces of sulfuric acid, conditions on Earth's evil twin essentially reverse that formula: its cloud layer is mainly sulfuric acid with just a bit of water.

VENUS REVISITED

Venus remains an underexplored place. "Despite its being literally the planet next door, there are many mysteries that still need to be solved," Wong says. To rule out all nonliving explanations for the creation of phosphine, researchers will have to learn a great deal more about the planet itself, including its chemistry, geology and atmospheric physics, he adds.

Another issue might be the detection of phosphine itself. Noisy ripples that make resolving any particular line somewhat challenging are superimposed on Venus's spectrum in the team's data. These wavy structures could mimic a phosphine signature, says Bruno Bézard, a spectroscopist at the Paris Observatory. "I don't see a strong argument to say it's not a ripple," he says.

Greaves counters that the odds of finding the same signal using two separate facilities, JCMT and ALMA, is statistically small. Nevertheless, she and her colleagues are hoping to do additional observations at other wavelengths, such as infrared, to further test their initial results. Making higher-resolution maps of where the phosphine appears and seeing if it exhibits any kind of seasonal variation could also help tie it to biological processes.

In many ways, the unexpected finding appears analogous to the 1996 announcement of potential microscopic life in an ancient Martian meteorite designated Allan Hills 84001. Along with structures that looked like fossil bacteria, the sample contained an unusual form of iron crystals that appeared identical to those produced by microbial creatures on Earth. It took many years before researchers were able to figure out an inorganic explanation for those crystals.

Although life did not pan out as an explanation in that case, "it got everybody thinking, 'Well, why not?' " Grinspoon says. "Everything we know about Mars is consistent with that possibility. That led to a huge movement and catalyzed astrobiology as a field."

The phosphine finding might play a similar role in getting planetary scientists to pay more attention to Venus. In recent years there has already been a contingent of researchers clamoring for more missions to our sister planet. Russia has proposed sending its Venera-D mission, which would include an orbiter and lander, to Venus as early as 2026. The European Space Agency similarly has the EnVision spacecraft on its drawing board, and it could reach its target in the next decade.

NASA is currently considering proposals for two different Venus missions for funding under its Discovery Program: the orbiting VERITAS and DAVINCI+. The latter would fly the first probe through Venus's atmosphere since the Soviet Vega balloons in 1985. A selection is expected sometime next year.

Any of these efforts, along with additional observations using telescopes on Earth, could help bolster or weaken the case for phosphine on Venus. Until then, many in the field are likely to reserve their full judgment. "It's very speculative to say that there is life on Venus," Wong says. "But it's also speculative to say there definitely can't be life on Venus."

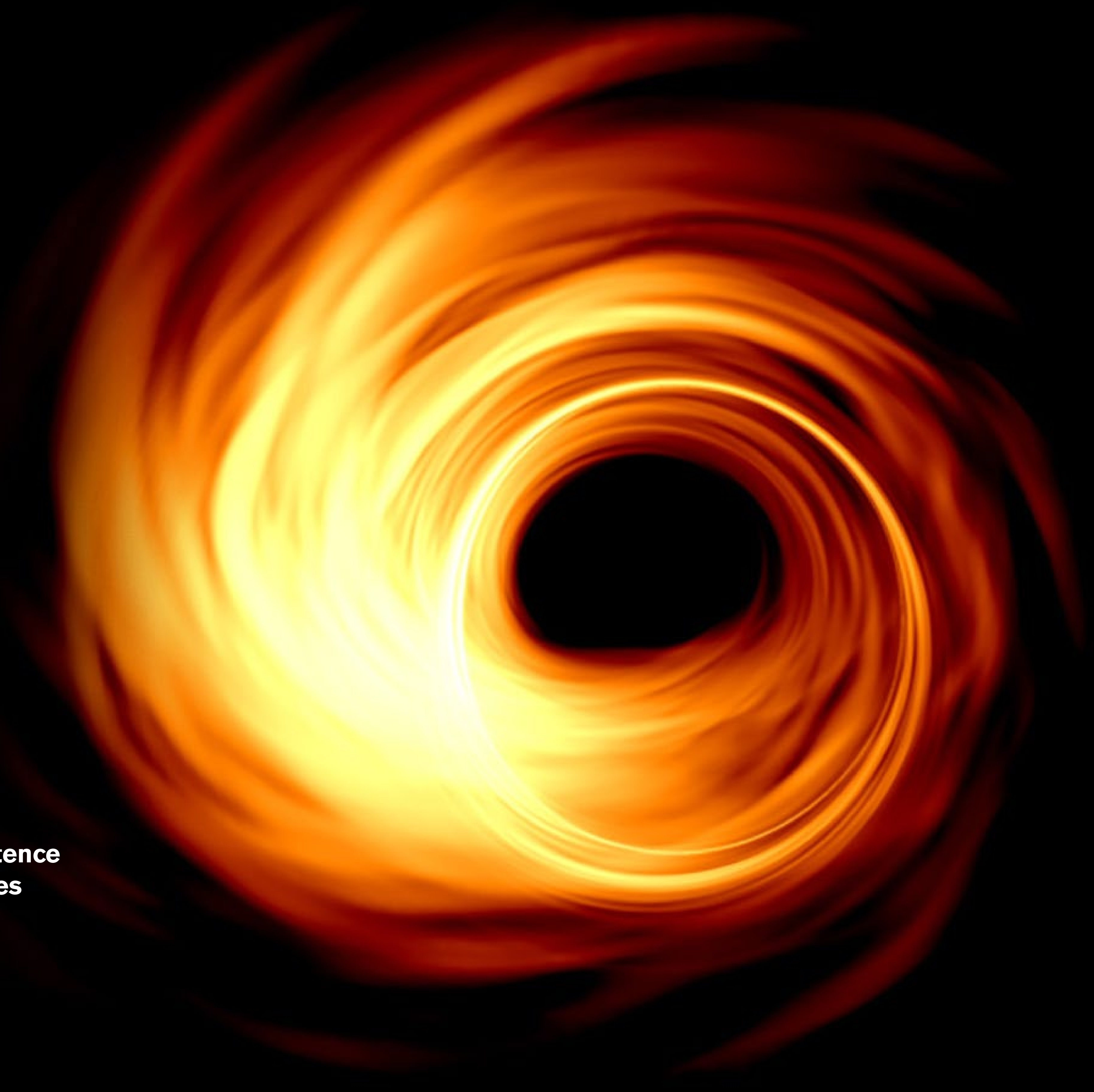
For her part, Sousa-Silva is hoping the rest of the scientific community will subject her and her colleagues' methods and conclusions in the study to rigorous scrutiny. "I'm confident our models and data reduction are good, but I'm still skeptical," she says. "I expect the world to come and point out the mistakes I've made."

Such debates are important for science because similar conundrums are going to unfold every time someone claims evidence for life on a planet in our solar system or beyond, Sousa-Silva says. "I think it's very hard to prove something like this," she adds. "We have an innate desire to find life, and then we have our own rational minds that say, 'None of this is sufficient evidence.' We want to not be alone, but we also want to not be wrong. Sometimes those two things are hard to make coexist."

Nobel Prize Work Took Black Holes from Fantasy to Fact

Over the past century the existence of these invisible cosmic bodies has become unmistakable

By Daniel Garisto



HOTAKA SHIOKAWA

Daniel Garisto is a freelance science journalist covering advances in physics and other natural sciences. His writing has appeared in *Nature News*, *Science News*, *Undark*, and elsewhere.

AS THE CARNAGE OF THE EASTERN FRONT RAGED AROUND HIM, a German lieutenant in World War I digested Albert Einstein's new theory. Less than two months after Einstein published his general theory of relativity, Karl Schwarzschild, who had enlisted despite being older than 40 and a physicist, found a way to use it to describe the spacetime of a spherical, nonrotating mass such as a stationary star or planet. Hidden inside Schwarzschild's work was an implication that hinted at the ultimate warpers of spacetime: black holes. He was just 42 when he died months later, in May 1916. But the quest Schwarzschild started has continued for a century, eventually leading to this year's Nobel Prize in Physics.

The 2020 prize was awarded to mathematical physicist Roger Penrose for his "discovery that black hole formation is a robust prediction of the general theory of relativity" and to astrophysicists Andrea Ghez and Reinhard Genzel "for the discovery of a supermassive compact object at the center of our galaxy." It is the first Nobel given specifically for black holes—an acknowledgment of their unmistakable existence (notwithstanding the hedging in the language of the second half of the award). "Nowadays we take these things for granted," says Leo Stein, a physicist at the University of Mississippi. "We've come so far that, at least within our astrophysical community, we think, 'Of course, there are black holes.'"

But it was not always so. For decades the concept of black holes was no more than a mathematical aberration. In the years following 1916, Schwarzschild's solution caused interest and some consternation among mathematicians and physicists. His work predicted a "Schwarzschild radius"—a radius that denotes how compact an object would need to be to prevent light from escaping its gravitational pull. The sun, for example, has a real radius of nearly 700,000 kilometers, but its Schwarzschild radius is only three kilometers.

Spacetime curves by an amount relative to an object's Schwarzschild radius divided by its actual radius. The closer the two values are, the more spacetime bends. So what happens when the object's radius is equal to its Schwarzschild radius? And what happens if an object's radius is zero? The answers to those questions were known as singularities—undefined solutions equivalent to dividing by zero on a calculator. At a singularity, spacetime seems to bend to a breaking point.

In the next few decades physicists made some progress, but the search was mostly a mathematical diversion with no ties to the real world. The exotic—and, at the time, entirely theoretical—objects suggested by Schwarzschild's work could be as heavy as the sun but smaller than Central Park or, stranger yet, contain a star's mass within a radius of zero. "People thought, 'Okay, this is just fanciful. We're completely outside of the realm of where our physical theory should apply,'" says Frans Pretorius, a physicist at Princeton University.

MONSTROUS MATH

In the 1960s Schwarzschild's solutions started to seem more relevant. Astronomers began to observe extreme phenomena, such as distant galaxies spewing jets of particles at energies and amounts impossible for a normal star (dubbed "quasars"—short for "quasi-stellar objects"—these energetic eruptions were eventually traced to feasting supermassive black holes). At the same time, theorists began to model the dynamics of ultracompact cosmic bodies, finding clever ways to avoid the pitfalls associated with singularities. Penrose, then a young mathematician with a keen interest in astrophysics, was in an optimal position to help scientists stymied by the math.

"[Physicists] would argue. They would get answers that didn't agree with each other," says Daniel Kennefick, an astrophysicist and historian of science at the University of Arkansas. "It turned out the reason was that they didn't really understand the structure of infinity, and Penrose solved that problem."

To deal with the complexities of general relativity where spacetime curved in the extreme, as with objects the same size as their Schwarzschild radius, Penrose came up with a set of mathematical tools. In particular, he introduced the mathematical notion of "trapped surfaces" that allowed physicists to confidently pinpoint an event horizon—the point at which even light can never escape the inexorable tug of gravity. (The event horizon of a nonrotating black hole is located at its Schwarzschild radius.) Event horizons helped deal with the trickiness of singularities by putting an inescapable barrier around them. “We really don’t like having singularities,” Stein says. “In fact, we could cut out the inside of the black hole spacetime and replace it with … pink elephants or what have you. And from the outside, you would never be able to tell the difference because it’s all hidden behind the horizon.” Penrose’s idea of “cosmic censorship” was that there could be no “naked” singularities: all of them would have to be “clothed” by an event horizon. Even when black holes crashed together and merged, the singularities—or pink elephants—would remain hidden by their event horizons, preventing their existence from throwing the outer cosmos into chaos.

A fascination with geometry and artists such as M. C. Escher also led Penrose to develop powerful, intuitive diagrams that captured dynamics of spacetime that were previously out of reach. His diagrams compacted space and time, placing infinities on the page instead of having them stretch off into the distance. “Once it’s on the page, you can study it,” Kennefick says. “Penrose was a tool maker par excellence. He invented many of the tools that were used in that period to understand black holes and that we still use today.” By the end of the 1960s the term “black hole” had become the accepted nomenclature to describe these hypothetical—but now much less improbable—consequences of general relativity.

ASTROPHYSICAL JUMP SCARE

It is hard to pinpoint exactly when a majority of physicists became believers, but by the mid 1990s black holes were taken for granted even without direct observations of them. Some of the most concrete evidence would come from Ghez’s and Genzel’s separate work on Sagittarius A*, the then suspected supermassive black hole at the center of the Milky Way. “Often when we’re interpreting astronomical observations, there’s some wiggle room for some other possibilities,” says Suvi Gezari, an astronomer at the University of Maryland, College Park. “What’s so beautiful about our galactic center is that the measurements don't allow for any other possibility than a four-million-solar-mass black hole.”

> **“[Physicists] would argue. They would get answers that didn’t agree with each other. It turned out the reason was that they didn’t really understand the structure of infinity, and Penrose solved that problem.”**
>
> ***—Daniel Kennefick***

To arrive at that level of precision, Ghez and Genzel each independently led teams that spent more than a decade following the path of S02, a star with a short elliptical orbit around Sagittarius A*. In the 16 years it took for S02 to orbit the galactic center, the researchers dramatically improved their telescopes’ measurements with a technology called adaptive optics, which uses lasers to correct for blurriness caused when light travels through Earth’s atmosphere.

By the time S02 made a complete orbit around a dark patch of nothing, the existence of black holes could not have been clearer. Since then, astronomers have made other direct observations of black holes.

In 2012 Gezari led a team that observed, with unprecedented detail, a tidal disruption event—a tame name for a black hole ripping apart the entrails of a star that got too close. A stellar homicide in another galaxy looks a bit like a brighter, longer supernova, thanks to the rest of the star being flung apart. “I used to call it the ‘fingerprints’ of the victim—which, in this case, is the star,” Gezari says.

More events, such as the merger of two black holes and the ensuing gravitational waves captured by the Laser Interferometer Gravitational-wave Observatory (LIGO) and the Virgo experiment, have given further proof that these objects exist. But perhaps the most stunning evidence thus far is the Event Horizon Telescope’s (EHT’s) image of a supermassive black hole with billions of solar masses at the center of the galaxy Messier 87 (M87). The now iconic image of a black circle ringed with the intense light of an accretion disk the size of our solar system has eliminated any room for doubt.

These observations of black holes and their shadows are more than just confirmations of Einstein’s theory. As the EHT’s resolution increases, it will test the very theories that first predicted their existence. “Black hole shadows are a good test in that alternative theories predict something different than what general relativity predicts,” says Feryal Özel, an astrophysicist at the University of Arizona and the EHT.

Earlier this month, by carefully scrutinizing the shape of the shadow seen by the EHT, Özel and her colleagues made some of the most precise measurements of general relativity. So far those measurements agree with predictions, but it is possible that with more precision, deviations from general relativity that hint at a deeper underlying theory will show up.

For astronomers, astrophysicists and mathematicians, black holes are, by turns, monstrous and beautiful; they are extraordinary in their physics but ordinary in their ubiquity. They continue to attract researchers hoping to unlock new secrets of the universe. For a watching public, there is some appeal, too. Evolutionary biologist “Stephen Jay Gould famously wondered, ‘Why have dinosaurs become so popular?’ and argued that it isn’t obvious that they should be,” Kennefick says. Black holes, he suggests, have some of the same features as dinosaurs: they seem big, they eat things, and they’re a little terrifying—but comfortably far away.

Hilton Lewis is director of the W. M. Keck Observatory.

PHYSICS

How Andrea Ghez Won the Nobel for an Experiment Nobody Thought Would Work

She insisted on doing it anyway—and ultimately provided conclusive evidence for a supermassive black hole at the core of the Milky Way

ALAMY

Standing in my office 25 years ago was an unknown, newly minted astronomer with a half-smile on her face. She had come with an outrageous request—really a demand—that my team modify our exhaustively tested software to make one of our most important and in-demand scientific instruments do something it had never been designed for—and risk breaking it. All to carry out an experiment that was basically a waste of time and couldn't be done—to prove that a massive black hole lurked at the center of our Milky Way.

My initial "no way" (perhaps I used a stronger expression) gradually gave way in the face of her cheerful but unwavering determination. It was my first encounter with a force of nature: Andrea Ghez, one of three winners of this year's Nobel Prize in Physics, for her work on providing the conclusive experimental evidence of a supermassive black hole with the mass of four million suns residing at the center of the Milky Way galaxy.

That determination and the willingness to take calculated risks has always characterized Andrea. For 25 years she has focused almost exclusively on Sagittarius A*—the name of our own local supermassive black hole. It is remarkable that an entire field of study has grown up in the intervening quarter century, of searching for and finding evidence of these monsters thought to lie at the heart of every large galaxy. And Andrea is without question one of the great pioneers in this search.

Andrea's co-prizewinner Reinhard Genzel has been involved in the same research from the outset—and it is the work of these two teams, each led by a formidable intellect and using two different observatories in two different hemispheres that has brought astronomy to this remarkable result—the confirmation of another of the predictions of Albert Einstein's more than century-old theory of general relativity.

As in so many fields of science, the competition has been intense, sometimes brutal, but out of this has been forged an unshakable result that has been tested and retested over a quarter century. And at the heart of the competition, two colleagues, great astronomers each, whose work has been as much defined by the science as by the availability of telescopes and instrumentation almost perfectly suited to this exact scientific endeavor.

Andrea did her work at the W. M. Keck Observatory's twin telescopes on Maunakea, Hawai'i, in the calm and clear air almost 14,000 feet above the Pacific Ocean. She started using the very first instrument commissioned on Keck Observatory's Near Infrared Camera (NIRC), now gracing the lobby at our headquarters. NIRC was never designed to do what Andrea needed—an ultrafast readout of images and then a restacking of the result to remove the effects of the atmosphere's turbulence. But she was not to be denied—and we made the changes. And it worked! It was supremely hard and time-consuming to make sense of the data, but Andrea persisted.

Out of that effort came the first evidence—not just hints—of stars orbiting the black hole. It was a fantastic result but a long way from full confirmation. At around that time, a new technology, adaptive optics (AO), was being installed on telescopes worldwide. Keck Observatory was the first of the most powerful observatories to be so equipped—and the results were electrifying. No surprise: Andrea immediately switched to using AO for her work. She always pushed for more performance and more capability—and the scientists and engineers at Keck Observatory and in our community of instrument builders responded. This push for more and more, and the scientific rewards that followed, is what helped make AO the immensely powerful tool it is today.

Andrea is fond of pointing out that one of the reasons for her success has been this tight and rapid loop between the needs of the astronomers and the engineers who respond to the challenge. In a way reminiscent of the tight synergy between mathematics and physics, science questions beget new technology and new technology begets new science. Andrea has always been in the forefront of this virtuous cycle, an enthusiastic proponent of "we can do more."

Andrea is a great scientist; not only does she do the science, she molds events to make it possible. In addition to doing research, she has created the U.C.L.A. Galactic Center Group to coordinate research and technical developments. And she imbued a cohort of graduate students and postdoctoral fellows with her passion and thrill of the chase. It is no exaggeration to say that Andrea has personally inspired aspiring scientists everywhere, and she serves as a role model for what ability, grit and commitment can accomplish.

Today Andrea sits at the pinnacle of scientific recognition for her achievements. But as she would be the very first to acknowledge, this triumph represents the combined efforts of so many. From the theoretical predictions of the peerless Einstein, through those who had the vision to build the amazingly complex machines we call simply "telescopes," to the siting at the best locations on Earth for this research, to those who conceive of and build the instrumentation and run the operations, to the science teams that do the research—all of it essential, the product of the work of thousands.

But in the end, one person had the idea for the research. One person had the chutzpah to propose it, and one person had the determination, tenacity and focus to make it happen, undeterred by all who said it was a waste of time. That person is my friend and longtime colleague, the one who refused to take "no" for an answer and who probably doesn't even have it in her vocabulary: Andrea Ghez, winner of the 2020 Nobel Prize in Physics.

Nikolai Sinitsyn is a theoretical physicist in the Theoretical Division at Los Alamos National Laboratory.
Bin Yan is a postdoc in the Center for Nonlinear Studies at Los Alamos National Laboratory.

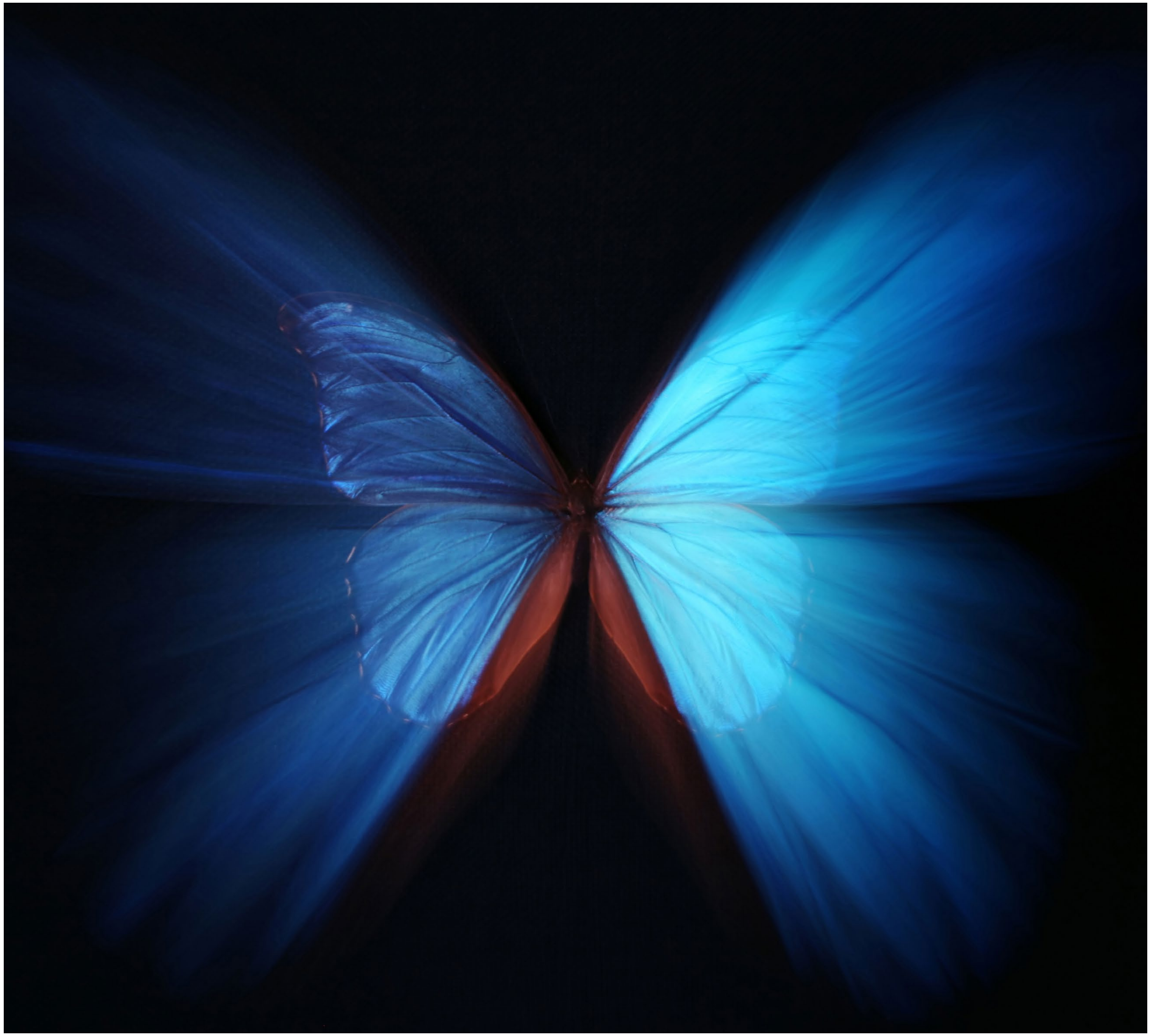
COMPUTING

The Quantum Butterfly Noneffect

A familiar concept from chaos theory turns out to work differently in the quantum world

Chaos theory says that a tiny, insignificant event or circumstance can have outsized influence in shaping the way a large, complex system evolves into the future. Many people are familiar with this so-called butterfly effect, an idea often traced to science-fiction author Ray Bradbury's 1952 story "A Sound of Thunder." In that tale, a man who has time-traveled into the deep past to hunt a *Tyrannosaurus rex* inadvertently crushes a butterfly under his foot. When he returns to the present, he discovers that this seemingly trivial act altered the course of history—and not in a good way.

In the early 1970s meteorologist and mathematician Edward Norton Lorenz articulated the butterfly effect in science and launched the field of chaos theory. In plain language, this version of the effect says that initial conditions strongly



GETTY IMAGES

influence the evolution of highly complex systems. In Lorenz's metaphor, the flapping of a butterfly's wings in Brazil could ultimately lead to a tornado in Texas that wouldn't have happened otherwise. By implication, if you could go back and alter the past even slightly, a different future would evolve within the system. The future containing your present would vanish.

The butterfly effect is well accepted in our everyday world, where classical physics describes systems above the atomic scale. But in the submicroscopic world, where quantum mechanics reigns, different—and very strange—rules apply. Does the butterfly effect still hold true? If not, what happens instead?

As we describe in a peer-reviewed article in *Physical Review Letters,* we explored this facet of quantum mechanics when we were developing a novel method to protect quantum information. Exploiting the property of quantum entanglement induced by a complex evolution, we wanted to put qubits (quantum bits) into a state where they would be immune to damage. Then they could be retrieved without alteration, even if someone tried to damage or steal the information. That ability would help secure quantum information and provide a method for hiding information as well.

To do so, we started with a theoretical analysis using the equations of quantum mechanics—good old whiteboard work. Then we ran an experiment on the IBM-Q quantum processor.

For the whiteboard theory phase, we compared the evolution of a complex quantum system with an identically designed system, but with locally changed initial conditions, by measuring and therefore altering one qubit. We expected a result similar to the classical result. That is, as the system evolved over a sufficiently long time, we thought the local variables that described a particular qubit in the once twin systems eventually would have very different values—in other words, the butterfly effect.

The butterfly effect is well accepted in our everyday world, where classical physics describes systems above the atomic scale. But in the submicroscopic world, where quantum mechanics reigns, different—and very strange—rules apply. Does the butterfly effect still hold true? If not, what happens instead?

In our thought experiment, we recruited every quantum theorist's old friends, Alice and Bob, our experimental avatars. The evolution that they considered involved a circuit that evolves in a complex way. The circuit applies many quantum gates randomly to many qubits. The gates perform an operation on the qubits, and each gate represents a step in time, like the tick of a clock.

This is the forward-in-time travel operation in our theoretical "world on a chip."

Alice prepares one of her qubits in the present time and runs the circuit backward, emulating travel back in time. In the past, Bob measures the qubit's polarization, which is the local information stored in Alice's qubit. Because measurement in the quantum world alters the state of the particle being measured, this measurement changes the polarization, which is the information in this case. Also, by the laws of quantum dynamics, this invasive measurement destroys all of the qubit's quantum correlations with the rest of the world on a chip. So, we thought this past world was altered in such a way that a return to the previous present—the future of this altered qubit—would change the entire world on a chip.

Next we ran the circuit forward in time to bring the world back to the present time. According to Ray Bradbury's vision, Bob's small damage to the state of the qubit should have been quickly magnified during the complex forward-in-time evolution. That would mean that Alice could not recover her information at the end. The squashed butterfly should have drastically altered her information in the present.

But it didn't.

For our next test of these results, we ran a similar experiment in a simulation on the IBM-Q quantum processor. To simulate time travel, we sent qubits through the computer gates in reverse order. The gates manipulate the qubits and represent time steps as well. Then we damaged information in this simulated past by measuring just one local qubit, while all the other qubits maintained their quantum correlations and remained entangled.

After the damaging measurement, we ran our forward-in-time protocol and then measured the qubit's state: it had returned to essentially the same state it had been in before backward evolution, plus some small background noise. Because the initial state of the whole system was strongly entangled in quantum correlations, the long complex evolution essentially recovered the information of the perturbed qubit.

To our surprise, we not only disproved the butterfly effect in a quantum system, but we also found a sort of no-butterfly effect, as if the system wants to protect the present.

Being strongly entangled in the quantum sense meant that the system initially had robust quantum correlations among its parts. Entangled qubits share various properties, such as polarization, and in some ways act as one. Even after changing the local information, purely quantum and global correlations across all the entangled qubits put guard rails on the quantum dynamics, guiding them to restore the damaged local variables. The longer and more complex the evolution is, the more quantum correlations it generates, so the better our predictions become, and the more robust the present.

You could say reality in quantum mechanics is self-healing.

Our theory applies to a sufficiently complex quantum evolution in which quantum correlations among the different qubits have time to appear during the backward-in-time evolution. This approach has practical applications, such as testing the quantumness of quantum computers. Where it is uncertain whether a quantum computer is actually using quantum mechanics to get its results—it might still be relying on classical physics—our no-butterfly effect can be used to test it because our effect is purely quantum-mechanical. Another potential application is protecting information because a random evolution on a quantum circuit can protect a qubit from attack.

Next, we hope to experimentally verify the effect in an actual, physical quantum system in a lab (not a quantum computer), probably using ultracold atoms, which behave quantum-mechanically. This will allow us to demonstrate the effect under conditions that could be applied to the practical problem of protecting quantum information.

Beyond these practical uses, the no-butterfly effect raises interesting questions about the differences between the quantum realm and the classical physics world of our everyday experience. Most physicists believe quantum mechanics apply to scale we can observe, anywhere we look, but it often produces the same predictions as classical physics. Physicists are still grappling with how the classical world emerges from the quantum world in our everyday life. To what extent the no-butterfly effect might apply in the macroscopic world of our lives is an open question, as is the degree to which the classical butterfly effect might apply in the quantum world. We hope to answer those questions in future research. Time will tell.

Paul Davies is Regents' Professor at Arizona State University, director of the Beyond Center for Fundamental Concepts in Science and co-director of the Arizona State University Cosmology Initiative.

PHYSICS

In Memoriam: John D. Barrow

Remembering the maverick physicist who pioneered an "anthropic" approach to cosmology

A truly great scientist not only makes significant technical contributions but also reshapes a discipline's conceptual landscape through a commanding depth and breadth of vision. Theoretical physicist John D. Barrow, who passed away on September 26 at the age of 67, was one such individual. Barrow's career spanned the golden age of cosmology, in which the subject was transformed from a scientific backwater to a mainstream precision science. He was both a player and a commentator in these heady times, producing several hundred research papers and scholarly articles, as well as a string of expository books, each a model of wit and clarity that made him a public intellectual worldwide.

John D. Barrow.

TANIA CONTRASTO AND REDUX

A Londoner by birth, Barrow obtained a doctorate from the University of Oxford in 1977 under the direction of Dennis Sciama, joining the ranks of a formidable lineup of mentees that included Martin Rees and Stephen Hawking. This came at a time of crisis in cosmology. Although the big bang hypothesis for the origin of the universe was well established, the originating event itself remained a mystery; in particular, there was puzzlement about the initial conditions. Analysis of the cosmic microwave background radiation—the fading afterglow of the big bang discovered in the late 1960s—indicated that the universe erupted into existence in an astonishingly uniform state. The expansion rate of the universe also matched its gravitating power to extraordinary precision. It looked like a fix. Barrow addressed these foundational questions in a series of papers on smoothing mechanisms applied to chaotic cosmological expansion, followed in later years by analyses that included extensions to Einstein's general theory of relativity and various alternative theories of gravitation. The currently popular inflationary universe theory, which explains the "fix" as resulting from a sudden burst of accelerating expansion in the first split second of cosmic existence, provided additional fertile ground for Barrow's theoretical explorations.

After a stint at the University of California, Berkeley, he took up a position at the then relatively new University of Sussex in the south of England, where he produced a stunning output of journal papers, soon making him something of a scientific celebrity. His research addressed issues as diverse as the asymmetry between matter and antimatter in the universe, the theory of black holes, the nature of dark matter and the origin of galaxies. His early preoccupation with initial cosmic conditions led Barrow to reinstate in physical science the ancient philosophical concept of teleology, which (in its various guises) takes into account final as well as initial states.

The centerpiece of this approach was a remarkable book published in 1986 and co-authored with physicist Frank Tipler entitled *The Anthropic Cosmological Principle*. It built on the recognition that if the initial state of the universe or the fundamental constants of physics had deviated—in some cases, by just a tiny amount—from the values we observe, the universe would not be suitable for life. The book is a detailed and extensive compilation of such felicitous biofriendly "coincidences," and it became a canonical reference text for a generation of physicists. It also provoked something of a backlash for flirting with notions of cosmic purpose and straying too close to theology in some people's eyes. Nevertheless, its style of "anthropic" reasoning subsequently became a familiar part of the theorist's arsenal, albeit a still contentious one.

More recently, Barrow was interested in the possibility that the fine-structure constant—an unexplained number that describes the strength of the electromagnetic force—might not be constant at all but rather vary over cosmological scales. He produced a theoretical basis for incorporating such a phenomenon in physical law while also remaining open-minded on the observational evidence. His adventurous choices of research problems typified Barrow's intellectual style, which was to challenge the hidden assumptions underpinning cherished mainstream theories. Fundamental problems in physics and cosmology may appear intractable, he reasoned, because we are thinking about them the wrong way. It was a mode of thought that resonated with many colleagues, this writer included, who are drawn to reflect on the deepest questions of existence.

In 1999 Barrow moved to the University of Cambridge as a professor in the department of applied mathematics and theoretical physics and became a fellow of Clare Hall College. In parallel, he completed two separate periods as a professor at the select Gresham College, founded in 1597 to organize free public lectures in London. Barrow's Cambridge appointment included his directorship of the Millennium Mathematics Project. This is an educational program that caters to the needs of elementary and high school children in imaginative ways. But this demanding array of teaching responsibilities did not deter Barrow from his prodigious research output.

Barrow had many talents beyond the realm of theoretical physics and mathematics. In his younger years, he was an Olympic-standard middle-distance runner. Barrow followed sports in general, and running in particular, with undiminished enthusiasm throughout his life. He was a strikingly stylish dresser and regularly traveled to Italy for his sartorial purchases. He was also a connoisseur of fine dining, making him the ideal traveling companion. An engaging raconteur, Barrow boasted a fund of humorous stories about politics, academia and the humanities. Touch on almost any subject, and he would have something entertaining to say about it. Barrow's scholarship and writing extended to art theory, musicology, history, philosophy and religion—a grasp of human culture aptly recognized by an invitation to deliver the prestigious Centenary Gifford Lectures at the University of Glasgow in 1989 and also by the 2006 Templeton Prize. These acknowledgments were in addition to many notable scientific and academic honors, including being made a Fellow of the Royal Society.

The Barrow family's members loved Italy, where they maintained many professional and social contacts over the decades. It was in Milan that another remarkable John Barrow project culminated: the premiere of the stage play *Infinities,* which he had written. It duly received the Premi Ubu Italian theater prize. It was thus, with some poignancy, that John and his wife, Elizabeth, were able to make one last trip there just a few months ago, in the face of onerous coronavirus-related travel restrictions and the debilitating effects of treatment for his colon cancer. John Barrow died at home and is survived by his wife and three children.

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