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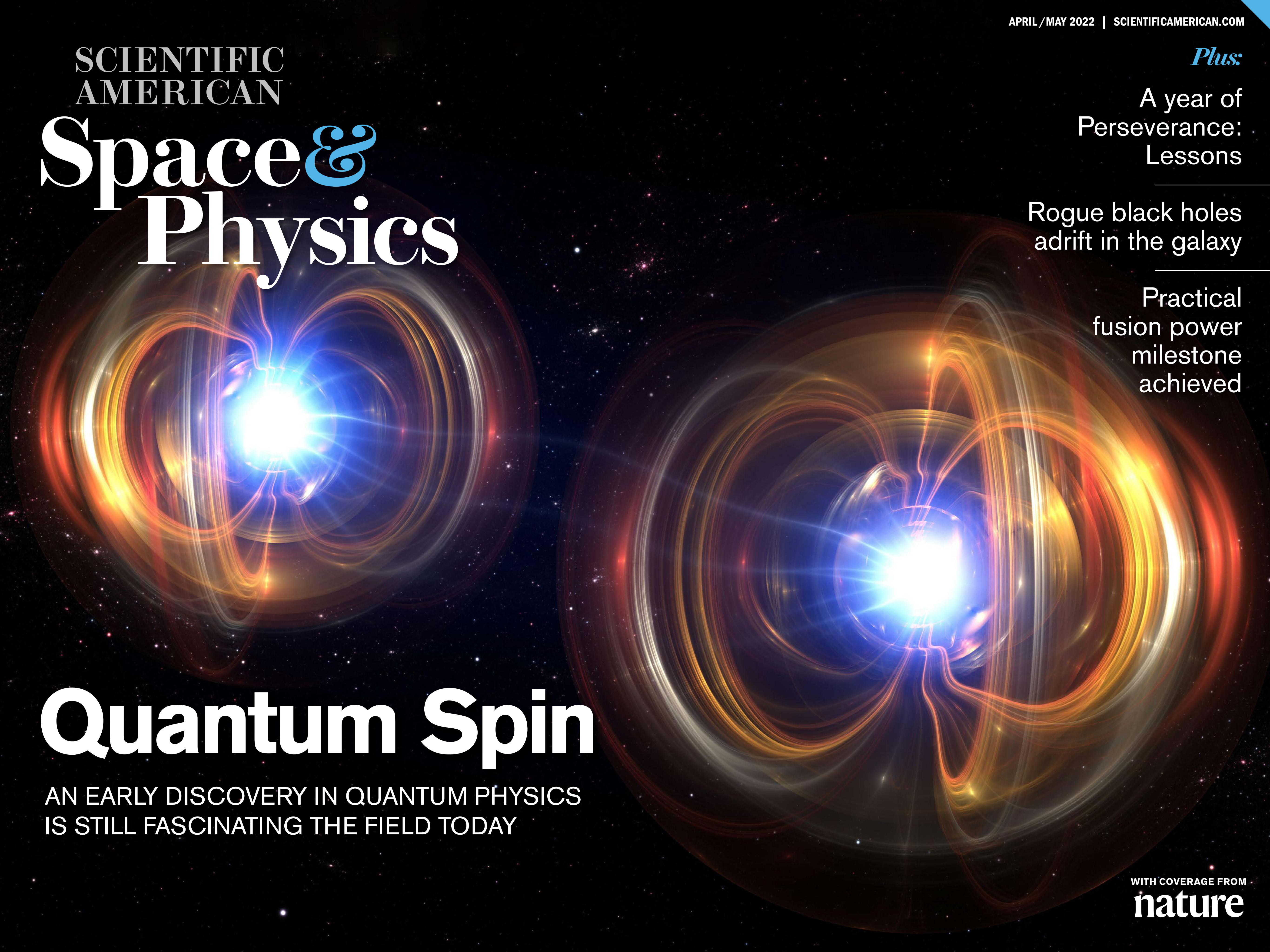

SCIENTIFIC AMERICAN

Space & Physics

Plus:

A year of Perseverance: Lessons

Rogue black holes adrift in the galaxy

Practical fusion power milestone achieved

Quantum Spin

AN EARLY DISCOVERY IN QUANTUM PHYSICS
IS STILL FASCINATING THE FIELD TODAY

WITH COVERAGE FROM
nature

FROM THE EDITOR


Liz Tormes

Humans and the Quantum Experience

In physics, some hypotheses can take more than a lifetime to confirm—as happened in 2019, when researchers saw the first image of a black hole, a cosmological phenomenon whose existence was theorized by Albert Einstein a full century before but never observed directly. Other ideas in physics have endured decades of debate, without resolution or further clarity. In this issue, reporter Davide Castelvecchi profiles the fascinating history of a landmark experiment from 1922 that recorded the quantum spin of an elementary particle, the interpretation of which is still ongoing (see "Hundred Years Ago a Quantum Experiment Explained Why We Don't Fall through Our Chairs").

Elsewhere in this issue, columnist John Horgan contemplates what a radical new quantum theory means for our perception of reality (see "Does Quantum Mechanics Reveal That Life Is but a Dream?"). He writes that quantum researchers share a notable trait with artists "who try to turn the chaos of things into a meaningful narrative." I would take his idea further and say that finding sense among life's challenges is an inherent part of all human experience.

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Space& Physics

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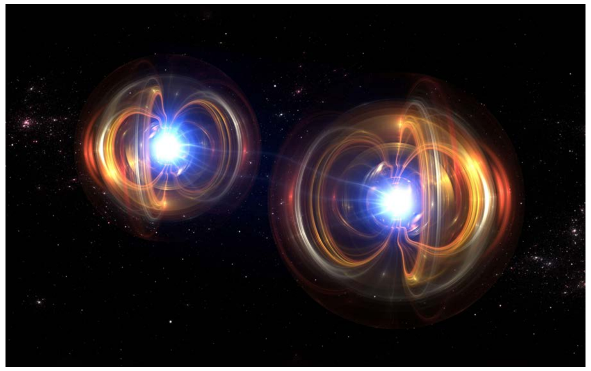
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On the Cover

An early discovery in the field of quantum physics is still fascinating the field today

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April–May 2022
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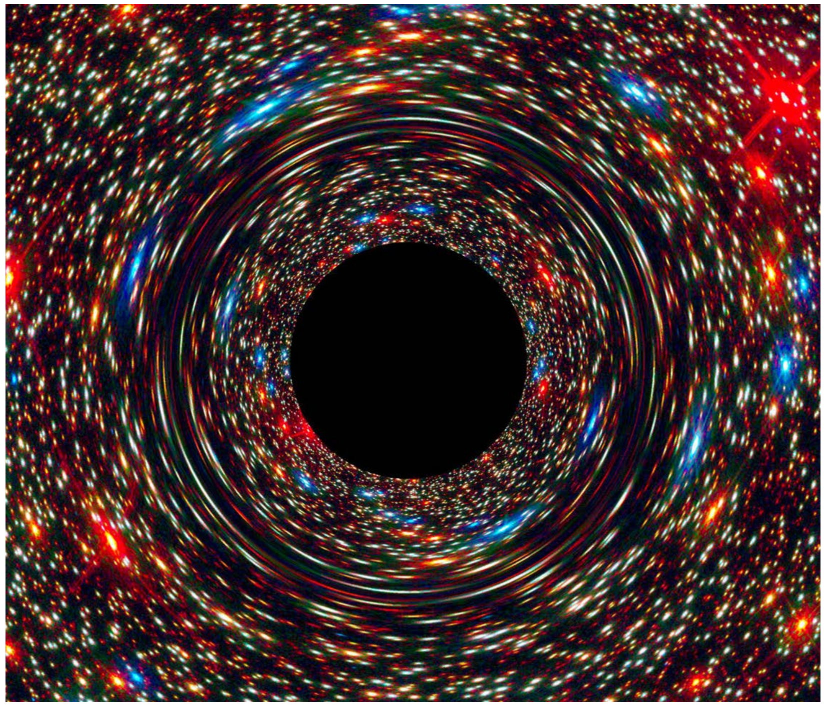
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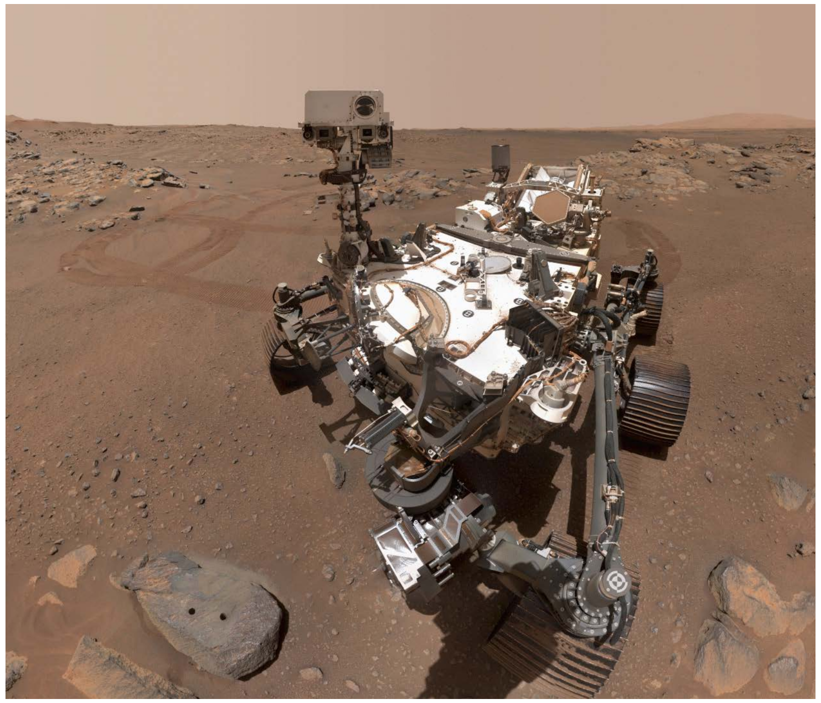
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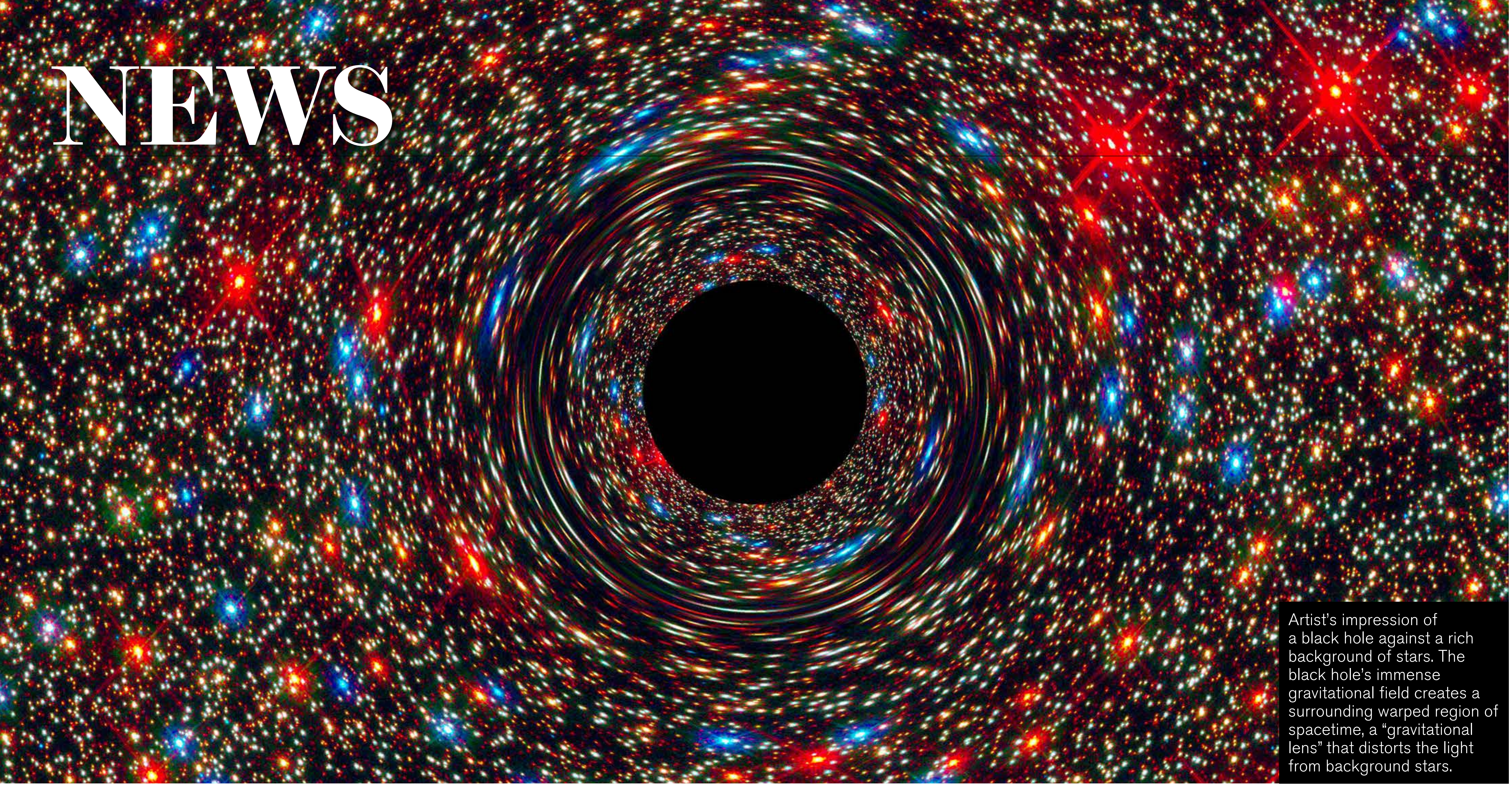


Artist's impression of a black hole against a rich background of stars. The black hole's immense gravitational field creates a surrounding warped region of spacetime, a "gravitational lens" that distorts the light from background stars.

NASA, ESA, and D. Coe, J. Anderson, and R. van der Marel/STScI

Astronomers Find First-Ever Rogue Black Hole Adrift in the Milky Way

Weighing in at seven times the mass of our sun, the dark object is by far the best-yet candidate for a free-floating stellar-mass black hole

These are boom times for astronomers hunting black holes. The biggest ones—supermassive black holes that can weigh billions of suns—have been found at the centers of most every galaxy, and we have even managed to image one. Meanwhile researchers now routinely detect gravitational waves rippling through the universe from smaller merging black holes. Closer to home, we have witnessed the dramatic celestial fireworks produced when the Milky Way's own supermassive black hole and its more diminutive cousins feed on gas clouds or even entire stars. Never before, though, have we seen a long-predicted phenomenon: an isolated black hole drifting aimlessly through space, born and flung out from the collapsing core of a massive star.

Until now.

Scientists have announced the first-ever unambiguous discovery of a free-floating black hole, a rogue wanderer in the void some 5,000 light-years from Earth. The result, which appeared January 31 on the arXiv preprint server but has not yet been peer-reviewed, represents the culmination of more than a decade of ardent searching. “It’s super exciting,” says Marina Rejkuba of the European Southern Observatory in Germany, a co-author on the paper. “We can actually prove that isolated black holes are there.” This discovery may be just the start; ongoing surveys and upcoming missions are expected to find dozens or even hundreds more of the dark, lonely travelers. “It’s the tip of the iceberg,” says Kareem El-Badry of the Harvard-Smithsonian Center for Astrophysics, who was not involved in the paper.

In 1919 British astronomer Arthur Stanley Eddington performed a famous experiment. Einstein’s theories of special and general relativity had postulated that massive objects should cause a dent in spacetime, bending nearby rays of light in a process known as gravitational lensing. Eddington proved this to be true during a total solar eclipse, when the sun’s glare was minimized so that background stars adjacent to it in the heavens could be seen. Using a technique known as astrometry, he carefully noted these stars’ positions before and during the eclipse, revealing a subtle change in their apparent locations in the sky as a result of their light being warped by our star’s considerable gravitational pull. “The apparent position of the stars had a tiny shift,” says Feryal Özel of the University of Arizona, who was also not involved in the paper.

In the subsequent decades, scientists realized a novel use for this technique. Stars greater than about 20 times the mass of our sun should form black holes at the end of their lives, when their heavy cores collapse under their own weight following the exhaustion of their thermonuclear fuel. The birth of such a stellar-mass black hole—a city-sized sphere containing up to dozens of times our sun’s mass—is often accompanied by a bright supernova from the enormous energies released by the core collapse. These forces can be so great they sometimes kick the newborn black hole right out of its womb on an endless interstellar cruise. That cosmic wanderlust—plus the black holes’ small sizes and inherent darkness—should make them almost impossible to see.

Eddington’s work, however, suggested these outcasts could be found by observing their lensing effects—typically a telltale transient brightening of any background stars the black holes flit across within our field of view. The odds of seeing such an event for an isolated black hole were slim, but given that millions of stellar-mass black holes are predicted to be drifting through our galaxy, some might turn up in sufficiently broad and deep surveys of the sky.

Several projects now search for these and other so-called microlensing events, including the Optical Gravitational Lensing Experiment (OGLE), run by the University of Warsaw in Poland, and the Microlensing Observations in Astrophysics (MOA) survey run by researchers in New Zealand and Japan. In June 2011 these two surveys spotted something of note: a suddenly brightening star 20,000 light-years away toward the densely packed galactic bulge in the Milky Way's center. Could this have been a microlensing event from a rogue black hole? Astronomers raced to find out.

Among them was Kailash Sahu of the Space Telescope Science Institute in Baltimore, the lead author on the arXiv preprint detailing the object’s discovery. Using the Hubble Space Telescope, he and his colleagues zoomed in on the star within weeks of its brightening, then returned to it again and again over the next six years. They were able to confirm the star’s light had been magnified, pointing to the presence of an unseen lensing object, but they found something even more important. The star’s apparent position in space had shifted by a minuscule amount. The effect was “1,000 times smaller than what Eddington measured,” says Sahu, and was near the limits of Hubble’s capabilities. Something hidden had amplified and warped the light from the star. The best candidate? An invisible stellar-mass black hole, 7.1 times the mass of our sun.

“There was no possibility other than a black hole,” Sahu says. Two things were needed to confirm that to be the case. “The first criterion was there should be no light coming from the lens,” Sahu says, to rule out more prosaic objects such as a failed star known as a brown dwarf. The second was that the magnification effect should have a long duration, given the expansive size of a black hole’s gravitational sphere of influence. Lasting for about 300 days, the June 2011 event fit the bill. “It’s a pretty thorough and careful analysis,” El-Badry says. “They’ve done their due diligence.”

The amount of lensing and deflection of light from the star then allowed Sahu and his collaborators to peg the suspected black hole’s mass at just over seven solar masses. That places it “smack in the middle” of what we would expect for stellar-mass black holes, Özel says. The team was also able to calculate its speed. “It’s moving at about 45 kilometers per second,” Sahu says. This is relatively fast compared to nearby stars—the exact sort of thing one would expect if the black hole had been given an ejecting kick from a dying massive star. It is not clear when that event would have happened, but it “may be somewhere close to 100 million [years ago],” Sahu says. “We can’t really tell, because we don’t know where exactly it came from.”

This is not, however, the first observational hint of microlensing from rogue stellar-mass black holes; several other candidates predate this one. What is different now is the successful measurement of the lensing object’s gravitational deflection of the star’s light, rather than its mere amplification, allowing the lensing object’s mass—and thus its true nature—to be conclusively surmised. “There have been detections of black hole candidates before, but they didn’t have these astrometric measurements,” says David Bennett of the NASA Goddard Space Flight Center, a co-author with Sahu and others on the discovery paper. “This technique is the best one to use for isolated stellar-mass black holes. This is the first attempt to do it. All the black holes that have been found before have been found because they’re not isolated.”

> **“There have been detections of black hole candidates before, but they didn’t have these astrometric measurements.”**
> ***—David Bennett***

This black hole’s mass offers further evidence that astrophysicists’ formation models are correct—that solitary black holes can rise from the ashes of especially hefty stellar progenitors. It is possible, though, that these black holes can also form in binary systems, too, before becoming nomads in the void. For this particular object, it is not possible to say with certainty which origin story occurred. What is certain, though, is that finding more isolated black holes will allow researchers to probe and refine those models in more detail. “We’ve never been able to study black holes that are by themselves,” Özel says. “So, this new way of finding them, and being able to determine their mass, is definitely exciting. Are they forming differently? Is their mass distribution different?”

Answers to such questions could arrive quite soon. The European Space Agency’s Gaia telescope is currently mapping the positions of billions of stars in our Milky Way. In 2025 scientists on the project will release lensing data from its observations, expected to contain evidence for many more stellar-mass singletons bolting around our galaxy. “Gaia’s data will be of similar or even better quality than Hubble’s,” says Lukasz Wyrzykowski of Warsaw University, a co-author on this latest discovery paper, who also hunts for rogue black holes with Gaia. The forthcoming lensing data, he estimates, will contain dozens of additional candidates.

The Vera C. Rubin Observatory in Chile, which is scheduled to begin a 10-year survey of the night sky next year, is also expected to harvest its own crop of rogue black holes, as is NASA’s Nancy Grace Roman Space Telescope, set to launch in 2027. Rubin and Roman alike have very wide fields of view, allowing each to capture panoramic star-filled vistas in which vast numbers of free-floating black holes must lurk. “The expectation is that these data will be there,” El-Badry says. “The hope is that [Rubin and Roman] will be able to measure this astrometric shift for many [stars].”

For now, this dark discovery forecasts a bright future for the search. Rogue stellar-mass black holes, long predicted but only now observationally confirmed, might well be sufficiently common in our galaxy to support demographic studies of their population. Pinning down their true abundance, masses and other properties could shore up our still incomplete theories of stellar evolution—or reveal important new gaps in our understanding. “We’ve been waiting for this discovery for many, many years,” Wyrzykowski says. “It shows this method works. Gravitational microlensing is the way to find these isolated black holes.”

—Jonathan O’Callaghan

Artist's rendering of a hypersonic missile

DARPA

Hypersonic Weapons Can't Hide from New Eyes in Space

Tracking the missiles is like picking out one lightbulb against a background of lightbulbs, but new technology aims to see them more clearly

China's test flight of a long-range hypersonic glide vehicle late last year was described in the media as close to a "Sputnik moment" in the race to develop new ultrafast maneuvering weapons. But even as senior U.S. military officials publicly fretted about missiles that are, for the moment at least, effectively invincible, the Pentagon was quietly making strides on an entirely novel way to help shoot down these weapons.

Late last December the U.S. Department of Defense's Missile Defense Agency (MDA) gave the green light to a pair of contractors—L3Harris Technologies and Northrop Grumman—to pivot from design to prototype fabrication of a Hypersonic and Ballistic Tracking Space Sensor (HBTSS) system. This technology is intended to solve one of the Pentagon's most vexing technical challenges: how to detect and track the hypersonic glide vehicles that exploit blind spots in today's radar networks.

Both Russia and China have fielded hypersonic glide vehicles, in 2019 and 2020 respectively, but the U.S. is not expected to deploy a comparable offensive weapon until 2023. In contrast to ballistic missile payload trajectories, hypersonic glide vehicles can maneuver on the way to a target. This makes it extremely difficult to track them. These weapons start their journey when a large rocket boosts them to an altitude near the edge of space and releases them. Then the glide vehicles divert to a flatter trajectory—either exiting the atmosphere or staying just within it—and sail on unpowered. They use aerodynamic lift to skip across the atmosphere to their targets at hypersonic speeds. This near-space trajectory and the ability to shift course let hypersonic glide vehicles evade the combination of space and terrestrial sensors used to track ballistic missiles. The Pentagon can detect the launch—but the hypersonic glide vehicle then slips out of view until late in the weapon's flight because of ground radar's line-of-sight limitations. As a result, defensive systems have little, if any, time left to halt an incoming weapon.

HBTSS is intended to solve this problem by continuously tracking long-range missiles from launch to impact. It will also have the ability to hand off critical information to ships, aircraft and ground forces, enabling them to fire their own missiles at incoming threats. The detection system relies on a new network of orbiting sensors, a critical part of a dense and multilayered constellation of satellites the Pentagon has already begun placing in low Earth orbit.

Experimental and prototype payloads were sent into orbit last June, and initial operational payloads are slated for launch in 2022 and 2023. These sensors detect heat signatures to identify missile launches and will give the U.S. military the ability to track targets, described as cradle-to-grave target custody.

Some of the pivotal components of HBTSS are "signal to clutter" algorithms designed to distinguish a fast-moving threat from the warm and irregular surface of Earth. This is a much more difficult task than that of ground radar, which tracks missiles as they move across the cold and featureless background of the sky. "Just imagine a lightbulb moving across a background of lightbulbs, and you have to pick out that lightbulb," says Paul Wloszek, director of missile defense at L3Harris Space & Airborne Systems. "You have to know where it's at—and how fast it's going—to be able to shoot it down."

To address this problem, in October 2019 the Pentagon separately tapped L3Harris and Northrop Grumman (and two other companies subsequently bumped from the competition) to develop tracking algorithms sensitive enough to distinguish the signal from the noise. In late 2020 L3Harris and Northrop Grumman paired their respective algorithms with compact, powerful computer processors small enough to be incorporated into space vehicles. Both companies performed a successful "signal chain demonstration," which proved their systems' ability to detect and track dim targets against a cluttered background. The signal chain demonstration verified the sensitivity necessary to support the so-called hypersonic kill chain—the discrete actions required in sequence between identifying and striking a target.

Other space-based assets already provide the U.S. with overhead infrared sensing. But the key characteristic that sets HBTSS apart is a requirement to generate what the Pentagon calls "fire control quality" tracking data. This is very precise information that can be used by terrestrial command-and-control systems to steer guided-missile interceptors against hypersonic threats.

"Being able to see down from space, warm tracks going over a warm Earth—that is really tough science," said MDA director Vice Admiral Jon Hill at a hearing of the Senate Committee on Armed Service's Subcommittee on Strategic Forces late last spring. "But we've got that licked. We've shown that we can do that on the ground. That sort of capability gives us global coverage."

On December 27, 2021, President Joe Biden signed the National Defense Authorization Act for Fiscal Year 2022, which includes $256 million for HBTSS. The funding will support continued development of the tracking algorithms, as well as beginning the assembly of infrared sensors bound for launch in 2023. Both L3Harris and Northrop Grumman are set to deliver two HBTSS prototypes each, including software and hardware. Congress, however, is currently at an impasse over fiscal year 2022 appropriations. If the government cannot reach an agreement, HBTSS could be limited to 2021 spending levels for the project: $130 million, a sum that would likely imperil the project's schedule. In that case, the Pentagon could stitch together existing systems to deliver something HBTSS-like, says hypersonics expert David Wright, a research affiliate at the Massachusetts Institute of Technology's Laboratory for Nuclear Security and Policy.

"HBTSS would be nice to have, but it's not clear to me that it gives you unique capabilities," Wright says. He explains that the capabilities promised by HBTSS could also be achieved without a new space-based program by relying on ground sensors placed in the correct locations. This might involve carefully positioning ships equipped with powerful radar in order to expand defensive zones. "I think it's a system I can imagine the military wanting because they'd like to be able to track these systems continually—and it could do that tracking outside of the [ground] radar range—but I'm not convinced that that's necessary," Wright adds.

Victoria Samson, a military space expert at the Secure World Foundation, agrees there is a need to track advanced threats across their entire flight path but notes that advocates of HBTSS may be underestimating the task of dealing with this high-profile challenge. "I think it's a lot more complicated than the supporters would let on, and adding hypersonic to the [operations] requirement may be more a nod to its increased visibility among national security folks than anything else," Samson says.

Along with sensors, the Pentagon is thinking anew about the guided missiles needed to defeat hypersonic glide vehicles. In late May 2021 the MDA revealed it had certified the currently deployed Standard Missile-6 as a last line of defense for aircraft carrier strike groups to use against hypersonic glide vehicles. And in November 2021 MDA tapped three companies to advance designs for a new weapon, called a Glide Phase Interceptor, intended to counter hypersonic threats. This sets up a three-way contest between Lockheed Martin, Raytheon and Northrop Grumman to field a new weapon within the decade.

—Jason Sherman

U.S. Project Reaches Major Milestone toward Practical Fusion Power

In a world first, the National Ignition Facility has generated a "burning plasma," a fusion reaction on the cusp of being self-sustaining

Nuclear fusion could potentially provide abundant, safe energy without the significant production of greenhouse gas emissions or nuclear waste. But it has remained frustratingly elusive as a practical technology for decades. An important milestone toward that goal has now been passed: a fusion reaction that derives most of its heat from its nuclear reactions themselves rather than the energy pumped into the fuel from outside.

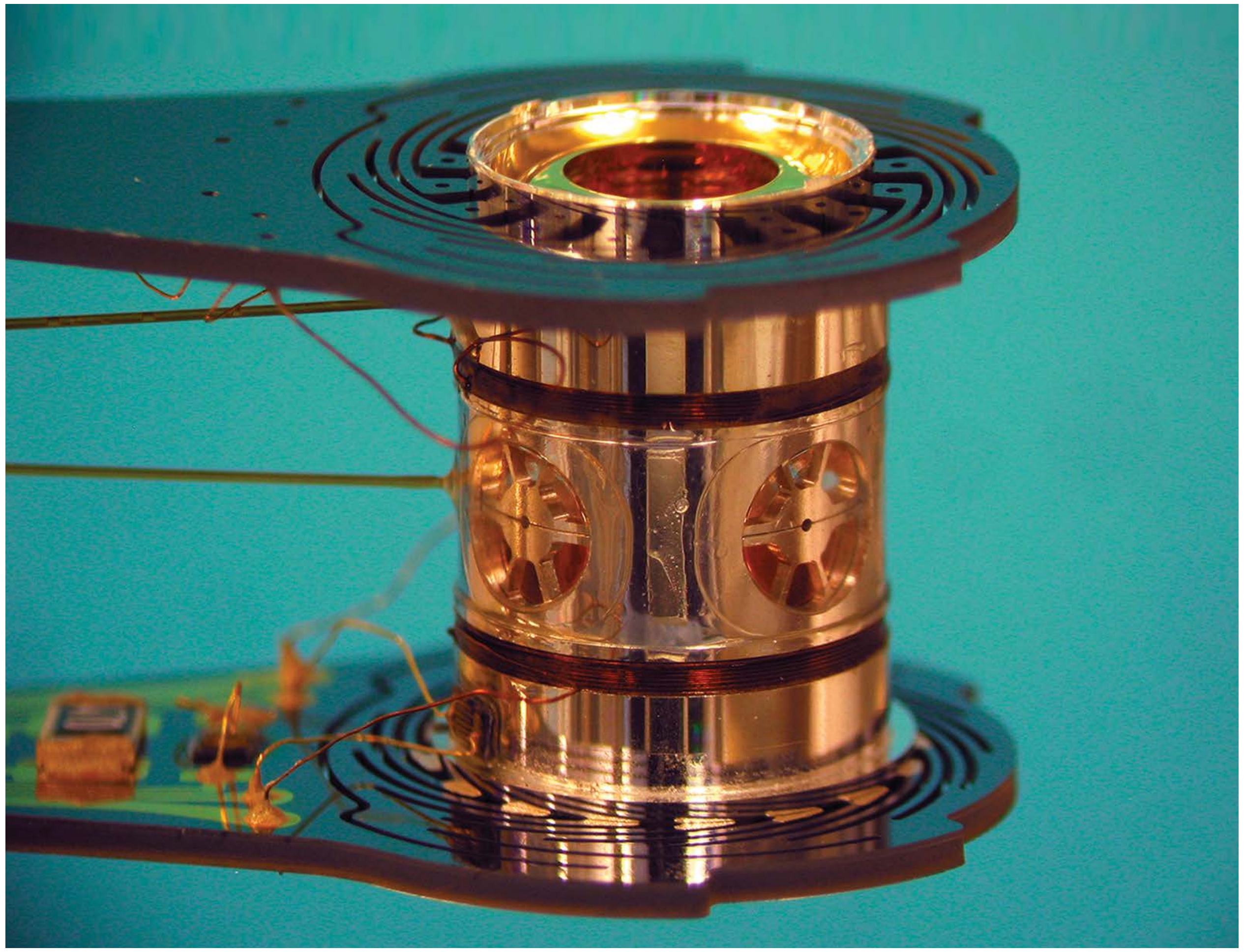
A team at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in California has reported this so-called burning plasma condition using an approach called inertial-confinement fusion, where the ferociously high temperatures and pressures needed to initiate fusion in a fuel of hydrogen isotopes are produced by intense pulses of laser light. The researchers' findings appear in *Nature,* with companion papers published in *Nature Physics* and on the preprint repository arXiv.org. "The data clearly show that they have reached that condition," says fusion physicist George Tynan of the University of California, San Diego, who was not involved in the work.

"The NIF results are a really big deal," says fusion physicist Peter Norreys of the University of Oxford, who was not part of the studies. "They show that the pursuit of an inertial fusion reactor is a realistic possibility for the future and not built on difficult and insurmountable physics." Plasma physicist Kate Lancaster of the University of York in England, who was also not involved in the research, agrees. "This is an incredible achievement, which is a culmination of a decade of careful, incremental research," she says.

Nuclear fusion, the process that fuels stars and that is triggered explosively in hydrogen bombs, requires extreme heat and pressure to give atoms enough energy to overcome the electrostatic repulsion between their positively charged nuclei so that they can fuse and release energy. The usual fuel for producing controlled fusion in reactors consists of a mix of the heavy hydrogen isotopes deuterium and tritium, which may unite to make helium. The energy this releases can be harnessed for electricity generation—for example, by using the heat to drive conventional power turbines. Unlike nuclear fission—the process used in all nuclear power plants today—fusion does not use or generate large quantities of long-lived radioactive materials. And in contrast to fission, fusion does not involve a chain reaction, which makes it inherently safer: any changes to the working conditions of a fusion reactor will cause it to automatically shut down in an instant.

Fission's advantage is that it typically occurs in reactors at temperatures of a little more than 1,000 kelvins, whereas deuterium-tritium (D-T) fusion starts at temperatures of around 100 million kelvins—hotter than the heart of the sun. Handling such a seething plasma is, to put it mildly, immensely challenging. One approach is to confine it with magnetic fields into a doughnut shape inside a chamber called a tokamak. This is the method of choice for many fusion projects, including the International Thermonuclear Experimental Reactor (ITER). for which a global collaboration is building a massive experimental reactor in France that is slated to achieve sustained fusion no earlier than 2035.

Inertial fusion does not try to trap the plasma but instead relies on inertia alone to hold it together for a brief instant after fusion is triggered by an ultrafast compression of the fuel. That creates a very brief outburst of energy—a tiny thermonuclear explosion—before the burning fuel expands and dissipates its heat. "Fusion energy schemes based on inertial confinement involve repeating the pulsed process over and over again, much like the pistons in an internal-combustion engine, firing several times per second to give nearly continuous power," says Omar Hurricane of LLNL, chief scientist for the NIF's Inertial Confinement Fusion program, who was a team leader for the latest experiments.



Metallic case called a hohlraum holds the fuel capsule for National Ignition Facility experiments. Target-handling systems precisely position the target and freeze it to cryogenic temperatures (18 kelvins, or –427 degrees Fahrenheit) so that a fusion reaction is more easily achieved.

Lawrence Livermore National Laboratory (CC BY-NC-SA 4.0)

Although inertial-confinement fusion does not have to solve the problem of maintaining a hot, wobbly plasma inside a tokamak, it does require tremendous inputs of energy to trigger the fusion process. The NIF team used 192 high-power lasers, all focused into a chamber called a hohlraum that is about the size and shape of a pencil's eraser and contains the fuel capsule of deuterium and tritium. The laser energy heats and vaporizes the capsule's outer layer, blowing it away and creating a recoil that compresses and heats the fuel in the center. In the NIF method, the laser beams do not directly spark detonation but instead strike the hohlraum's inner surface, unleashing a furious bath of capsule-compressing x-rays within the tiny chamber.

Researchers demonstrated the feasibility of starting fusion this way back in the 1970s. But getting to the burning-plasma point has been a slow process, full of technical hurdles and setbacks. "For many decades, researchers have been able to get reactions to occur by using a lot of external heating to get the plasma hot," says Alex Zylstra of LLNL, a member of the NIF team. "In a burning plasma, which we have now created for the first time, the fusion reactions themselves provide most of the heating." Those conditions last only for about 100 trillionths of a second before the plasma's energy is dissipated.

"There was no one secret that allowed them to make this breakthrough but a whole bunch of smaller advances," Tynan says. To have any hope of getting the fusion process to sustain itself, the energy it produces should be deposited mostly in adjacent fuel layers rather than leaking from the capsule to heat the surroundings. This means that the capsule has to be sufficiently large and dense to keep the energy inside while still collapsing symmetrically—which is one of the issues the NIF team has cracked. The researchers have also tweaked the hohlraum's design to ensure its interior uniformly fills with x-rays, ultimately creating a smoother, stronger and more efficient implosion of the fuel capsule. "We had to learn how to better control the symmetry while making the implosion bigger," Hurricane says. Such improvements have required decades of effort. "It's been a very long trial-and-error process, guided by computations," Tynan says.

Of the experimental runs that the NIF researchers have reported, four conducted in 2020 and early 2021 exceeded the threshold fusion output for a burning plasma. The most recent of these were in February 2021, so "it clearly took some time for them to convince colleagues of the validity of their results," says Vladimir Tikhonchuk, a plasma physicist at the University of Bordeaux in France, who was not involved with the work. But they have evidently done so. "I truly believe publication of these papers is an important scientific event," Tikhonchuk adds.

Making fusion viable requires more than merely burning plasma, however. For one thing, although the plasma is self-heating, it might still radiate more heat than it generates, including the energy lost when the implosion blows itself apart after reaching peak compression. "Even if you have burning, the reaction fizzles out if the radiative losses are too high," Tynan says. But the NIF team notes that, in one of its runs, the heating exceeded such losses.

That brings the scientists closer to the next big goal: ignition, where the net energy release from the fusion reaction exceeds the energy injected to produce it. On average, they can produce about 0.17 megajoule of fusion energy for an input laser energy of 1.9 megajoules. In other words, these NIF shots channel the energetic equivalent of a half-kilogram of exploding TNT into the tiny hohlraum only to get about 10 times less energy out. But that is still close enough to the break-even point to get fusion researchers fired up. "They are right on the threshold of achieving a propagating ignition burn," Tynan says.

Lancaster is optimistic about that. "We are now in a regime where modest improvements can create massive gains in output energy," she says. "We have definitely moved from an 'if' to a 'when' for ignition."

> **"They are right on the threshold of achieving a propagating ignition burn."**
> —*George Tynan*

Even achieving ignition would be just the end of the beginning for fusion. For one thing, net energy gain must not only be demonstrated but also improved to compensate for inefficiencies in converting the heat into electricity. Better methods must also be developed for on-site production and handling of tritium to use as fuel. And in the specific case of inertial-confinement fusion, the exquisitely designed fuel capsules must somehow be made in abundance—and on the cheap. "Right now they cost $1 million and are custom pieces of kit made in the lab," Tynan says. But for any inertial-fusion power plant to turn a profit, "you have to be able to make hundreds of thousands of them a day at 10 cents a piece." And these spectacular results for burning plasma in inertial confinement "do not really translate to tokamaks" at all, Hurricane warns.

"People working in this domain understand very well that there is a large gap between the [eventual] demonstration of ignition and a commercial fusion reactor," Tikhonchuk says. That gap certainly will not be closed at the NIF, which is geared toward exploring the basic physics of fusion, especially in the context of nuclear stockpile management and national security. "We do not yet have lasers of a needed energy and power operating with a repetition rate of a few shots per second," Tikhonchuk adds—although Lancaster says that these "are well on the way, with big programs in the U.K., the U.S., France and Germany, for example."

"Now that the NIF has demonstrated that [burning-plasma conditions] can be done in a controlled laboratory setting," Norreys says, solutions to the remaining challenges "need to be studied in the coming years with renewed vigor."

"The challenge is [pivoting] from 'Is the physics even possible?' to 'Can we engineer a viable system that has sufficient lifetime and that is safe enough and do all those things at an affordable price?'" Tynan says. "That's still the big open question in front of the research community." *—Philip Ball*

How Light Is a Neutrino? The Answer Is Closer Than Ever

The latest effort to weigh the elusive particle produces a more precise estimate of its upper limit

A component of the Karlsruhe Tritium Neutrino (KATRIN) experiment in Germany, which has produced the best-yet measurement of the neutrino's mass.

dpa picture alliance/Alamy Stock Photo

Physicists have taken a step toward nailing down the mass of the neutrino, perhaps the most mysterious of all elementary particles.

The team at the Karlsruhe Tritium Neutrino (KATRIN) experiment in Germany reports that neutrinos have a maximum mass of 0.8 electron volt. Researchers have long had indirect evidence that the particles should be lighter than 1 eV, but this is the first time that this has been shown in a direct measurement. The results were reported on February 14 in *Nature Physics*.

The previous upper limit of 1.1 eV was reported by KATRIN in 2019. The experiment has so far been able to put only an upper bound on the mass. But researchers say that it might be able to make a definite measurement once it finishes collecting data in 2024, and it is the only experiment in the world capable of doing this.

“If the KATRIN experiment was to pinpoint a neutrino mass before reaching the sensitivity goal of 0.2 eV, it would be extremely exciting,” says Julia Harz, a theoretical particle physicist at the Technical University of Munich in Germany. In particular, it could give guidance on how to improve cosmological theories, she adds.

ENERGETIC ELECTRONS

KATRIN weighs neutrinos produced by the nuclear decay of tritium, a radioactive isotope of hydrogen. When a tritium nucleus transmutes into a helium one, it ejects an electron and a neutrino (or, more accurately, a particle with an equal mass called an antineutrino). The neutrino is lost, but the electron is channeled into a 23-meter-long, steel vacuum chamber shaped like a Zeppelin airship, where its energy is measured precisely.

The electron carries almost all of the energy released during the tritium's decay, but some is lost with the neutrino. The value of this shortfall can be used to calculate the particle's mass.

KATRIN's 2019 results were based on an initial run of the experiment in April and May that year, when the tritium beam was operating at one quarter of its full strength. The latest result is based on data from the first full-strength run, which took place later in 2019. These data imply an upper bound of 0.9 eV, which goes down to 0.8 eV when combined with the earlier results.

Although the estimate has tightened, it is still not possible to report a lower bound for the neutrino's mass. The data still do not rule out the possibility that the mass is zero, says KATRIN member Magnus Schlösser, a particle physicist at the Karlsruhe Institute of Technology. But other lines of evidence, in particular from cosmological observations, show that the neutrino cannot be massless.

It is still possible that even after 2024, KATRIN will be unable to measure the neutrino's minimum mass: if the mass is less than 0.2 eV, it could lie outside the experiment's sensitivity.

Schlösser compares the quest to the Spanish conquistadors' search for a mythical city of gold. "It's like looking for El Dorado," he says. "You shrink the possibility for where you can find it." *—Davide Castelvecchi*

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Record-Breaking Supernova Is Part of a New Class of Objects

A recently spotted bright light in the sky is improving astronomers' understanding of stellar death

The night sky is filled with blips and flashes, a constantly changing sea of lights. Some of these changes are from Earth-bound happenings such as aircraft flying overhead, but some are from distant sources in space. Astronomers hunt for these fleeting phenomena, known as astronomical transients, by observing the sky regularly and looking for differences that appear.

Researchers recently found a transient that outshines all others like it—a supernova known as AT2020mrf. They described their discovery in a paper posted on the preprint server arXiv.org last December and submitted to the *Astrophysical Journal*. They also presented it at a virtual press conference at the 2022 American Astronomical Society meeting in January 2022. This supernova was one of the brightest and most energetic stellar deaths ever seen, and it might provide a rare glimpse into how massive stars give birth to some of the universe's strangest objects: black holes and neutron stars.

The biggest stars die in spectacular fashion. They explode with the energy of a nonillion (that is "1" with 30 zeros behind it) atomic bombs in a supernova, shining so bright that we can sometimes even see them in the night sky with our naked eyes. AT2020mrf was 10,000 times brighter in x-rays than a typical supernova. It followed a few other superbright events that have been observed in recent years—astronomers refer to them as "cow-like" supernovae, or "cows," after the first of their type discovered: AT2018cow. Unlike traditional supernovae, cows shine brightly in high-energy x-rays and radio emission (most supernovae shine brightest in visible light). But AT2020mrf was the brightest cow of the bunch—20 times brighter than the original.

Astronomers Yuhan Yao and Shri Kulkarni, both at the California Institute of Technology, along with Anna Ho of the University of California, Berkeley, and Daniel Perley of Liverpool John Moores University in England, first spotted this explosion in June 2020 in visible-light images from the Zwicky Transient Facility (ZTF), an automated telescope at California's Palomar Observatory. The bright spot they saw originally seemed like something unremarkable, and the astronomers ignored this event until almost a year later.

In April 2021 Russian scientists collaborating with Yao's group noticed the same event while reviewing data from their Spectrum-Roentgen-Gamma (SRG) x-ray observatory. Their images from July 2020 showed x-rays at the same location as the bright spot in the ZTF data. Upon hearing the news, Yao's mind jumped straight to the mysterious cow-like events because they are the only type of supernova known to emit so many x-rays. Although a year had passed, the initial explosion from AT2020mrf was so incredibly bright that Yao suspected she might still be able to see it with the Chandra X-ray Observatory. Her calculations were correct, and observations showed it clearly, glowing 200 times brighter than the original cow a year after AT2020mrf's explosion.

"It was really very rewarding when SRG saw this source because we had been thinking that maybe [cow-like events] can be discovered in the x-ray first," Yao says. "This is the first time that one was really discovered in the x-ray."

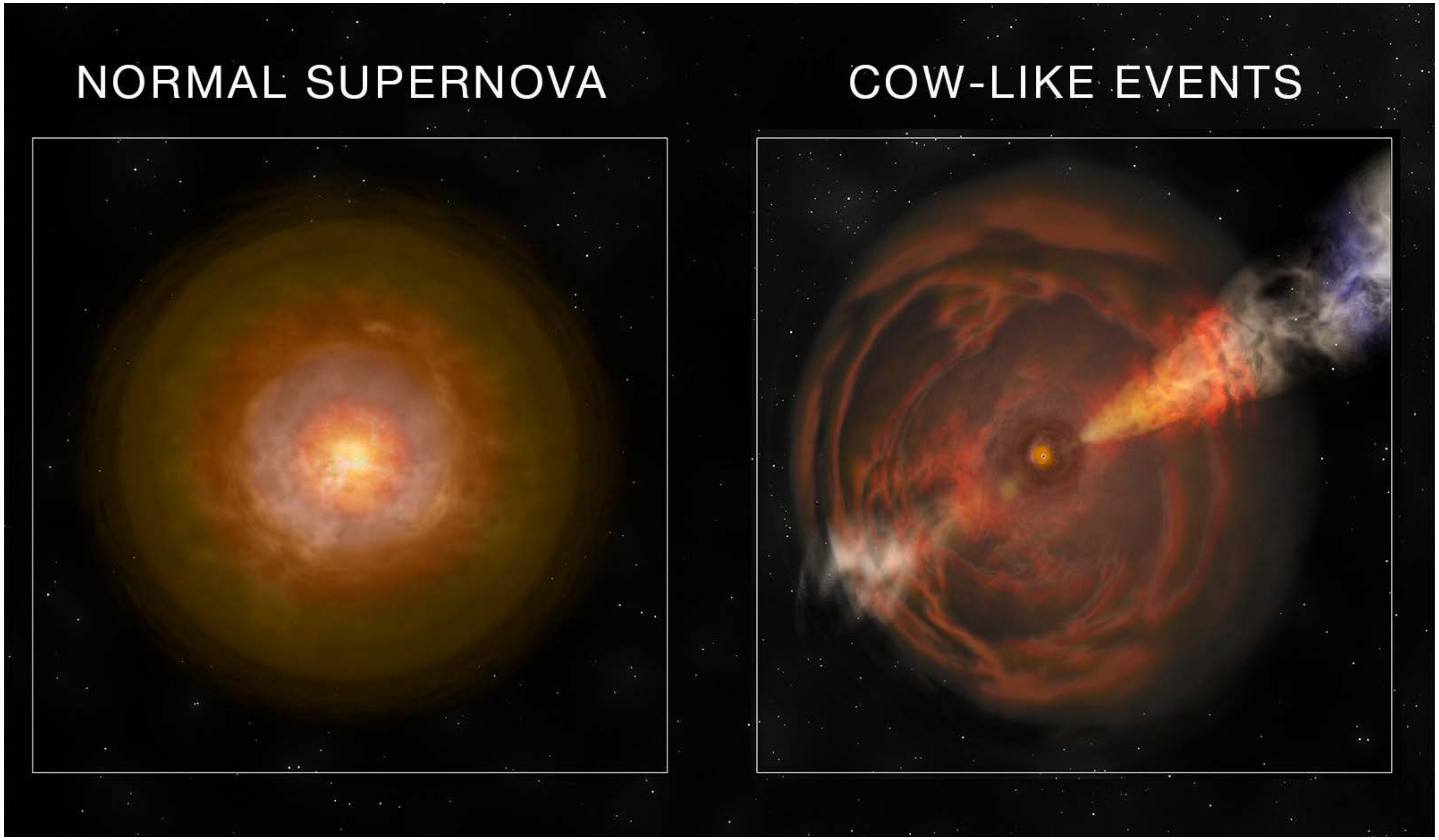
Astronomers are still puzzling out what makes these supernovae special. The current theory is that cows have a very active "central engine"—something left behind by the star's core, such as a black hole devouring matter or a neutron star rapidly spinning, that provides energy to the supernova. They also have less material shrouding this central region than most exploding stars, providing a view of their interesting center.

The stars that produce cow-like events appear to spew out material as they approach their death, making the environment around them denser and the stars themselves a bit smaller. When they explode, there is less gas in the immediate area around the star's core, allowing x-rays from the central engine to escape.

The shockwave the supernova sends through the surrounding space heats up the newly dense environment, too, creating the radio emission astronomers observe. Yao thinks that maybe AT2020mrf was even brighter than most cows because it had thrown off even more mass, allowing the central engine to shine through so brightly in x-rays.

"AT2020mrf is indeed an exciting event, both for what it confirms about the growing class of [cow-like objects] and what it tells us about the diversity of these mysterious stellar explosions," says Brian Metzger, an astrophysicist at Columbia University and the Center for Computational Astrophysics.

With only four previously known cow-like events, AT2020mrf more firmly establishes this group as a new category of explosion. The recent blast also stands out from its classmates, showing the fascinating



Artwork compares a normal supernova with a cow-like supernova.

Bill Saxton/NRAO/AUI/NSF

diversity of stellar deaths. Although scientists understand the broad strokes of how massive stars die, the details are still fuzzy. This is especially true for certain stages of the end of a star's life, such as the silicon burning stage, the last round of fusion a large star can complete, when it fuses silicon together to create iron. This period lasts only around 18 days out of the star's million- to billion-year lifetime. Cows may provide a window into that hard-to-observe time frame and sharpen our understanding of how black holes and neutron stars are born within supernovae.

AT2020mrf and the other cows are also simply thrilling to scientists. "I like the excitement when I just see how one source is different from all others," Yao says. "You know, maybe once in a lifetime, you'll find one of those events, and you need to take action. You need to stay on top of everything to tell the story of the object." Future observations with the Vera C. Rubin Observatory, an upcoming sky-surveying powerhouse, and other telescopes will hopefully give astronomers even more information to work with.

—Briley Lewis

Quantum Friction Explains Water's Freaky Flow

Physicists have finally solved the long-standing mystery of why water moves faster through narrower nanotubes

Whenever you get around to doing dishes, how easily water slides down a dirty plate depends on how uneven and crusty the plate's surface is. At the nanoscale, however, where surface features can be hundreds of thousands of times smaller than the average width of a human hair, water can experience friction even on surfaces that seem perfectly smooth. Consider, for instance, the puzzling case of carbon nanotubes: Experiments have shown that, against common sense, the narrower these minuscule pipes are, the less friction water "feels" within them and the faster the resulting flow. This is the exact opposite of how plumbing works in our familiar macroscale world.

Now, after decades of confusion, physicists at the Flatiron Institute in New York and the French National Center for Scientific Research (CNRS) in Paris have explained this odd observation as a product of quantum mechanics. Their work, published in *Nature* in February, reveals that it is not so much the surface of nanotube walls that matters as much as what the electrons inside of it are up to. This insight may lead to improvements in nanotube-augmented applications such as water purification.

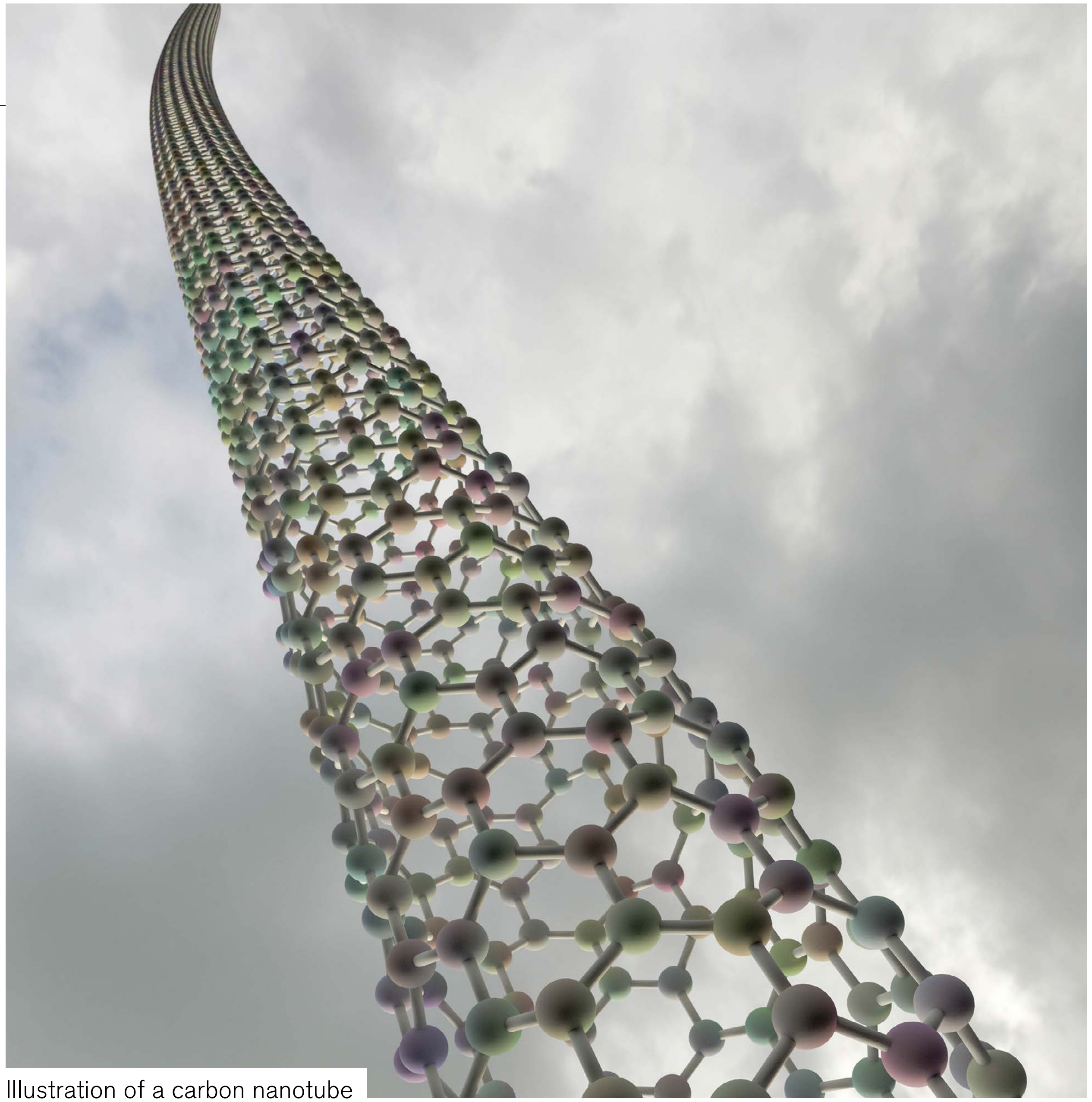


Illustration of a carbon nanotube

Robert Brook/Science Photo Library/Getty Images

"Twenty years ago there was an experiment with water flowing across a membrane made of carbon nanotubes that was quite disturbing. It showed extremely fast water flows," says Lydéric Bocquet, physicist at CNRS and the new study's co-author. "We started an experimental program to measure the flow of water inside a single nanotube and ended up with the same result. But we could not explain it." In Bocquet's telling, after all commonly used theoretical methods failed, he turned to Nikita Kavokine, a collaborator and the study's first author who is now a postdoctoral fellow at the Flatiron Institute, hoping that Kavokine would be able to employ the oftentimes odd rules of quantum mechanics to explain the bizarre experiment. "We had some idea that there was a missing ingredient and that we would maybe need to include some quantum effects, but we had no idea how far we would have to go," Kavokine recalls.

Ultimately, to find the long-sought answer they had to zoom in beyond the nanoscale. Instead of just considering how a water molecule rubs against a carbon atom, the team developed equations that describe the subatomic interactions of electrons within water molecules and carbon atoms alike. In this view, a carbon nanotube wall transforms from a smooth, static surface into a dynamic pool of electrons that can buckle and ripple when disturbed. This different perspective allowed the researchers to identify electrons as the main culprit behind friction between the carbon nanotube and water. Water molecules have slightly different charges on each of their ends, so when they flow along nanotube walls, the electrons within those walls respond to the molecules' slight electric nudge by all moving in synchrony.

Thus, friction still occurs even within a perfectly smooth nanotube as electrons dance in unison to a tune set by water molecules. In narrow carbon nanotubes, there are simply fewer carbon atoms and so fewer electrons to make water drag. In wider nanotubes, where more electrons can join the communal choreography, the effect is enhanced, and water flows less easily.

This electronic, quantum friction has been previously studied for metal surfaces, but calculating it in detail has always been challenging, says Wenjie Dou, a physicist at Westlake University in China, who was uninvolved in the study. "Calculating the exact [form] of electronic friction will always be very intense," he says, adding that many of physicists' favorite mathematical tricks and approximations fail in this case. Marie-Laure Bocquet, a CNRS chemist and a study co-author, notes that computational attacks on this problem do not help much either. "State-of-the-art simulation tools were not enough to explain experiments," she says. "That's the exciting thing about this: we had to go beyond the state of the art."

Part of the difficulty lies in how many different quantum interactions must be tracked to model the emergent effect; even the most powerful computer and the most cleverly programmed software cannot simulate how every water molecule interacts with every other water molecule, how every electron interacts with every other electron, and how all the water molecules collectively interact with the whole community of all the electrons, all at once, explains Christoph Schran, a chemist at University of Cambridge, who was also not involved in the study. To deal with these complexities, the study team had to use sophisticated mathematical methods that are not typical for studies of fluids.

Although this is an advance in theoretical physics, the study does have obvious real-world implications. For example, understanding flows through carbon nanotubes could improve water-desalination processes, says Jeffrey Sokoloff, a physicist at Northeastern University, who was not part of the study. "There's a lot of friction experienced by the water as it goes through the filters. So knowing that you have these [carbon] nanotubes that are very low friction, that could be a very good way of doing desalination," he explains. He is also eager to see more experiments exploring the fundamentals of quantum friction as detailed in this theoretical study. "One has to do more experiments, and maybe this paper will stimulate people to do them," he says.

Schran agrees. "This new mechanism of friction is definitely very interesting and exciting," he says. "But what is missing in my opinion is a clear benchmark measurement." Quantifying, for instance, how friction changes based on water's interaction with single versus multiple layers of carbon atoms could go a long way to fully verifying the new theory, which predicts that greater numbers of electrons in the multilayered carbon will boost friction.

The study team is already progressing along this path and dreaming of what lies beyond. The scientists are hoping to eventually test their theory with flowing liquids other than water and nanotubes composed of elements besides carbon. In such cases, molecules in the liquid and the electrons within nanotube walls would follow different patterns of interaction, possibly leading to changes in the degree of quantum friction. Lydéric Bocquet says that it may even be possible to control the amount of friction a flowing liquid experiences by constructing nanotubes with electron behavior explicitly in mind.

The new study sets the stage for years of complex exploration by experimental and theoretical physicists alike and, according to Kavokine, also signals a fundamental shift in how physicists should think about friction. "Physicists have long thought that it is different at the nanoscale, but this difference was not so obvious to find and describe," he says. "They were dreaming about some quantum behavior arising at these scales—and now we have shown how it does."

—Karmela Padavic-Callaghan

Could Echoes from Colliding Black Holes Prove Stephen Hawking's Greatest Prediction?

Subtle signals from black hole mergers might confirm the existence of "Hawking radiation"—and gravitational-wave detectors may have already seen them

In 1974 Stephen Hawking theorized that black holes are not black but slowly emit thermal radiation. Hawking's prediction shook physics to its core because it implied that black holes cannot last forever and that they instead, over eons, evaporate into nothingness—except, however, for one small problem: there is simply no way to see such faint radiation. But if this "Hawking radiation" could somehow be stimulated and amplified, it might be detectable, according to some astrophysicists. And they are now claiming to have seen signs of it in the aftermath of the most massive collision of black holes ever observed.

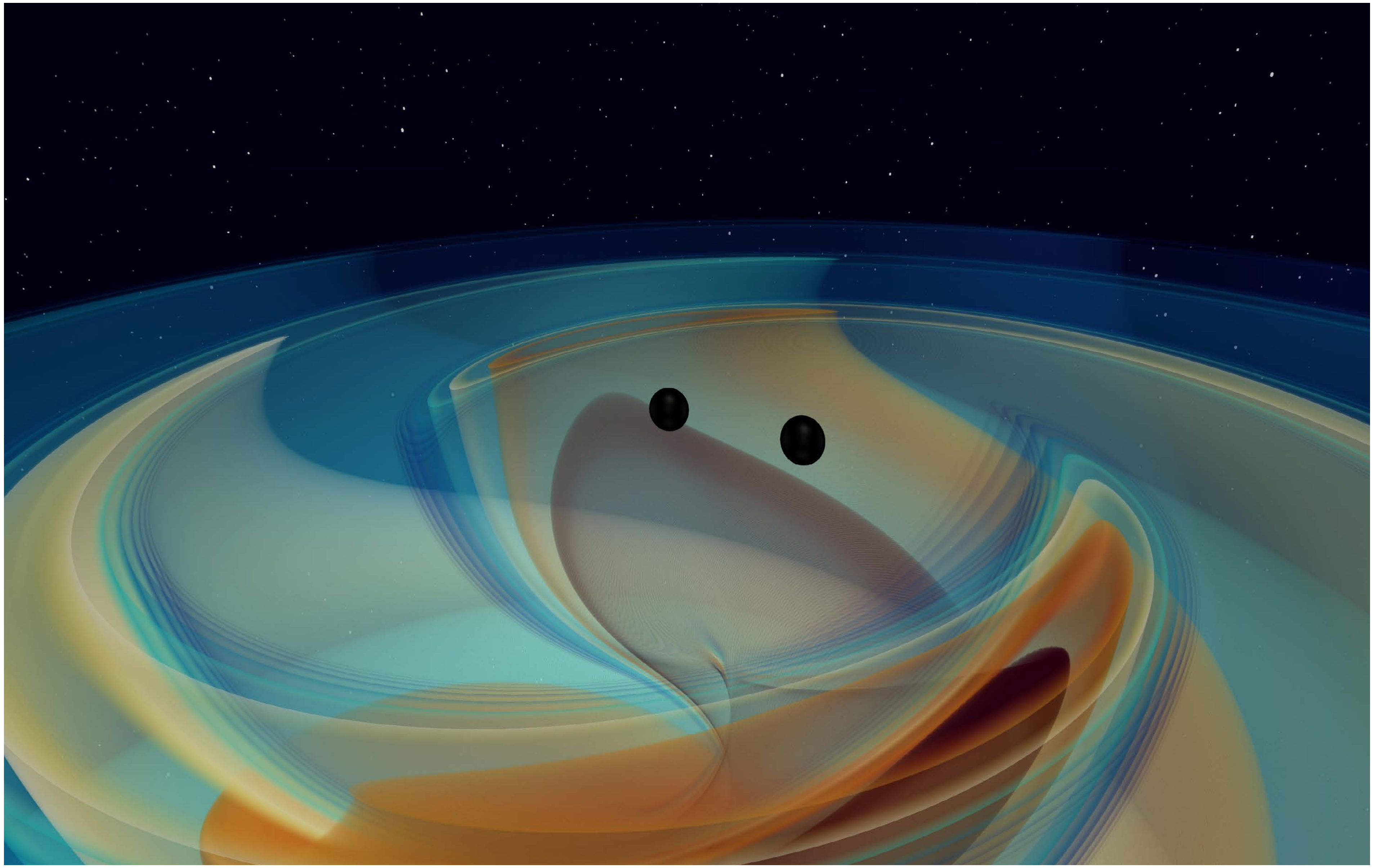
The claim, however, is extremely controversial because other searches for such echoes of gravitational waves have come up empty-handed.

In May 2019 the Laser Interferometer Gravitational-wave Observatory (LIGO) in the U.S. and Virgo in Italy observed gravitational waves—ripples in the fabric of spacetime—from the merger of two black holes that had a total mass of 151 suns. The merger left behind a black hole of 142 solar masses. The difference of nine solar masses was radiated away, almost all of it in the form of gravitational waves. "This is the most massive event observed to date," says Jahed Abedi of the University of Stavanger in Norway, who co-authored a preprint paper in which he and his colleagues claim to have measured the Hawking radiation of this merger.

The gravitational waves from this event, named GW190521, not only rippled out to eventually interact with LIGO's and Virgo's detectors on Earth; they also washed over the remnant black hole produced by the initial collision. What happened next depends on your view of black hole physics. If black holes are described entirely by Einstein's general theory of relativity, then they have an event horizon—a one-way boundary that anything can fall into but from which nothing can escape. "In the standard black hole picture, the event horizon of a black hole absorbs all the radiation," says Paolo Pani, a theoretical physicist at Sapienza University of Rome. So the inward-going gravitational waves should just disappear.

But that might not be what happened. Physicists think that some combination of quantum physics and general relativity is needed to fully describe black holes, in which case it is possible that a portion of the infalling gravitational waves could be reflected—either because of quantum effects near the horizon or because the dense, compact object created by the merger lacks a horizon and has some internal structure. If so, echolike signatures of this could be present in the information collected by LIGO, Virgo and other detectors. Similar to sonic echoes, such signatures would be much weaker and ever so slightly delayed, compared with the original gravitational waves from the merger.

Exactly what such echoes would look like depends on the exact physics being modeled. For example, the region just outside a black hole's horizon is thought to be a bustling place, abuzz with pairs of virtual



Two massive black holes spiral together and emit copious gravitational waves moments before colliding in this image from a numerical simulation of the merger known as GW190521.

N. Fischer, H. Pfeiffer and A. Buonanno/Max Planck Institute for Gravitational Physics/Simulating eXtreme Spacetimes (SXS) Collaboration

particles popping in and out of existence. Sometimes one of the pair falls into the black hole, and the other escapes. These escaping particles constitute Hawking radiation. This is an agonizingly slow process. In the case of the GW190521 remnant, Abedi and his colleagues argue that the production of Hawking radiation by the remnant could be sped up substantially—stimulated, in other words—by the infalling gravitational waves.

The principle is somewhat similar to what occurs during stimulated emission of radiation in atoms. In this process, photons of light hit "excited" electrons in atoms, causing the electrons to drop to lower energy levels while spitting out photons that have the same wavelength as the incident photons. In certain situations, this stimulated emission can far exceed the spontaneous "background" emission of radiation (where an electron, on its own, drops from a higher energy level to a lower one and emits a photon). Abedi and his colleagues theorize that gravitational waves interacting with a black hole's event horizon should similarly stimulate the production of Hawking radiation to levels that far exceed spontaneous emissions, thus making it detectable. This radiation would constitute gravitational waves of the same wavelength as the incident waves, albeit with much lower intensity.

The researchers claim to have seen signs of this stimulated emission of Hawking radiation from the GW190521 remnant. They used two different methods to analyze the GW190521 data collected by LIGO and Virgo. The first method compares two models: one based purely on general relativity, with no postmerger echoes or signals, and another that includes stimulated Hawking radiation. “If you compare them, the [general relativity] plus postmerger stimulated radiation is preferred seven times more,” Abedi says.

The second method was agnostic about any specific model and simply looked for coherent bursts of postmerger gravitational waves from different detectors. The team claims it found such bursts. “[The two methods] are consistent with each other,” Abedi says.

The researchers’ statistical analysis gives 0.5 percent odds (about a one-in-200 chance) that the putative signal is instead merely noise. Normally, for physicists to claim a discovery, the odds of a false alarm have to be lower than one in a million. Consequently, Pani, who was not part of the team, is circumspect. “The statistical evidence they have is ... definitely too low to claim a measurement,” he says.

“This is not [a] very loud signal,” Abedi acknowledges, adding that nonetheless it is the best that can be done with current gravitational-wave detectors. “Our target is next-generation detectors.”

Pani agrees that a facility such as the Laser Interferometer Space Antenna (LISA), a European Space Agency–led project slated for launch in the late 2030s, would be better suited for such studies. “With future detectors, if there is something, we will get the evidence necessary to claim a measurement,” he says.

Even if the evidence for a signal was statistically more significant, however, Pani remains critical of Abedi and his colleagues’ claim that this would be evidence for Hawking radiation. “They could have claimed measurement of gravitational-wave echoes. [It] is a big conceptual step [to] saying that this is stimulated Hawking radiation,” Pani says. “In other models, it might be something else.”

Last December members of LIGO, Virgo and the Kamioka Gravitational Wave Detector (KAGRA) in Japan teamed up and posted a preprint of their latest analysis of gravitational-wave data. They looked at 15 events, 14 in which two black holes merged and one in which a black hole merged with a neutron star. All the events had been observed by two or more detectors. “This analysis included GW190521. We find no evidence for echoes or any other deviations from the predictions of general relativity,” says Daniel Holz, a LIGO team member at the University of Chicago. “It would be incredibly exciting if echoes existed or any of the other speculative deviations from general relativity, but it looks like there’s no compelling evidence for them in the data thus far. Einstein’s theory has passed all tests to date. It is embarrassingly effective and accurate.”

Pani, meanwhile, is keeping his eyes on the horizon to see whether or not the claim made by Abedi and his colleagues about stimulated Hawking radiation, or echoes in general, is confirmed. “If this will be confirmed in the future, it’ll be a great step,” Pani says, “especially for the field in general because it will give a sort of portal to the quantum properties of black holes that otherwise would be impossible to see by other means.”

—Anil Ananthaswamy

Hundred Years Ago a Quantum Experiment Explained Why We Don’t Fall through Our Chairs

The basic concept of quantum spin provides an understanding of a vast range of physical phenomena

By Davide Castelvecchi

Otto Stern

Alamy Stock Photo

Davide Castelvecchi is a staff reporter at *Nature* who has been obsessed with quantum spin for essentially his entire life. Follow him on Twitter @dcastelvecchi.

The moment I meet Horst Schmidt-Böcking outside the Bockenheimer Warte subway stop just north of the downtown area of Frankfurt, Germany, I know I have come to the right place. After my "Hi, thank you for meeting me," his very first words are "I love Otto Stern."

My trip on this prepandemic morning in November 2018 is to visit the place that, precisely a century before February 8, 2022, saw one of the most pivotal events for the nascent quantum physics. Without quite realizing what they were seeing, Stern and his fellow physicist and collaborator Walther Gerlach discovered quantum spin: an eternal rotational motion that is intrinsic to elementary particles and that, when measured, only comes in two possible versions—"up" or "down," say, or "left" or "right"—with no other options in between.

Before the Roaring Twenties were over, physicists would reveal spin to be the key to understanding an endless range of everyday phenomena, from the structure of the periodic table to the fact that matter is stable—in other words, the fact that we don't fall through our chairs.

But the reason why I have a personal obsession with the Stern-Gerlach experiment—and why I am here in Frankfurt—is that it provided nothing less than a portal for accessing a hidden layer of reality. As physicist Wolfgang Pauli would explain in 1927, spin is quite unlike other physical concepts such as velocities or electric fields. Like those quantities, the spin of an electron is often portrayed as an arrow, but it is an arrow that does not exist in our three dimensions of space. Instead it is found in a 4-D mathematical entity called a Hilbert space.

Schmidt-Böcking—a semiretired experimentalist at Goethe University Frankfurt and arguably the world's foremost expert on Stern's life and work—is the best guide I could have hoped for. We walk around the block from the station, past the Senckenberg Natural History Museum Frankfurt, to the *Physikalischer Verein,* the local physicists' society, which predates Goethe University Frankfurt's 1914 founding. In this building, in the wee hours of February 8, 1922, Stern and Gerlach shot a beam of silver atoms through a magnetic field and saw that the beam neatly split into two.

Once we are upstairs in the actual room of the experiment, Schmidt-Böcking explains that the whole experimental setup would have fit on a small desk. A vacuum system, made of custom blown-glass parts and sealed with Ramsay grease, enclosed the contraption. I find it hard to picture that in my mind, though, because the room, now windowless, is taken up by some of the nearby museum's collections—specifically, cabinets with tiny specimens of bryozoans, invertebrates that form coral-like colonies.

Stern and Gerlach expected the silver atoms in their beam to act like tiny bar magnets and therefore to react to a magnetic field. As the beam shot horizontally, it squeezed through a narrow gap, with one pole of an electromagnet bracketed above and the other below. It exited the magnet and then hit a screen. When the magnetic field was turned off, the beam would just go straight and deposit a faint dot of silver on the screen, directly in line with the exit path of the beam from the magnet. But when the magnet was switched on, each passing atom experienced a vertical force that depended on the angle of its north-south axis. The force would be strongest upward if north pointed straight up, and it would be strongest downward if north pointed down. But the force could also take any value in between, including zero if the atom's north-south axis was horizontal.

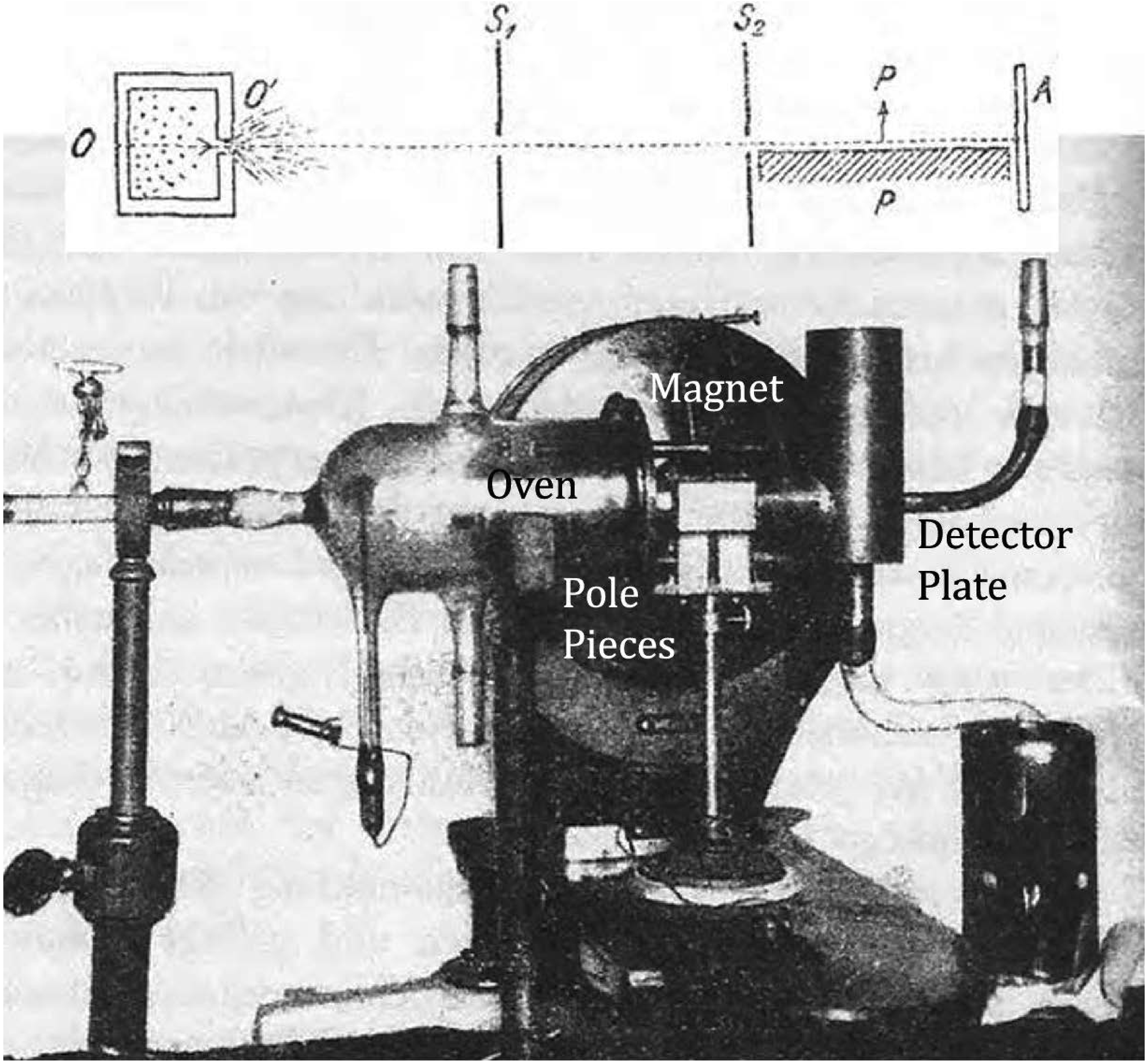
In these circumstances, a magnetic atom that came in at a random angle should have its trajectory deflected by a corresponding random amount, varying along a continuum. As a result, the silver arriving at the screen should have painted a vertical line. At least, that was Stern and Gerlach's "classical" expectation. But that's not what happened.

Unlike classical magnets, the atoms were all deflected by the same amount, either upward or downward, thus splitting the beam into two discrete beams rather than spreading it across a vertical line. "When they did the experiment, they must have been shocked," says Michael Peskin, a theoretical physicist at Stanford University. Like many physicists, Peskin practiced doing the Stern-Gerlach experiment with modern equipment in an undergraduate lab class. "It's really the most amazing thing," he recalls. "You turn on the magnet, and you see these two spots appearing."

Later that day in 2018, I get to see some of the original paraphernalia with my own eyes. Schmidt-Böcking drives me north in Frankfurt to one of the university's campuses, where he keeps the artifacts inside well-padded boxes in his office. The most impressive piece is a high-vacuum pump—a type invented only a few years before the experiment—that removed stray air molecules using a supersonic jet of heated mercury.

It all looks tremendously fragile, and it is: According to witnesses, when the pieces were used, some glass part or other broke virtually every day. Restarting the experiment then required making repairs and pumping the air out again, which took several days. Unlike in modern experiments, the displacement of the beams was tiny—about 0.2 millimeter—and had to be spotted with a microscope.

At the time, Stern was shocked at the outcome. He had conceived the experiment in 1919 as a challenge to what was then the leading hypothesis for the structure of the atom. Formulated by physicist Niels Bohr and others starting in 1913, it pictured electrons like little planets orbiting the atomic nucleus. Only certain orbits were allowed, and jumping between them seemed to provide an accurate explanation for the quanta of light seen in spectroscopic emissions, at least for the simple case of hydrogen. Stern disliked quanta, and together with his



Apparatus used for the Stern-Gerlach experiment in 1922, equipped with modifications made a few years later. The schematic shows a silver beam emerging from an oven (O) and passing through a pinhole (S1) and a rectangular slit (S2). It then enters a magnetic field, whose direction is indicated by the arrow between the two pole pieces (P), and finally reaches a detector plate (A).

“Otto Stern's Molecular Beam Method and Its Impact on Quantum Physics,” by Bretislav Friedrich and Horst Schmidt-Böcking, in *Molecular Beams in Physics and Chemistry*. Edited by Bretislav Friedrich and Horst Schmidt-Böcking. Springer, 2021 (CC BY 4.0)

friend Max von Laue, he had pledged that “if this nonsense of Bohr should in the end prove to be right, we will quit physics.”

To test Bohr’s theory, Stern had set about exploring one of its most bizarre predictions, which Bohr himself did not quite believe: that in a magnetic field, atomic orbits can only lie at particular angles. To pursue this experiment, Stern realized that he could look for a magnetic effect of the electron’s orbit. He reasoned that the outermost electron of a silver atom, which according to Bohr is orbiting the nucleus in a circle, is an electric charge in motion, and it should therefore produce magnetism.

In Stern and Gerlach’s experiment, the physicists detected the splitting of the beam, which they saw as confirmation of Bohr’s odd prediction: the atoms got deflected—implying that they were magnetic themselves—and they did so not over a continuum, as in the classical model, but into two separate beams.

It was only after modern quantum mechanics was founded, beginning in 1925, that physicists realized that the silver atom’s magnetism is produced not by the orbit of its outermost electron but by that electron’s intrinsic spin, which makes it act like a tiny bar magnet. Soon after he heard about Stern and Gerlach’s results, Albert Einstein wrote to the Nobel Foundation to nominate them for a Nobel Prize. But the letter, which Schmidt-Böcking discovered in 2011, was apparently ignored because it nominated other researchers as well, against the foundation’s rules. Stern did not quit the field. Eventually he was one of the most Nobel-nominated physicists in history, and he did get his prize in 1943, while World War II was raging.

Stern’s prize did not honor his work with Gerlach, however. Instead it was awarded for another tour de force experiment in which Stern and a collaborator measured the magnetism of the proton in 1933—shortly before the Nazi regime drove Stern out of Germany because of his Jewish background. That result was the earliest indication that the proton is not an elementary particle: we now know that it is made of three building blocks called quarks. Gerlach never won a Nobel Prize, perhaps because of his participation in the Nazi regime’s attempt to build an atomic bomb.

Today the concept of quantum spin as a 4-D entity is the foundation for all quantum computers. The quantum version of a computer bit, called the qubit, has the same mathematical form as the spin of an electron—whether or not it is in fact encoded in any spinning object. It often is not.

Even so, to this day, physicists continue to argue about how to interpret the experiment. According to now textbook quantum theory, initially, the silver atom’s outer electron does not know which way it is spinning. Instead it starts out in a “quantum superposition” of both states—as if its spin were up and down at the same time. The electron does not decide which way it is spinning—and therefore which of the two beams its atom travels in—even after it has skimmed through the magnet. When it has left the magnet and is hurtling toward the screen, the atom splits into two different, coexisting personas, as if it were in two places at the same time: one moves in an upward trajectory, and the other heads downward. The electron only picks one state when its atom arrives at the screen: the atom’s position can only be measured when it hits the screen toward the top or bottom—in one of the two spots but not both. Others take what they call a more “realist” approach: the electron knew all along where it was going, and the act of measurement is simply a sorting of the two states that happens at the magnet.

A recent prominent experiment seems to lend added credence to the former interpretation. It suggests that the two personas do coexist when the two spin states are separated. Physicist Ron Folman of Ben-Gurion University of the Negev in Israel and his colleagues re-created the Stern-Gerlach experiment using not individual atoms but a cloud of rubidium atoms. This was cooled to close to absolute zero, which made it act like a single quantum object with its own spin.

The researchers suspended the cloud in a vacuum with a device that can trap atoms and move them around using electric and magnetic fields. Initially the cloud was in a superposition of spin up and spin down. The team then released it and let it fall by gravity. During its descent, they first applied a magnetic field to separate the atoms into two separate trajectories, according to their spin, just as in the Stern-Gerlach experiment. But unlike in the original experiment, Folman’s team then reversed the process and made the two clouds recombine into one. Their measurements showed that the cloud returned into its initial state. The experiment suggests that the separation was reversible and that quantum superposition persisted after being subject to a magnetic field that separated the two spin orientations.

The experiment goes to the heart of what constitutes a measurement in quantum mechanics. Were the spins in the Stern-Gerlach experiment “measured” by the initial sorting done by the magnet? Or did the measurement occur when the atoms hit the screen—or perhaps when the physicists looked at it? Folman’s work suggests that wherever a measurement happened, the separation was not at the first stage.

The results are unlikely to quell the philosophical diatribes around the meaning of quantum measurement, says David Kaiser, a physicist and historian of science at the Massachusetts Institute of Technology. But the impact of the Stern-Gerlach experiment remains immense. It led physicists to realize “that there was some internal characteristic of a quantum particle that really doesn’t map on to analogies to things like planets and stars,” Kaiser says.

NASA's Perseverance Mars rover snapped this selfie on
September 10, 2021—the 198th Martian day of the mission.

NASA/JPL-Caltech/MSSS

What We Learned from the Perseverance Rover's First Year on Mars

Despite some unexpected challenges, team members are setting lofty goals for the rover in 2022

By Nadia Drake

Nadia Drake is a science journalist who specializes in covering astronomy, astrophysics and planetary science. Her byline has appeared in *National Geographic*, the *New York Times* and the *Atlantic*, among other publications.

One year ago NASA's Perseverance rover plunged through the Martian atmosphere and safely landed in Jezero Crater, a 45-kilometer-wide gouge that scientists suspect once hosted a deep, long-lived lake. The rover's ultimate target is near Jezero's western edge: a large, fan-shaped pile of sediments that washed into the basin through a notch in the crater rim about 3.5 billion years ago. In other words, the target is a river delta—the exact type of environment that could preserve signs of ancient Martian life-forms.

Perseverance is the tip of the spear in humanity's grand quest to find traces of a relict Martian biosphere. The $2.7-billion mission's overarching objective is to collect dozens of Martian rock samples, many of them from the delta. Then, sometime in the early 2030s, a sequence of spacecraft should return those samples to Earth for up-close scrutiny, possibly allowing scientists to at last answer the question of whether the solar system was ever home to more than one life-bearing world.

"Perhaps past microbial life could have existed on Mars when it was a little warmer and a little wetter," says Lori Glaze, director of NASA's planetary science division. "The surface of Mars—the geology, the geologic history—is preserved. We can see back 4.3 billion years on the surface.... You can't do that other places."

Perseverance's early observations are already revealing that Jezero's geologic history is richer than previously imagined, with dramatic shifts in environmental conditions. Now, as the rover ramps up its sample-collection campaign, scientists back home are eager to send it west, toward the alluring river delta and its potential biological treasure. Mars, however, does not always play by the rules. Already the planet has thrown a few unanticipated challenges into the rover's first Earth year on the Martian surface.

"Every time we've sent a mission to Mars, we've had to learn more about how Mars actually is going to treat our spacecraft, and we have to learn how to operate in that environment," Glaze says. But Perseverance is doing well, she adds. "Things are moving along at a really good clip. [The team is] making pretty great progress."

EARLY SCIENCE OUTSIDE THE LANDING STRIP

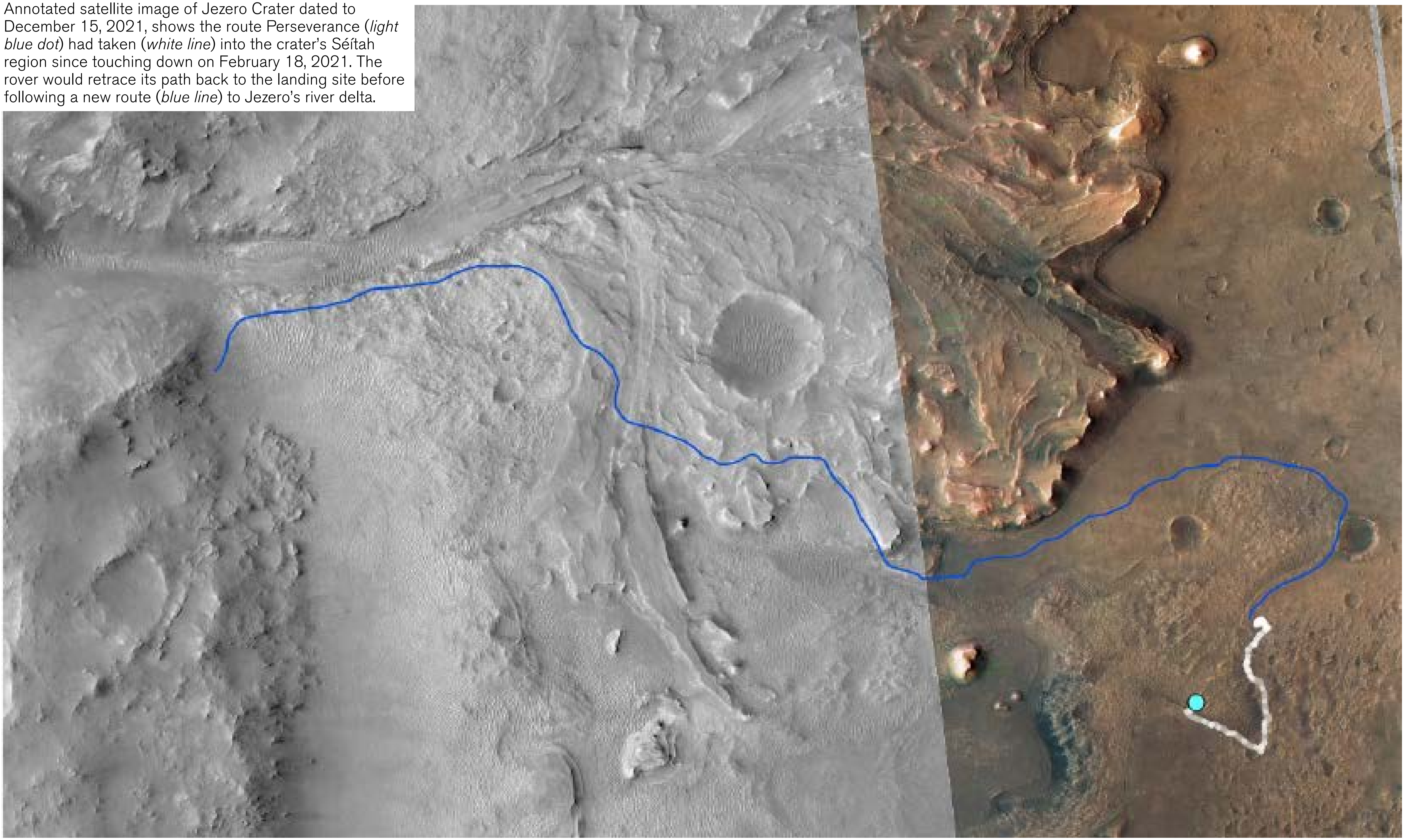
Perseverance is not alone in celebrating its first Martian anniversary. It was one of three space missions to reach Mars last February. The United Arab Emirates' Hope orbiter is still circling the planet. And China's multicomponent Tianwen-1 mission—composed of an orbiter, a lander and a rover—is there, too. That mission's rover, Zhurong, is currently exploring a Martian plain called Utopia Planitia, some 1,800 kilometers northeast of Perseverance's location.

Back in Jezero Crater, however, Perseverance's Martian adventures took an unexpected turn almost right away, starting with where the rover touched down on February 18, 2021.

"In all of the simulations that were done beforehand, the most likely place to land was a big, flat area that we started calling 'the landing strip' right in front of the delta—I mean, literally within 100 meters of the front of the delta," says the California Institute of Technology's Ken Farley, the mission's project scientist. "So we were joking around that on February 19 we were going to wake up looking at a wall in front of us. And, um, we didn't."

As the rover descended to the surface, an onboard navigation system autonomously guided Perseverance to an area the software had deemed "safe"—which it was. But instead of landing within an Earth day's drive of the delta, the rover ended up about 2.5 kilometers away, on the other side of a treacherous, sandy, rock-strewn terrain called Séítah, which is Navajo for "amid the sand." Circumnavigating that patch would more than double the length of the rover's path to its primary exploration target. Yet as Perseverance scouted its immediate surroundings, mission controllers chose to let it linger on the crater floor and explore Séítah before doubling back and heading to the delta.

"I worked on Curiosity ever since it landed in Gale Crater," says Perseverance's deputy project scientist Katie



Annotated satellite image of Jezero Crater dated to December 15, 2021, shows the route Perseverance (*light blue dot*) had taken (*white line*) into the crater's Séítah region since touching down on February 18, 2021. The rover would retrace its path back to the landing site before following a new route (*blue line*) to Jezero's river delta.

NASA/JPL-Caltech

Stack Morgan of the NASA Jet Propulsion Laboratory (JPL). "And [with] that very first image that we got down from Perseverance, I looked at that landscape and thought, 'Wow, we are not in Gale Crater anymore.' This is nothing like [what] I have ever seen in Gale."

Instead of landing in lake sediments, the rover found itself on fractured bedrock littered with bizarre, sometimes dusty rocks. Many of those rocks are covered in an intriguing purplish coating that resembles desert varnishes on Earth—patinas associated with hardy, radiation-resistant types of terrestrial microbes. Initially the rock textures and geochemistry defied classification. But once the rover had ground through the weathered surface of a Jezero rock, scientists saw exactly what they would have expected in a lava flow—not a lake bottom.

"All of the rocks that we have confidently identified are igneous," Farley says. "They have nothing to do with the lake."

Produced volcanically, the igneous rocks on Jezero's floor contain large olivine crystals that typically form near the bottoms of thick lava lakes and flows. Scientists still do not know how or when the rocks ended up in Jezero, but it is now clear that the surface Perseverance is rolling across is not the original crater floor. Further investigations revealed that the rocks have been altered by water, which excavated small tunnels and pockets in their interiors that are now filled with salty minerals. At least on Earth, such minerals are perfect for preserving signs of life. Their presence, plus the mysterious purple varnishes, makes these volcanic rocks unexpectedly tantalizing targets.

”Igneous rocks are typically not where you look to find signs of life, because they come from really hot magmas that life doesn't necessarily favor," Stack Morgan says. "But when you have these rocks sitting on the surface or in the subsurface interacting with water, then you're creating small niches within the rock itself that could be habitable. You've got chemical ingredients in there; you've got water in there; you've got precipitation of salt minerals."

As Perseverance cast its gaze farther afield, it spied Jezero's mountainous crater rim and the wall of the delta. ("We confirmed we do a have a delta, so check that box," Stack Morgan says.) It also spotted a curious rocky outcrop called Kodiak, which team members have used to gauge the depth of Jezero's ancient waters. Patterns on the rock suggest that on at least one occasion, water levels dipped surprisingly low, falling to more than 100 meters below an outflow channel to the east. Other observations provide hints of a deluge that gushed into the crater with enough power to carry along the large

Rock layers of Kodiak, a flat-topped hill near the center of this image, reveal ancient chapters of Jezero Crater's history marked by gradual sediment deposition followed by massive flooding.

NASA/JPL-Caltech/ASU/MSSS

boulders now haphazardly strewn in some areas. In other words, Jezero's lake was occasionally stable and placid and at other times flushed by periods of intense runoff.

And oddly, Jezero appears to be much windier than anticipated. Fortunately, that has not bothered Perseverance's robot friend, the helicopter named Ingenuity. Since April 2021 Ingenuity has been performing well—so well, in fact, that after its initial tests, the team began using it to help guide the rover through tricky terrains such as Séítah. "It aced those tests," Farley says. "Now it is our companion, and it is continuing to fly and do recon for us."

GO WEST, YOUNG ROVER

Collecting and storing samples has also turned out to be trickier than anticipated. Last August, when Perseverance took its first shot at collecting a rock core, mission personnel were optimistic. They had tested the machinery on terrestrial rocks and performed extensive troubleshooting on the software guiding the process. The target rock showed no obvious challenging quirks. The task should have been easy.

But the first coring tube was devastatingly empty. "To come up with a zero-volume empty tube was just mind-blowing, unfortunately," says JPL's Jessica Samuels, sample-caching system lead for the mission. "That was never something we were worried about—not acquiring the sample. We were worried about so many other things."

The rock, it turned out, had been so altered by water that it crumbled under the pressure of Perseverance's drill—not an ideal result but one that left the team with a useful tube full of Martian atmosphere. That first sample failure was stressful, however, and if the problems continued, they could have scuttled the once-in-a-lifetime chance to gather and return pristine material from Mars.

Since then, the team has regrouped and successfully collected six rock cores, which Samuels says is validation that the system actually works as planned. "It's not us. It's Mars," she says. Indeed, Mars served up another episode of sample-collecting shenanigans when pebbles recently wedged themselves into the rover's sample-caching hardware, and Perseverance had to do a bit of a shimmy to shake them loose.

"There's never a dull moment in sampling," Samuels says. "It's keeping us on our toes. And it's keeping us continuing to think about the different environmental conditions."

Overall, retrieving a small cache of samples from Mars is an audacious task that is just barely within our technological grasp, even if each of the mission's moving parts performs perfectly. "We're pushing the limits of the technology we have today to land and launch a rocket from Mars that is essentially just big enough to get a basketball into orbit," says Albert Haldemann, chief Mars engineer at the European Space Agency, a partner in the overall sample-return effort.

Perseverance's already collected igneous rock cores can be used to measure the strength of Mars's ancient magnetic field and to precisely pin ages on the crater's epochs. For now, scientists guess that water sloshed around in Jezero around 3.5 billion years ago, but Farley says there are half a billion years of uncertainty in that estimate. Soon, team members say, they will begin deciding when and where Perseverance should deposit a preliminary cache of materials—just in case the rover is no longer functioning by the time the next spacecraft arrives to retrieve its bounty.

"If everything is onboard Perseverance, and Perseverance dies unexpectedly, we've got nothing," Haldemann says. "So a safety cache will be put down at a potential landing spot—sooner rather than later."

Before it leaves the crater floor, Perseverance will fill two more of its 43 onboard, ultraclean sample tubes. Then it will turn west and make haste: "We're gonna gun it for the delta," Stack Morgan says.

John Horgan directs the Center for Science Writings at the Stevens Institute of Technology. His books include *The End of Science, The End of War* and *Mind-Body Problems*, available for free at mindbodyproblems.com. For many years he wrote the popular blog Cross Check for *Scientific American*.

Does Quantum Mechanics Reveal That Life Is but a Dream?

A radical quantum hypothesis casts doubt on objective reality

My girlfriend, “Emily,” often tells me her dreams, and I, less often, tell her mine, which are usually too murky and disjointed to share. We try to make sense of our dreams, to find meaning in them. What do they reveal about our fears and desires?

Interpreting dreams is an imperfect, highly subjective art, as Sigmund Freud, in his rare moments of humility, would surely have granted. Dreams are entirely private, first-person experiences, in his rare moments of humility, would surely have granted. Dreams are entirely private, first-person experiences that leave no traces beyond the dreamer’s fallible memory.

gremlin/Getty Images

And yet making sense of dreams, it occurs to me lately, is not wholly dissimilar from making sense of “reality,” whatever that is. Yes, we all live in the same world. We can compare notes on what is happening and draw inferences, in a way impossible with dreams.

And yet your experience of the world is unique to you. So is your interpretation of it, which depends on your prior beliefs, yearnings and aversions and on what matters to you. No wonder we often disagree vehemently, violently, on what has happened and what it means.

Science offers our best hope for achieving consensus about what happens. Scientists accumulate bits of evidence and try to assemble these fragments into a coherent story. After much haggling and second-guessing, scientists converge on a plausible narrative. Modern humans evolved from apelike creatures living in Africa millions of years ago. A novel, deadly coronavirus has emerged in China and is spreading across the world.

As philosopher Michael Strevens points out in *The Knowledge Machine,* science resolves disputes by means of repeated observations and experiments. Strevens calls scientists' commitment to empirical data the "iron rule of explanation." Ideally the iron rule produces durable, objectively true accounts of the world.

But subjectivity is hard to expunge even in physics, the foundation on which science rests. Quantum mechanics, a mathematical model of matter at very small scales, is science's most rigorously tested theory. Countless experiments have confirmed it, as do computer chips, lasers and other technologies that exploit quantum effects.

Unfortunately, quantum mechanics defies common sense. For more than a century, physicists have tried to interpret the theory, to turn it into a coherent story, in vain. "Every competent physicist can 'do' quantum mechanics," a leading textbook says, "but the stories we tell ourselves about what we are doing are as various as the tales of Scheherazade, and almost as implausible."

Many physicists ignore the puzzles posed by quantum mechanics. They take a practical, utilitarian attitude toward the theory, summed up by the admonition, "Shut up and calculate!" That is, forget about those quantum paradoxes and keep working on that quantum computer, which might make you rich!

Others keep probing the theory. In 1961 a prominent theorist, Eugene Wigner, proposed a thought experiment similar to the conundrum of Schrödinger's cat. Instead of the fabled cat in a box, imagine that a friend of Wigner is inside a laboratory monitoring a radioactive specimen. When the specimen decays, a detector flashes.

Now imagine that Wigner is outside the lab. If Wigner's friend sees the detector flash, he knows that the specimen has decayed. But to Wigner, standing outside the lab, the specimen, his friend and the entire lab hover in a blur of possible states. Wigner and his friend seem to occupy two distinct realities.

In 2020 physicists performed a version of Wigner's thought experiment and concluded that his intuitions were correct. In a story for *Science* headlined "Quantum Paradox Points to Shaky Foundations of Reality," physics reporter George Musser says the experiment calls objectivity into question. "It could mean there is no such thing as an absolute fact," Musser writes, "one that is as true for me as it is for you."

A newish interpretation of quantum mechanics called QBism (pronounced "Cubism," like the art movement) makes subjective experience the bedrock of knowledge and reality itself. David Mermin, a prominent theorist, says QBism can dispel the "confusion at the foundations of quantum mechanics." You just have to accept that all knowledge begins with "individual personal experience."

According to QBism, each of us constructs a set of beliefs about the world, based on our interactions with it. We constantly, implicitly, update our beliefs when we interact with relatives who refuse to get vaccinated or sensors tracking the swerve of an electron. The big reality in which we all live emerges from the collisions of all our subjective mini realities.

QBists hedge their mind-centrism, if only so they don't come across as loons or mystics. They accept that matter exists as well as mind, and they reject solipsism, which holds that no sentient being can really be sure that any other being is sentient. But QBism's core message, science writer Amanda Gefter says, is that the idea of "a single objective reality is an illusion." A dream, you might say.

Proponents bicker over definitions. Physicists and philosophers fond of objectivity reject QBism entirely. All this squabbling, ironically seems to confirm QBism's premise that there is no absolute objectivity; there are only subjective, first-person viewpoints.

Physicists have more in common than most would like to admit with artists, who try to turn the chaos of things into a meaningful narrative. Some artists thwart our desire for meaning. T. S. Eliot's poem *The Waste Land* is an anti-narrative, a grab bag of images that pop in and out of the void. The poem resembles a dream, or nightmare. Its meaning is that there is no meaning, no master narrative. Life is a joke, and the joke is on you if you believe otherwise.

If you are a practical person, like one of the finance majors in my freshman humanities class, you might conclude, along with T. S. Eliot, that efforts to comprehend existence are futile. You might urge friends majoring in philosophy to enjoy life rather than fretting over its meaning. You might summarize this advice with a catchy slogan: "Shut up and procreate!" But even those pragmatists must wonder now and then what our communal dream means.

Matthew Beddingfield is a whistleblower attorney and writer who works in Washington, D.C. He previously worked as a legal reporter for *Bloomberg* and attended the E. W. Scripps School of Journalism at the Ohio University. He is a grandson of James D. Gleaves, the mechanical lead technician for North American Aviation during the events of the *Apollo 1* (*AS-204*) tragedy.

Whistleblowers Make Spaceflight Safer, Says Witness to Apollo Tragedy

As we continue to push into space, the 55th anniversary of the deadly fire reminds us to prioritize both safety and people

The drive from the Kennedy Space Center's Visitor Complex to the launch facilities that line the Atlantic coast offers spectators a beautiful glimpse into American innovation: the gargantuan Blue Origin facility, the SpaceX landing zones and multiple NASA launch complexes.

It's on this path that the now deserted Launch Complex 34 sits, "ABANDON IN PLACE" spray-painted in black on the four columns holding up the concrete launching cradle. A barely noticeable plaque fastened to the structure reads, "Ad Astra Per Aspera (A Rough Road Leads to the Stars)."

In the early 1960s the site was bustling with the activity of NASA engineers and contractors,

On January 27, 1967, veteran astronaut Virgil "Gus" Grissom, first American spacewalker Edward White and rookie Roger Chaffee (*left to right*) were preparing for what was to be the first crewed *Apollo* flight. The astronauts were sitting atop the launch pad for a prelaunch test when a fire broke out in their capsule. The investigation into the fatal accident led to major design and engineering changes, making the *Apollo* spacecraft safer for the coming journeys to the moon.

NASA

but today it stands as a reminder of one of NASA's most tragic days. It's where, 55 years ago, my grandfather experienced one of the most traumatic days of his life.

When the clock ticked 6:31 p.m. at Cape Canaveral on January 27, 1967, an electrical fire erupted inside the command module where astronauts Gus Grissom, Ed White and Roger Chaffee were conducting what was supposed to be a routine "plugs-out" test, one month before Apollo 1, the first crewed mission of the Apollo program, was scheduled to take flight.

At the time of the accident, my grandfather, James Gleaves, was the lead technician for North American Aviation, the NASA contractor that designed and manufactured the command and service module (CSM-012) that caught fire. As panic consumed the white room, he worked frantically with several other men to open the three-layered hatch holding the crew members captive, but the inferno ripped through the interior within seconds, killing each of the men inside.

On this 55th anniversary of the tragedy, as space exploration becomes more privatized and technological capabilities become more advanced, the *Apollo 1* fire serves to remind those people trying to push space exploration forward of many things, but most important why we need to value a culture of safety and create a framework that incentivizes the people who speak up when that culture is forsaken—the whistleblowers—to come forward.

My grandfather has been reluctant to speak about the accident; he is humble, has dealt with the pain of the memory for many years, and initially was misquoted in news reports. Only recently has he divulged the weight of the constant pressure he and his fellow contractors felt to meet incentive deadlines and the shortcuts that inevitably had to be taken. My grandfather tried to fix issues as they arose, but when another colleague spoke out, his concerns were dismissed.

Men slept on shift, took egregiously long bathroom breaks and, to the shock of those on the prime crew, left tools scattered about the CSM, creating a messy, disorganized work environment. In one example of shocking behavior, my grandfather recalls men siphoning grain alcohol—intended to clean the command module—into baggies to take home and consume or sell.

The culture during that time was one of productivity and timeliness, leaving scant opportunity for critiques that could cause delays. Ensuring safety is often a time-consuming part of any space endeavor.

Everyone knew about safety issues, including the crew. Despite the *Apollo 1* astronauts airing confidence to the media, behind closed doors they let their colleagues know they had concerns, In one famous instance, Grissom hung a lemon on the faulty Apollo simulator as a sign of his discontent.

This was the site (known as Space Launch Complex 34) of the launch pad accident that killed *Apollo 1* astronauts Grissom, White and Chaffee. They died in a flash fire on January 27, 1967, during a test in preparation for their flight.

Michael Williamson/The Washington Post via Getty Images

But in the end, the project moved forward, even as a combination of several ignored red flags, tight deadlines wrought by a "go fever" mentality, groupthink and lackluster workmanship paved the path to tragedy.

Promoting a truly transparent workplace where safety concerns are paramount simply makes good business sense, and could very well have prevented the *Apollo 1* disaster. That's why Elon Musk's recent comments toward whistleblowers are even more disappointing given his successes in the industry thus far and his purported dedication to the cause. He should know better than most what's at stake when things go awry.

It wasn't until after the fire that many of the warnings about the Apollo capsule's pure oxygen environment, exposed wiring and excessive use of flammable materials came to light. The dawn of a new era in safety at NASA, most famously ushered in by Gene Kranz's "tough and competent" speech, didn't come until it was too late and can be easily forgotten if the culture surrounding today's projects don't prioritize a "flat" hierarchy of opinion.

And while the need for an open culture should pervade the next generation of spaceflight, perhaps the most valuable lesson from the *Apollo 1* fire is remembering that space exploration needs people, as well as automation. We stand to gain a tremendous amount from automating many of the processes involved, on top of rapid advancements in the field, but what do we stand to lose by not taking the time to look back?

As time has given him an opportunity to reflect, grieve and process the events, my grandfather, among others, has become more willing to discuss how the events 55 years ago affected his life. He remembers the smell of smoke when fire billowed out of the capsule, the ashes that filled the room falling like confetti, and the panic he felt knowing he might not make it home to his daughters, one of whom would eventually become my mother.

It took time, but the man who declined an invitation to attend the prime crew's funeral at Arlington National Cemetery and who refused to be a part of a documentary on his receiving the NASA Medal for Exceptional Bravery is now in a place to share his story. And for that, our understanding of U.S. space history has benefited.

What these space veterans know, understand and feel is important to the development of the next grand achievement in space. They are living, breathing testimonials of our country's history in space, and we need to take advantage of their insights because we are losing them. Whether it's in the aftermath of successes or disasters, our journey into this new era will suffer if we fail to recognize and promote their memories.

Although the horrific event of the *Apollo 1* fire paradoxically changed the trajectory of the U.S. space program for the better, with later improvements in safety protocols and processes, it also led to lawsuits, conspiracy theories, an astronaut's widow's suicide, and a burnt capsule languishing in a dark and isolated NASA storage unit.

This is all only part of the story.

A monument honoring Grissom, White and Chaffee sits in Arlington National Cemetery, and an exhibit dedicated solely to the *Apollo 1* mission is open at the Kennedy Space Center. The tributes are the result of years of work by those who believe humankind's raison d'etre is a constant search for the unknown and who refuse to let the events of that day become a mere footnote in the history of American space exploration. We would know so little of the emotion and the story of those moments if all we'd had were data logs and diagnostics.

During my family's trip to see the *Apollo 1* exhibit, my grandfather, in usual fashion, spoke very little. When walking through the exhibit, he stared at a picture of his younger self on the North American employee tag that was on display. I asked him to tell us what he was thinking, but he politely declined.

It wasn't until the tour guide was passing Launch Complex 34 that he spoke up, saying he'd like to see that. For the first time in decades, he walked into the site that 55 years ago, he almost didn't walk out of.

As our group looked around, admiring the memorial plaque bearing the names of the three men lost on that day, our tour guide commented that he had heard present-day astronauts use the site as a sort of holy ground for contemplation before taking off on journeys of their own.

I remember thinking how apt that was. A place of tragedy turned into a place of reflection. Then I turned to my grandfather, who was looking down at his feet, giving a gentle nod and smile.

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It's Time for a Global Ban on Destructive Antisatellite Testing

The orbital debris created in the explosions is dangerous, long-lasting and a threat to the growing space economy

janiecbros/Getty Images

In November 2021 Russia ignited an international uproar with a weapon test that launched an interceptor against a defunct military satellite. When it hit, that deliberate collision shattered the satellite into more than 1,500 trackable pieces of debris.

This space debris is dangerous; it could hit and severely damage an orbiting space station, akin to the opening scenes of the movie *Gravity*. The debris from this test could knock out any of dozens of satellites working to monitor climate and weather, not to mention those that provide critical national security information and perform other vital services for us on Earth. The debris could threaten the tens of thousands of new satellites planned for launch in the coming years and intended to provide global broadband access and other in-space activities as part of a growing space economy. And some of this orbital debris is long-lived, meaning that it could pose a future risk to anything that might launch into the same altitude for years to come.

It is past time for the global community to put an end to such antisatellite testing—but doing so will not be easy.

Antisatellite weapons have been part of the superpower rivalry from the beginning of the space age. And, to be fair, Russia is not the only country to carry out a test that created significant amounts of orbital debris.

Between 1959 and 1995 the U.S. and the Soviet Union conducted more than 50 antisatellite (ASAT) tests in space, in which a dozen weapons hit satellites, creating more than 1,200 pieces of trackable orbital debris. Although decades have passed, nearly 400 trackable pieces of that debris are still in orbit, not to mention many more still dangerous pieces too small to be tracked with current systems. Since 2005 the U.S., Russia, China and India have conducted another 26 ASAT tests in space, five of which have destroyed satellites and created more than 5,300 pieces of trackable orbital debris that will remain in orbit for decades to come.

The latest Russian venture is the first time in seven years of testing that the nation has attempted to use this weapon—a ground-based interceptor called Nudol or A-235—against an actual satellite as a target. And it happened at an altitude of approximately 480 kilometers; both the International Space Station and China's Tiangong space station orbit at an altitude of around 400 kilometers.

With this much possibility of calamity, it is unfortunate that policy makers have had such little success in trying to prevent such tests, let alone in addressing the broader issue of space weapons. The international community has been trying for decades to limit the development or use of space weapons, such as ASATs, through discussions of what has been called the Prevention of an Arms Race in Outer Space (PAROS) at the United Nations General Assembly (UNGA). PAROS has been an annual agenda item there since the 1980s; however, this item has become a pro forma vote with little actual resulting action.

The other main multilateral body where one might expect to see negotiations on space arms control, the Conference on Disarmament in Geneva, has been bogged down in disagreement over what the real threat to space is. Russia, China and their allies argue that the focus should be on banning the placement of space-to-Earth weapons in orbit. The U.S. and its allies instead argue that threatening behavior in space—such as uncoordinated close approaches to another country's satellite or the deliberate creation of large amounts of debris—is what is destabilizing. Furthermore, the two sides are split over whether the steps taken should be a legally binding treaty or voluntary guidelines and political norms of behavior.

Despite the disagreements that have prevented a ban on ASAT testing to date, there is perhaps a glimmer of hope. In December 2020 the UNGA passed Resolution 75/36, calling on countries to submit reports on what they saw as the most pressing threats to space security and recommend steps on how to move forward. More than 30 countries replied, with many supporting the idea of limiting specific technologies in space rather than enacting any bans and working toward identifying and promoting responsible behavior in space. In October 2021 the U.N. First Committee voted to hold a new Open-Ended Working Group (OEWG) on space threats (and formalized it in the UNGA with a vote in December 2021). The OEWG would be open to all countries and would meet in 2022 and 2023 to develop concrete proposals for addressing space threats.

Although the prospects of a new multilateral treaty banning the existence of space weapons are dim, there are other things that can be done to minimize the dangerous consequences of these weapons. First and foremost, the countries that are developing and testing such weapons—China, India, Russia and the U.S.—can unilaterally declare a moratorium on further testing that creates orbital debris. Doing so would send a strong signal to the international community that they are committed to the long-term sustainability of space and for delegitimizing the testing of these weapons against satellites.

Second, all countries should participate in and contribute to the OEWG on space threats to discuss how to move toward a global ban on destructive ASAT testing. Countries should come to the table with ideas for addressing other pressing threats to space security. This includes nonconsensual close encounters with another country's satellites and attempts to disrupt satellite operations by targeting them with ground-based lasers. Although less obviously threatening than kinetic attacks where a satellite is physically destroyed, such acts are increasing in frequency and could inflame tensions, potentially leading to misperceptions or mistakes that then spark actual armed, hostile conflict in space.

That would be devastating to the entire planet.

There is much work that still needs to be done to establish the foundations for any new space arms control agreement. One unresolved issue is that there is no agreed-on space arms control lexicon; one is needed to overcome the existing cultural, language and geopolitical differences among the major space powers. Another is a better understanding of what incentives are driving the testing of ASAT weapons and how those can be shifted. Finally, a verification regime needs to be developed that will enable all countries to monitor whether or not the conditions of any agreement are being followed. Improving space situational awareness data collection and sharing will be a key part of this monitoring.

Russia's most recent ASAT test, like earlier tests conducted by it and the U.S., China and India, has made operating in low Earth orbit more dangerous for years to come. All satellite operators and crewed vehicles will need to spend time, effort and fuel on avoiding collisions as the debris from these tests gradually reenters Earth's atmosphere. But if the international community can leverage this test as the wake-up call to enact an ASAT test moratorium and enter into space arms control discussions in good faith, some good may still be salvaged.

By establishing agreed-on norms of behavior in space and generating binding restrictions on ASAT testing, the international community can ensure that space is stable, secure and accessible to all for generations to come.

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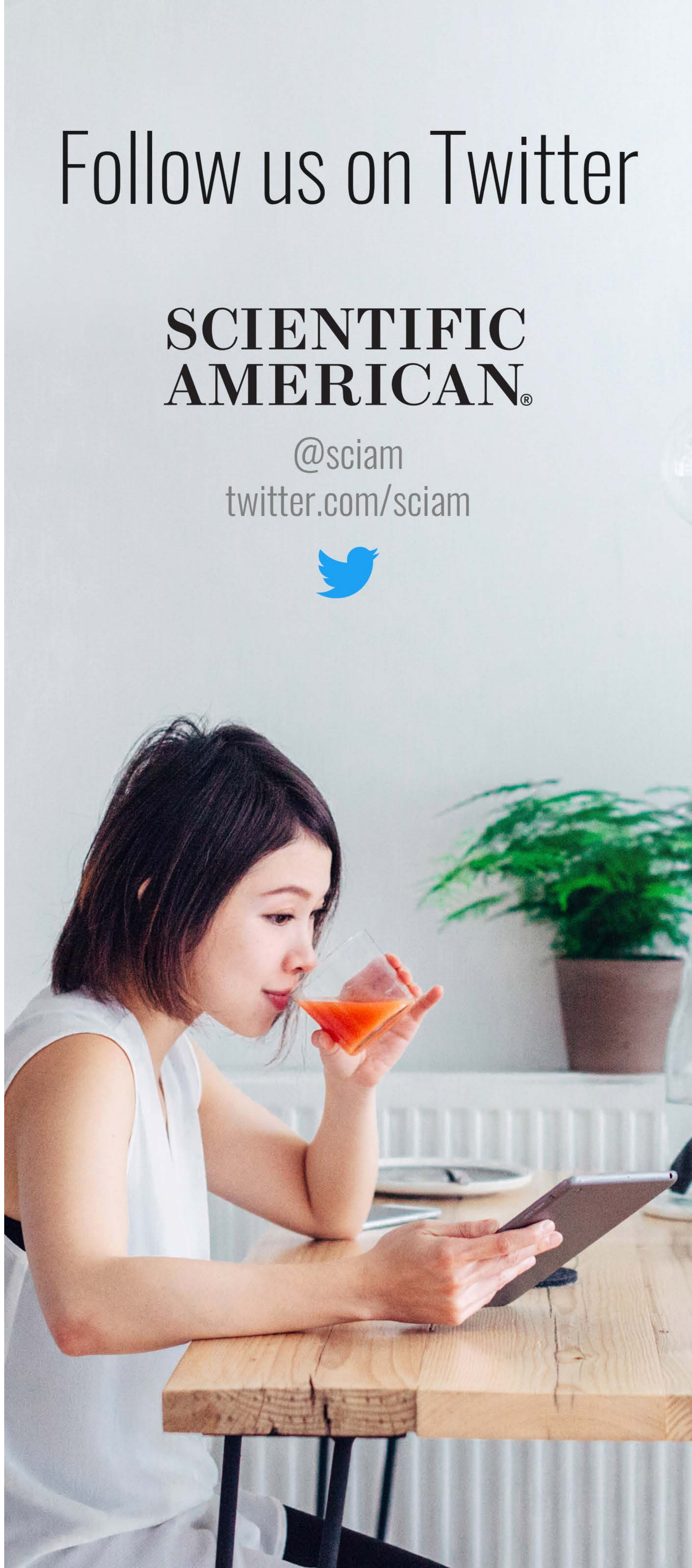


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