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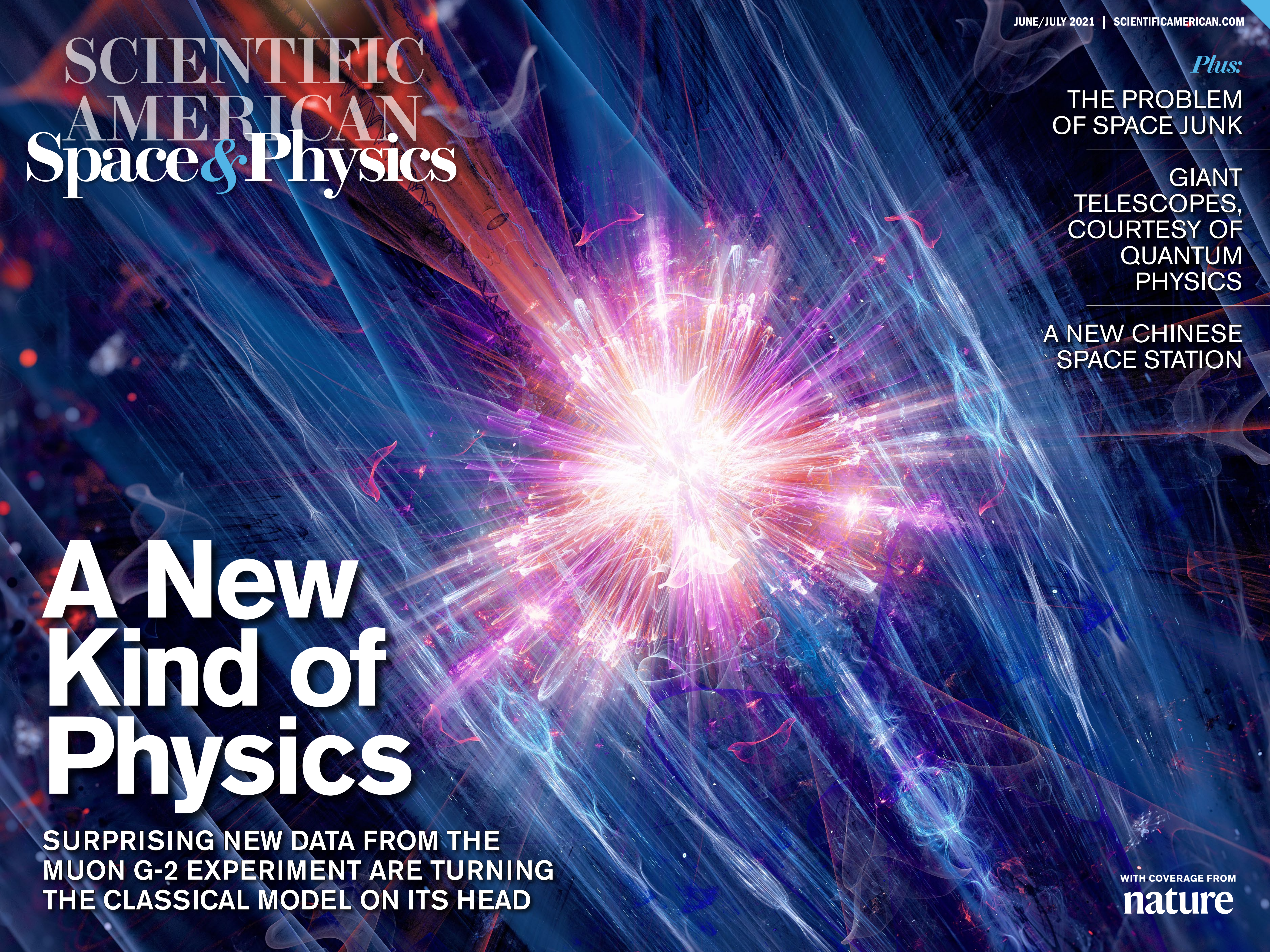

Plus:

THE PROBLEM OF SPACE JUNK

GIANT TELESCOPES, COURTESY OF QUANTUM PHYSICS

A NEW CHINESE SPACE STATION

A New Kind of Physics

SURPRISING NEW DATA FROM THE MUON G-2 EXPERIMENT ARE TURNING THE CLASSICAL MODEL ON ITS HEAD

WITH COVERAGE FROM nature

LIZ TORMES

The Subatomic Keys to the Universe

In April a team of physicists at Fermi National Laboratory in Batavia, Ill., announced anomalous behavior in the magnetic wiggle of the muon. The signal suggests that there may be other forces at work affecting the particle's behavior besides those predicted by the Standard Model of physics (see "Long-Awaited Muon Measurement Boosts Evidence for New Physics"). But as physicist Sabine Hossenfelder outlines in her fascinating analysis of this finding, whether or not this discovery upends the classical rules depends on mind-bending statistics and higher-level calculations aided by computers to determine whether we have seen something significant or are merely observing a number-crunching fluke (see "Is the Standard Model of Physics Now Broken?").

Elsewhere in the subatomic world, researchers are hoping that quantum hard drives might one day collect and store photon data from optical telescopes spread across the planet (see "Quantum Astronomy Could Create Telescopes Hundreds of Kilometers Wide"). Though invisible to human eyes, subatomic particles have been called the building blocks of matter and may be the key to understanding the nature of our universe.

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Surprising new data from the Muon g-2 experiment are turning the classical model on its head

GETTY IMAGES

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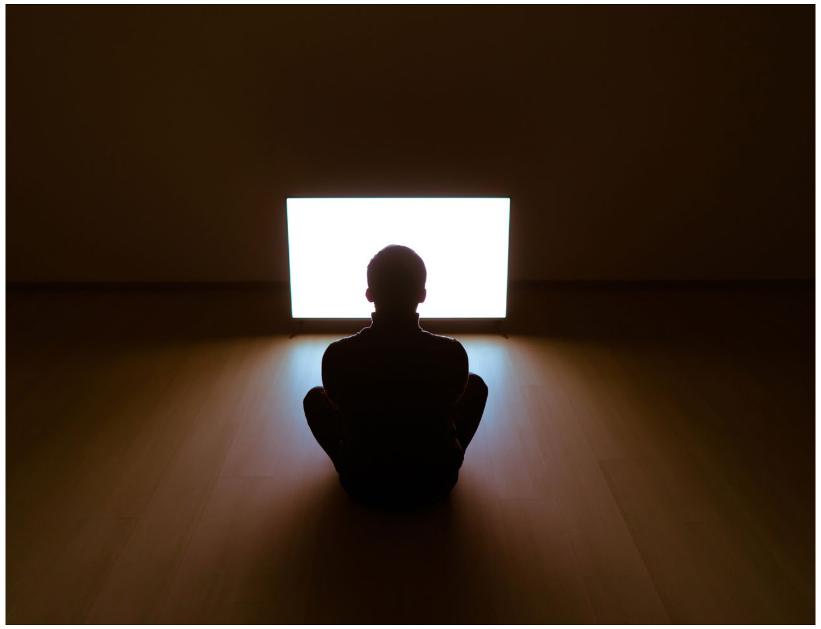

ARTEM PERETIATKO *GETTY IMAGES*

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China Launches First Module of Massive Space Station

The new orbiting laboratory will host research from Chinese and international scientists

Since the Soviet Union launched the first space station, Salyut 1, 50 years ago, humans have lived on a total of 11 such facilities in Earth orbit. China recently added one more to that list. With the core module of the Chinese Space Station (CSS) successfully launched at the end of April, the culmination of a project the nation's government initially envisioned in 1992 is finally entering the construction phase.

China plans at least 10 more launches of other major modules, as well as crewed and cargo missions, to complete the station's assembly by the end of 2022. At that time the CSS will join the International Space

ALEJANDRO MIRANDA *ALAMY*

Station (ISS) as the only fully operational space stations in orbit.

PUTTING IT TOGETHER

The T-shape, 100-metric-ton CSS will comprise three major modules: the 18-meter-long core module, called Tianhe ("Harmony of the Heavens"), and two 14.4-meter-long experiment modules, called Wentian ("Quest for the Heavens") and Mengtian ("Dreaming of the Heavens"), which will be permanently attached to either side of the core. As the station's management and control center, Tianhe can accommodate three astronauts for stays of up to six months. Visiting astronauts and cargo spaceships will hook up to the core module from opposite ends. Both it and Wentian are equipped with robotic arms on the outside, and Mengtian has an airlock for the maintenance and repair of experiments mounted on the exterior of the station. Tianhe has a total of five docking ports, which means an extra module can be added for future expansion. The station is designed to operate for more than 10 years.

The CSS has less than one-fourth the mass of the ISS—the largest and most expensive human-made structure in space, which was cooperatively built by 15 nations. "We did not intend to compete with the ISS in terms of scale," says Gu Yidong, chief scientist of the China Manned Space program. Instead the three-module configuration is "based on China's needs for scientific experiments" and "what we consider a reasonable size for the sake of cost-effectiveness."

To develop the CSS, China followed a three-step strategy by first building crewed spacecraft (the Shenzhou missions), followed by mini space stations (Tiangong-1 and 2), and then the multimodule station launching soon. Construction of the CSS was officially approved in 2010. Although China's heavy-lift rocket had a launch failure in 2017, delaying the liftoff of Tianhe by over a year, the country's space leaders hope to stick to the goal of completing space station construction by 2022 through intensive launches in the next two years.

DOMESTIC AND INTERNATIONAL EXPERIMENTS

The CSS will house 14 refrigerator-size scientific experiment racks and a few general-purpose racks that provide power, data, cooling and other services to various research projects. There will also be more than 50 docking points for experiments that will be mounted on the outside of the station to study how materials react to space exposure. The science inside and out will include space physiology, life science, fluid physics, materials science, astronomy and Earth observation. So far about 100 experiments have been selected from more than 800 domestic proposals, Gu says. Some of them could start collecting data as early as next year.

For instance, the station will use the world's most precise clocks and coldest atoms to support fundamental research in general relativity and quantum physics. The clocks on the CSS are designed to reach incredibly low levels of instability, with only one second of error every three billion years. The ultracold-atoms experiment rack can cool atoms to 10^{-10} kelvins, the lowest temperature achievable with current technologies. Some racks will be the first of their kind on a space station, including one dedicated to studying phase changes between the liquid and gas states of matter because those processes become much more distinct in microgravity. These studies could, for instance, help to develop smaller and more efficient cooling devices for spacecraft and even laptops.

The station will also reserve the space and resources for a number of international experiments. Tricia Larose, a medicine researcher at the University of Oslo, is leading Tumors in Space, a 31-day experiment that will fly on the CSS and test if weightlessness can slow or stop the growth of cancer, among other goals. As one of the nine international projects selected by the China Manned Space Agency (CMSA) and the United Nations Office for Outer Space Affairs (UNOOSA), the mission will use three-dimensional stem cell organoids, or "mini colons," grown from cancerous and healthy colon tissues of the same patient to study how DNA mutations are affected by microgravity. "All previous cancer experiments in space have used two-dimensional cell lines," Larose says. "In comparison, organoids mimic the organ's structure and function and are the most physiologically relevant biosamples to use."

CALL FOR COLLABORATION

The CSS can expect company a year or two after its completion: China plans to launch a Hubble-size telescope that will operate in the same orbit a few hundred kilometers away. As a part of the CSS, the China Sky Survey Telescope (also called Xuntian) will have 300 times Hubble's field of view and will address a wide range of science in the near-ultraviolet and optical wave bands. The observatory will investigate cosmology, the large-scale structure of matter in the universe, and galaxy and stellar science, as well as dark matter and dark energy. It is designed to dock with the space station for servicing if needed, offering an easy, fuel-efficient and "better way to engage astronauts to ensure the performance of the telescope," Gu says.

Xuntian has similar designs and goals as the European Space Agency's Euclid mission and NASA's Nancy Grace Roman Space Telescope, both of which will launch in coming years, but they will be working in complementary wave bands. Gu believes that cooperation among the three telescopes and the sharing of observational data will lead to a deeper understanding of the universe and fundamental physics.

China welcomes collaboration on the CSS from scientists all over the world, Gu emphasizes. Soon the CMSA-UNOOSA collaboration will release a second call for international experiment proposals. Scientists can also apply through institutional partnerships for access to resources on the space station. It is not clear what level of international collaboration the CSS will receive, however, because of geopolitical hurdles. U.S. law heavily restricts NASA scientists from collaborating directly with China. In Europe, pressure from the agency also makes it difficult to get funding for projects that would involve the Chinese space program.

Larose notes that she and her colleagues encountered "an unexpected level of hesitancy" toward grant applications related to the CSS. It is frustrating, she says, because cancer knows no boundaries, and looking for better cancer treatment benefits everyone in every country on Earth. "When are we going to stop looking at our differences and start focusing on our similarities?" Larose asks.

—Lee Billings

Liftoff! First Flight on Mars Launches New Way to Explore Worlds

NASA's Ingenuity helicopter successfully hovered for 40 seconds in Mars's thin atmosphere

NASA has pulled off the first powered flight on another world. Ingenuity, the robot rotorcraft that is part of the agency's Perseverance mission, lifted off from the surface of Mars on April 19, in a 40-second flight that is a landmark in interplanetary aviation.

"We can now say that human beings have flown a rotorcraft on another planet," says MiMi Aung, the project's lead engineer at the Jet Propulsion Laboratory (JPL) in Pasadena, Calif.

Ingenuity's short test flight is the off-Earth equivalent of the Wright brothers piloting their airplane in 1903 above the coastal dunes at Kitty Hawk, N.C. In tribute, the helicopter carries a postage-stamp-sized piece of muslin fabric from the Wright brothers' plane. "Each world gets only one first flight," Aung says.

The flight came after a one-week delay because software issues kept the helicopter from transitioning into flight mode two days ahead of a planned flight attempt on April 11. On April 19, at 12:34 A.M. U.S. Pacific time, Ingenuity successfully spun its counterrotating carbon-fiber blades at more than 2,400 revolutions per minute to give it the lift it needed to rise three meters into the air. The $85-million drone hovered there and then, in a planned maneuver, turned 90 degrees and descended safely back to the Martian surface. "This is just the first great flight," Aung says.

Four further flights, each lasting up to 90 seconds, were planned in the coming weeks. In these, Ingenuity is likely to rise up to five meters above the surface and travel up to 300 meters from the takeoff point. Each successive flight will push Ingenuity's capabilities to see how well the drone fares in Mars's thin atmosphere, which is just 1 percent as dense as Earth's.

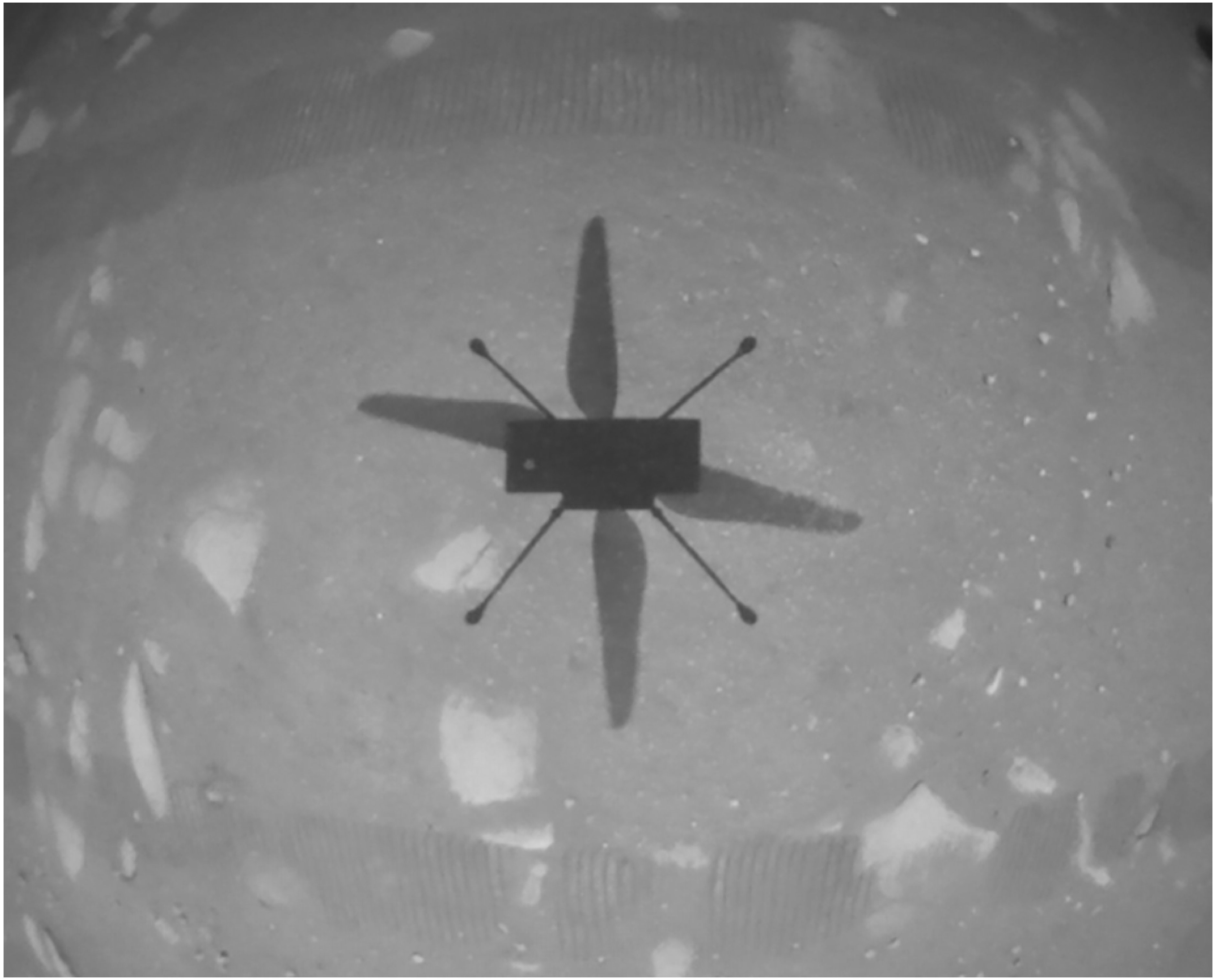
Space agencies have sent drifting aircraft to other planets before; for example, the Soviet Union's Vega 1 and Vega 2 missions sent balloons into Venus's atmosphere in 1985. But

Ingenuity's flight is the first controlled flight on another planet.

Its purpose is to test whether helicopters could be used to explore other worlds. As it flies across the terrain, it will snap black-and-white images of the surface below and color images looking toward the horizon. Future helicopters could help rovers, or even astronauts, to make their way across the surface, by scouting for interesting areas ahead and relaying images of what the landscape looks like.

Big rotorcraft could also get into areas that are inaccessible to rovers rolling across the ground, says Anubhav Datta, an aerospace engineer at the University of Maryland at College Park, who has been working on Mars helicopter concepts for decades. "If we are serious about human missions to Mars, we should be serious about sending large helicopters to truly explore what awaits there," he says. "The most interesting places we want to explore are not on flat land but up the slopes, on the cliffs, down the craters and into the caves." Cameras and other instruments onboard helicopters could capture information about such places.

NASA is already building a car-sized octocopter named Dragonfly that it plans to send to Saturn's moon Titan.



NASA's Mars helicopter Ingenuity took this shot of the Martian surface during its first flight on April 19, 2021.

NASA AND JPL-CALTECH

Set to launch in 2027, the copter would explore Titan's atmosphere, which is four times denser than Earth's and is rich in primordial organic compounds. That's a very different environment from the one that Ingenuity is experiencing on Mars. But the early flight lessons from Ingenuity will inform Dragonfly's design. "We're looking forward to learning from the Ingenuity team's experience flying in an extraterrestrial sky," says Elizabeth Turtle, a planetary scientist at the Johns Hopkins University Applied Physics Laboratory, who is Dragonfly's principal investigator.

Ingenuity arrived in Mars's Jezero Crater in February, nestled under the belly of the Perseverance rover. From its landing site, Perseverance drove to a flat "airfield" in the crater that is relatively free of rocks and deposited Ingenuity there. The rover then rolled to a slight rise 65 meters away, a vantage point from which it watched and videotaped Ingenuity's takeoff and flight.

The biggest challenge in designing Ingenuity was making it small and light enough to be carried under Perseverance's belly, while still being capable of flight, Aung says. The helicopter ended up weighing just 1.8 kilograms. Engineers tested it on Earth in a special chamber at JPL from which nearly all the air had been sucked out, to simulate the thin Martian atmosphere.

Compared with a similar-sized helicopter on Earth, Ingenuity has larger blades that spin much faster, to lift it into the thin Martian air. Datta says that he will be anxiously awaiting information on how much power the helicopter takes to hover; this knowledge will help engineers to better understand the aerodynamics on Mars.

Another researcher, William Farrell of NASA's Goddard Space Flight Center, is crossing his fingers that Ingenuity will help scientists to gain a better idea of the electrical properties of the Martian atmosphere. To do this, it would need to fly—or at least spin its blades—near dusk on Mars. Farrell and his colleagues recently calculated that the moving helicopter blades could become electrically charged through contact with the dust in the surrounding air, much as helicopter blades on Earth can build up charge in sand storms. That could cause a faint blue-purplish glow along the blades, best visible in the dim light of dusk. Farrell has asked the Ingenuity team if it could rotate the blades during dusk at some point—and if that happens, he will be watching closely.

The thin Martian atmosphere means that winds there are not particularly strong. Ingenuity can handle winds of a little over 10 meters per second while flying and stronger winds when it's sitting on the ground. It is powered by solar panels to keep it warm during the freezing Martian nights, when temperatures can sink to –90 degrees Celsius at Jezero Crater.

Ingenuity is designed to last just 30 Martian days, which ended on May 4. After that, even if the helicopter is still functional, it will have accomplished its mission and team scientists will turn their attention back to the rover on which it traveled to Mars. Ingenuity will rest in perpetuity in Jezero Crater as Perseverance trundles off on its main mission to collect rock samples for eventual return to Earth.

—Alexandra Witze

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Ketchup Is Not Just a Condiment: It Is Also a Non-Newtonian Fluid

Everybody's favorite red sauce may be thin or thick, depending on how it is handled

"People [experience] the fluid element to be … not yet solidified but remaining open to outside influences."
—Sensitive Chaos: The Creation of Flowing from of Water and Air, *by Theodor Schwenk (Rudolf Steiner Press, 1965)*

Ketchup is famous for being hard to get out of the bottle even when there is plenty of it left. In fact, all liquid foods—from red wine to cooking oil—leave some residue in the container. The reason has to do with the wettability of the container and the viscosity of the substance. Usually the residue is just a thin layer, but ketchup clings in thick layers to the inside of the bottle. If the bottle is still nearly full, merely tilting it or even turning it upside down will dislodge only a little sauce from the neck. Once the ketchup is on your plate, however, it disperses and spreads easily.

To liquefy the sauce, shake the bottle vigorously or thwack it with your hand. If you are not careful, a lot more will end up on your food than you intended. As experienced users know, there is no need to rush after shaking because the effect takes a certain amount of time: you can relax, remove the cap and take aim.

This annoying feature of ketchup inevitably raises the question of why food manufacturers have failed to address it. The simple answer is that ketchup was deliberately designed that way—not to irk people but because there are situations that require it. For example, a thin strip of ketchup should be applied to a hot dog so that it does not end up all over your clothes—even when you are cramming it into your mouth. Yet ketchup should not be sticky either: with each bite, the sauce should melt in your mouth and not require any chewing to be savored.

In physical terms, ketchup undergoes stress via shaking, spreading or eating. The bottom part of the mass, which is viscous at rest, sits on a solid base and is held by adhesion or other forces, while the upper layers are situated in a parallel direction. In "Newtonian" fluids, viscosity is independent of the pressure being applied to the fluid per unit of area. In the case of "non-Newtonian" fluids (ketchup), the situation is different: a stronger force reduces the viscosity.

This behavior, known as shear thinning, is caused by polymers that are added to the sauce (a concoction of tomato paste, sugar and other ingredients) in the form of a thickener. Polymers are microscopic complex molecules composed of long chains of atoms, which become entangled and release energy into their surroundings. In this state, the polymer is quite pulpy and viscous. Applying sufficiently large shear force, however, provides the energy needed to stretch the polymer molecules out and align them lengthwise. The chains now easily slide past one another, and macroscopically, the result is reduced viscosity.

Once the shear forces have subsided, and the ketchup is allowed to settle, the polymer molecules become entangled again and release energy. This process takes a bit of time, which explains why the sauce does not immediately resolidify after the shaking and shearing.

ALAMY

Everyday life offers other examples of shear-thinning substances such as shampoo. A small amount of shampoo flows very slowly into the palm of your hand, giving you time to lift it to your head and rub it into your hair. There is hardly any resistance because the shear force of lathering thins out the fluid. Despite the similarity between shampoo and ketchup, they have a notable difference: Shampoo flows freely under its own weight, whereas ketchup often does not. A squiggle of ketchup on a hot dog stays in place. Wall paint and toothpaste, two other non-Newtonian liquids, also stay put when they are applied.

If the viscosity of some fluids diminishes in response to shear stress, are there other fluids whose viscosity increases? In fact, one example of a common shear-thickening substance can be found in the kitchen: cornstarch mixed with water that forms a paste. The mixture is fairly easy to stir at a moderate speed. But when the speed picks up, the viscosity of the mixture increases until it finally becomes so firm that the stirring spoon gets stuck.

This starch-water mixture behaves similarly to quicksand. Under gentle force, the sand grains slide past one another because they are lubricated by water. Sudden pressure displaces the water from the gaps and forces the solid components together, dramatically increasing the resistance. As with quicksand, starch molecules are separated by a layer of water. And when strong forces bring them into contact, the mixture coalesces.

The food industry has found a way to deal with the vexing quality of ketchup: The condiment is now available in flexible plastic bottles. Just a slight squeeze is enough to overcome the resistance of the sauce. This solution certainly simplifies handling—but the sport of getting the sauce out of a bottle, and its moment of triumph when done cleanly, is lost.

—H. Joachim Schlichting

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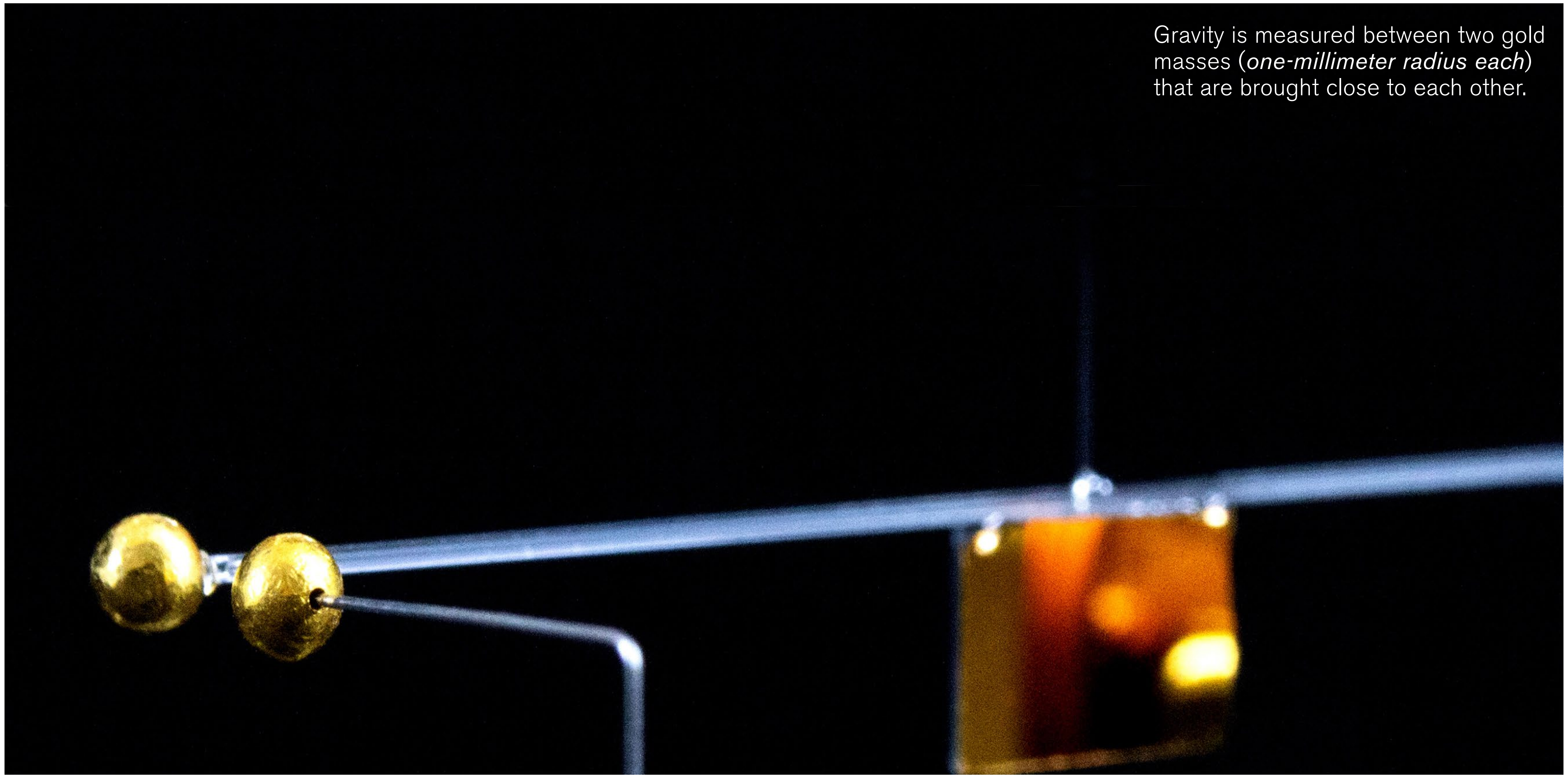


Gravity is measured between two gold masses (*one-millimeter radius each*) that are brought close to each other.

TOBIAS WESTPHAL *UNIVERSITY OF VIENNA*

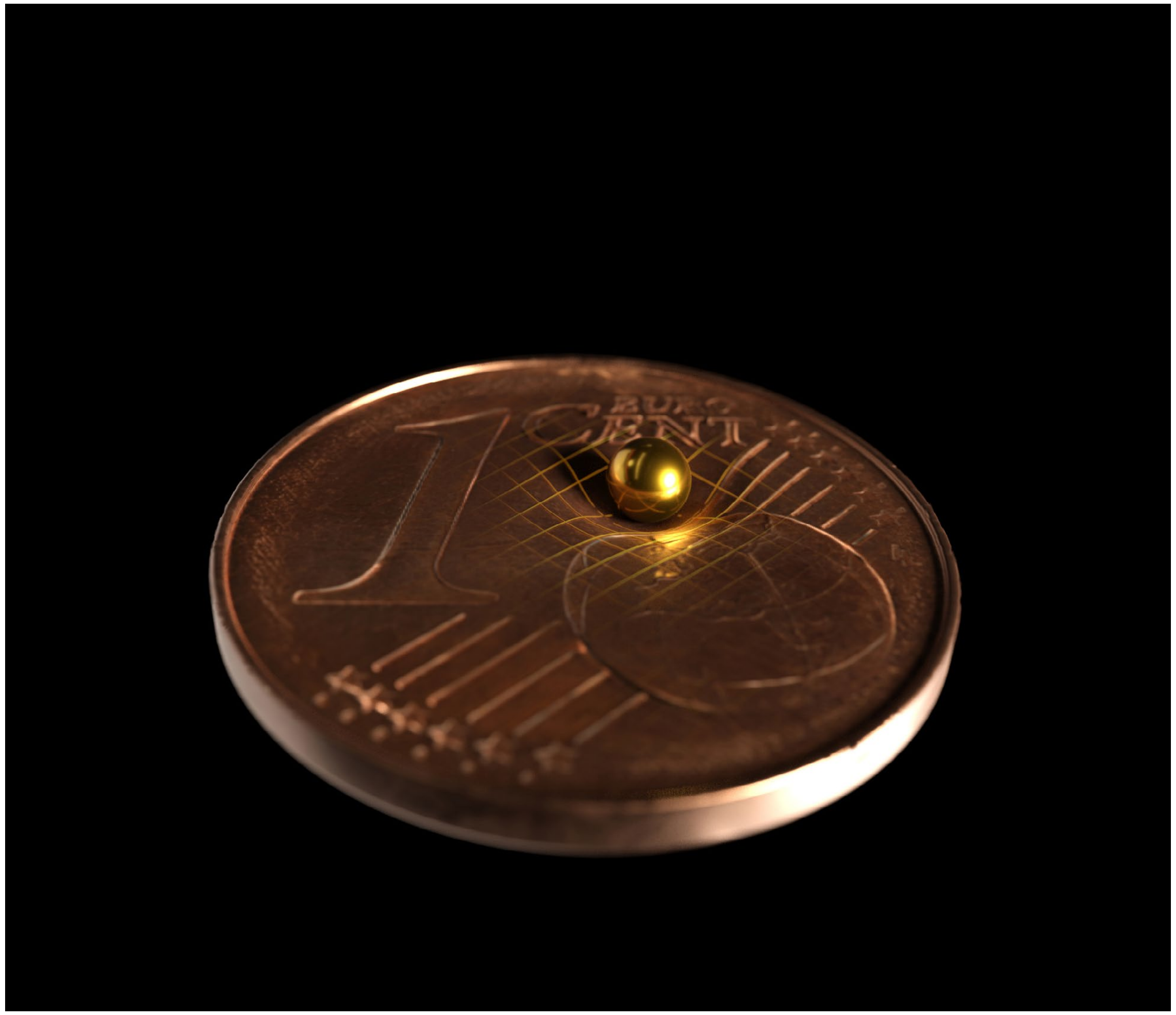
Physicists Measure the Gravitational Force between the Smallest Masses Yet

A laboratory experiment captured the pull between two minuscule gold spheres, paving the way for experiments that probe the quantum nature of gravity

Physicist Markus Aspelmeyer vividly remembers the day, nearly a decade ago, that a visitor to his lab declared the gravitational pull of his office chair too weak to measure. Measurable or not, this force certainly ought to exist. Ever since the work of Isaac Newton in 1687, physicists have understood gravity to be universal: every object exerts a gravitational force proportional to its mass on everything around it. The visitor's comment was intended to bring an increasingly fanciful conversation back down to Earth, but Aspelmeyer, a professor at the University of Vienna, took it as a challenge. “My resolution was ‘Okay, I am going to not only measure the gravitational field of this chair, but we are going to go small, small, small!'” he recalls.

The research effort born on that day has now produced its first result:

a measurement of the gravitational force between two tiny gold spheres, each about the size of a sesame seed and weighing as much as four grains of rice—the smallest masses whose gravity has been measured to date. The results, published in *Nature* in March, bring physicists one step closer to the distant goal of reconciling gravity with quantum mechanics, the theory underlying all of nongravitational physics.



Gravity can be understood as originating from a warping of spacetime, which is shown in this artist's impression.

PRECISION GRAVITY

It is hard to fathom just how extraordinarily weak gravity is for such small masses. The gravitational pull of one sphere (the “source mass”) on the other (the “test mass”) a few millimeters away is more than 10 million times smaller than the force of a falling snowflake. The central challenge facing Aspelmeyer's team was to design a detector exquisitely sensitive to this gravitational force yet totally insensitive to much larger background forces pushing and pulling on the test mass from all sides.

The researchers achieved this sensitivity using a detector called a torsion pendulum, which looks like a miniature version of a mobile hanging above a child's crib. The test-mass sphere is fixed to one end of a thin rod that is suspended at its midpoint by a four-micron-thick quartz fiber. An identical sphere on the other end of the rod acts as a counterweight. A force on the test mass causes the torsion pendulum to rotate until it is balanced by a restoring force from the twisting of the fiber. Such a thin fiber is extremely compliant, so even a very weak force yields a relatively large rotation. Critically, the torsion pendulum is very insensitive to forces from distant objects, which tug on the test mass and counterbalance together and thus do not induce rotation.

But even this clever torsion pendulum design did not totally isolate the test mass from the busy urban environment of daytime Vienna. “The sweet spots are always between midnight and 5 A.M., when no people are on the street,” Aspelmeyer explains. “[But] this was not true of Friday or Saturday.”

To measure the gravitational force of the source mass, the researchers did not simply place it near the test mass. Instead they moved it continuously back and forth around an average separation of a few millimeters. This technique, called modulation, is implicit in the design of turn signals and blinking bike lights: regular, periodic signals are much more visible against ever present background noise than constant ones. Sure enough, the scientists observed an oscillating force at precisely the right frequency. They then repeated this process many times, changing the average separation between the masses, and measured forces as small as 10 femtonewtons at separations between 2.5 and 5.5 millimeters. The team compared these measurements to Newton's famous inverse square law of gravity, which describes how the gravitational force between two objects depends on their separation: the data were consistent with Newton's law to within 10 percent.

"[That] you can measure these really, really, really tiny forces—I think that is pretty amazing," says Stephan Schlamminger, a physicist at the National Institute of Standards and Technology, who studies gravity but was not involved in the work.

But Aspelmeyer and his colleagues could not declare victory quite yet: they still had to rule out the possibility that the source mass modulation was generating other forces on the test mass that would oscillate at precisely the same frequency. Periodic rocking of the table supporting the experimental apparatus, caused by recoil from the barely visible motion of the source mass, was just one of a host of confounders the researchers had to carefully quantify. In the end, they found that all known nongravitational forces would be at least 10 times smaller than the gravitational interaction.

REACHING TOWARD QUANTUM SCALES

Aspelmeyer believes that an improved torsion pendulum will be sensitive to gravity from masses 5,000 times smaller still—lighter than a single eyelash. His ultimate goal is to experimentally test the quantum nature of gravity, a question that has perplexed physicists for nearly a century. Quantum mechanics is one of the most successful and precisely tested theories in all of science: it describes everything from the behavior of subatomic particles to the semiconductor physics that makes modern computing possible. But attempts to develop a quantum theory of gravity have repeatedly been stymied by contradictory and nonsensical predictions.

> **"The question of whether gravity fundamentally behaves quantum is an experimental question. We can't wait to go the whole nine yards and see how things turn out."**
> ***—Markus Aspelmeyer***

Particles described by quantum mechanics behave in remarkably counterintuitive ways. One of the strangest kinds of quantum behavior is a special form of correlation called entanglement: when two particles become entangled, their fates become inextricably linked, and they cannot be described separately. Entanglement and other quantum effects are most prominent in very small and well-isolated systems such as atoms and molecules, and they become increasingly fragile on larger scales where gravity is relevant. Until recently, tests of quantum gravity have seemed far beyond the reach of laboratory-scale experiments.

But the past few years have seen remarkable experimental progress toward discerning subtle quantum effects in ever larger systems. In late 2017 two groups of theoretical physicists independently proposed an ambitious but possibly realizable experiment that could make a definitive statement about the quantum nature of gravity. The effort would measure whether gravity can entangle two quantum particles. If so, "there's no escape from the fact that it has to be, in some sense, nonclassical," says Chiara Marletto, a theoretical physicist at the University of Oxford, who co-authored one of the proposals with her colleague Vlatko Vedral.

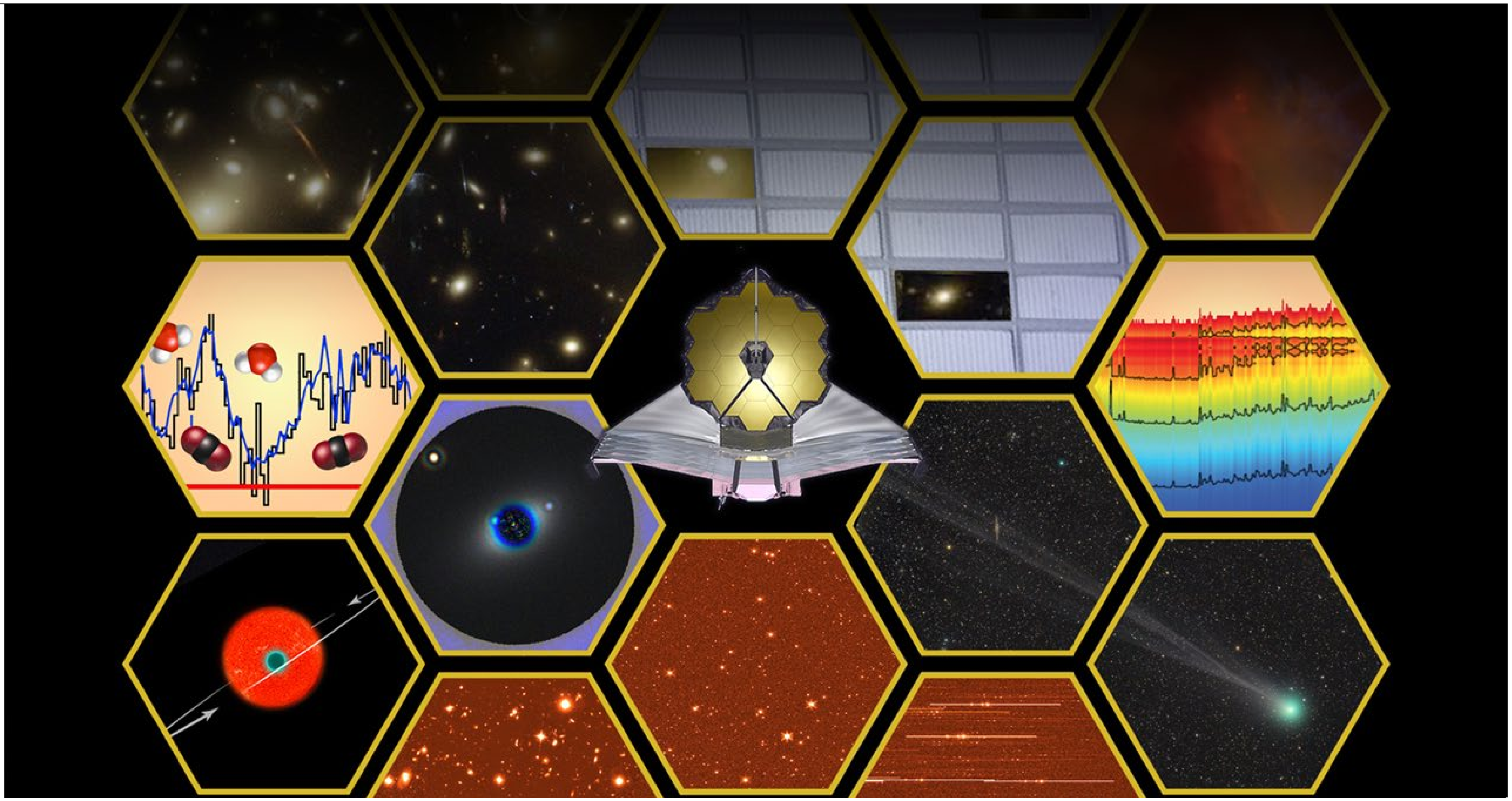
The observation of gravitationally induced entanglement would be groundbreaking. But a conclusive demonstration that gravity is quantum-mechanical would require proving that the two particles interacted only through gravity. Aspelmeyer's efforts to isolate gravitational forces between progressively smaller masses are a critical step toward such a definitive test. "Since quantum is going from small to big, there's a chance for gravity and quantum to meet somewhere in the middle," says Sougato Bose, a theoretical physicist at University College London, who co-wrote the other proposal with nine collaborators.

"The question of whether gravity fundamentally behaves quantum is an experimental question," Aspelmeyer says. "We can't wait to go the whole nine yards and see how things turn out."

—Ben Brubaker

The James Webb Space Telescope's First Year of Extraordinary Science Has Been Revealed

From more than 1,000 proposals, the scientists who hoped to perform the observatory's historic first studies now know their fate



Artist's concept of the James Webb Space Telescope's scientific capabilities. The infrared observatory's large mirror will allow astronomers to search for the universe's first galaxies and stars while also studying the atmospheres of nearby exoplanets.

NASA, ESA, AND A. FEILD (STSCI)

Years behind schedule and billions of dollars over budget, the James Webb Space Telescope (JWST) often finds itself the butt of jokes. From satirical Webcomics to more scathing criticism, the flagship project of NASA, the European Space Agency (ESA) and the Canadian Space Agency is an easy target. Yet many would argue that those delays and budget concerns are simply indicative of the telescope's unprecedented scope and soaring ambitions. When it hopefully launches on October 31, it will be, by far, the largest and most sophisticated observatory ever sent into space. JWST will be poised to revolutionize our understanding of the universe from its lofty perch some 1.5 million kilometers from Earth, beyond the orbit of the moon. But what will the telescope actually do that justifies the decades of effort and expenditure to get it off the ground?

Now we know. On March 30 the Space Telescope Science Institute (STScI) in Baltimore revealed the proposals selected for the General Observer (GO) programs for JWST's first year of operation, or Cycle 1. They constitute most of the observations the telescope will perform during Cycle 1, encompassing everything from looking for atmospheres on nearby rocky exoplanets to probing the universe's earliest galaxies. The projects could start around this time next year, after a high-stakes post-launch deployment of the telescope's giant 6.5-meter segmented mirror and multilayered sun shield, as well as a subsequent six-month phase of commissioning its instruments.

Once that prep work is done, Cycle 1 observations can properly begin. A portion of JWST's opening studies—some 460 hours—will be devoted to Early Release Science (ERS) programs designed to put the telescope's instruments through their paces. Nearly 4,000 hours will be dedicated to Guaranteed Time Observations (GTO) programs awarded to scientists who helped to build JWST's hardware and software. But the majority of the observation time in the first year—approximately 6,000 hours—will be given to GO programs proposed by scientists around the world to take advantage of the telescope's unique capabilities.

"This is a really big deal," says Kenneth Sembach, director of STScI, which will run and operate JWST as it does the project's predecessor, the Hubble Space Telescope. "The chance to be among the first accepted proposals in a brand-new observatory that has the potential to really revolutionize astronomy is something the community has been waiting for for a long time. These are pathfinders, the kinds of science proposals that are going to blaze the way forward for the observatory in the future."

A TELESCOPE FOR ALL

The total time allocation purposefully adds up to more than the number of hours in a year to ensure the telescope is "oversubscribed" and never left with nothing to do. A paucity of programs that led to an idle observatory was a mistake that occurred with early Hubble operations in the 1990s, says David Adler, lead of STScI's Long Range Planning Group. JWST's time will be carefully choreographed, allowing it to perform observations across different programs while pointing at particular regions of the sky. This arrangement will ensure it is not constantly swiveling its view back and forth, wasting fuel and running the risk of building up momentum that could place "unnecessary torque on the telescope," Adler says.

The programs range from high-impact science to trendsetting pathfinder observations, and they were chosen by panels of scientists in a double-blind process that prevented the disclosure of information, such as proposers' gender, that could have inappropriately influenced the decision-making process.

Of the 1,200 or so proposals received, the panels selected 266 from scientists in 41 countries, and a third of them will be led by women. About a third were from ESA member states. Europe, as a major partner in JWST, was guaranteed at least 15 percent of the telescope's observation time but ended up with 30 percent—and 2 percent were from Canada. Most proposals, however, came from American scientists.

To maximize scientific returns, the total observation time within Cycle 1's General Observer programs is split among a variety of subcategories: 32 percent for galaxies, 23 percent for exoplanets, 12 percent for stellar physics, and so on—down to 6 percent dedicated to our own solar system. Within those categories, there are small programs (25 hours or less of observation time), medium programs (more than 25 to 75 hours) and large programs (more than 75 hours). Some of the latter are also regarded as "treasury programs," which are expected to provide expansive data sets that will lay the foundations for subsequent studies by multiple generations of researchers.

INTO THE UNIVERSE

Across all the General Observer programs, the largest award went to Jeyhan Kartaltepe of the Rochester Institute of Technology and Caitlin Casey of the University of Texas at Austin, with 208.6 hours allocated for their COSMOS-Webb proposal. Kartaltepe, Casey and their colleagues intend to study thousands of the earliest galaxies in the universe, all of which formed within a billion years of the big bang. These galaxies are so faint that they were beyond the boundaries of investigation by humanity's telescopes, save for a handful of observations by Hubble, until now. "It's really incomparable," Kartaltepe says. "Hubble has chipped away, but it's really limited by its size and sensitivity. Webb is really going to clean up and detect much fainter things."

This could help us understand a key part of the universe's history known as the epoch of reionization, a period from 400,000 to one billion years after the big bang where the first stars and galaxies emerged. "We think reionization didn't happen everywhere at the same time," Kartaltepe says. "It happened in pockets or bubbles. Those bubbles are tied to the initial large-scale structure of the universe. We hope to map that structure."

Elsewhere, Natasha Batalha of NASA's Ames Research Center and Johanna Teske of the Carnegie Institution for Science were the recipients of the third-largest time allocation and largest exoplanet program for their proposal to study the atmospheres of a dozen exoplanets in a way never possible before. Over 141.7 hours of observations, the project will use JWST's giant mirror to watch these worlds transit their host stars, blocking the starlight as they pass in front, allowing the researchers to work out the basic composition and structure of any atmospheres present.

The worlds Batalha, Teske and their colleagues will observe, between one and three times the size of Earth, are thought to be intriguing super-Earths and sub-Neptunes, classes of planets JWST could transform our understanding of. "In order to get to a point where we're looking for biosignatures in true potentially Earth-like habitable planets, we really need to understand the full diversity of planets that has been discovered to date," Batalha says. "That full diversity includes these strange super-Earths [and] sub-Neptunes that have been highlighted as one of the most common types of planet in the galaxy. We really have no idea what they are. It's incredibly important for JWST to survey these planets."

Another popular target of study is TRAPPIST-1—a transiting planetary system 40 light-years from Earth that is thought to comprise seven Earth-sized worlds orbiting a single red dwarf star. Researchers consider some of the worlds to be potentially habitable, so to understand the system more, two of JWST's GTO programs and three of the telescope's GO programs will focus on it. Laura Kreidberg, director of the Max Planck Institute for Astronomy in Heidelberg, Germany, is lead of one of the GO programs. This project will use JWST to assess the temperature of the system's second-innermost world, TRAPPIST-1c, and to look for an atmosphere on that planet across nearly 18 hours of observations.

Although TRAPPIST-1c itself is thought to be too hot to support life, the presence of an atmosphere would suggest that cooler and possibly more habitable worlds in the system could host atmospheres, too. And for now only JWST can deliver those data.

"We need to observe far out in the infrared," Kreidberg says. "Earth is too hot. You have to have a telescope in space that is cold that has [sufficient] wavelength coverage. JWST is the only telescope that has ever been built that is capable of doing that."

NO PLACE LIKE HOME

In our own solar system, JWST's capabilities are also expected to be transformative. Noemi Pinilla-Alonso of the University of Central Florida plans to use the telescope to study 59 trans-Neptunian objects (TNOs)—icy bodies beyond the orbit of Neptune—in an unprecedented observation campaign lasting nearly 100 hours. JWST will be able to discern materials present on the bodies, such as water or complex organics—something that was only possible for 40 of the brightest TNOs before. "The broad knowledge we're going to have of the solar system with JWST has no comparison to what we have at this moment," Pinilla-Alonso says.

There are also some high-risk programs that rely on events taking place that JWST can quickly follow up on, known as targets of opportunity. Martin Cordiner of NASA's Goddard Space Flight Center is leading one such program, which hopes to observe an interstellar object passing through our solar system like 'Oumuamua in 2017 or Comet Borisov in 2019. "We're keeping our fingers crossed that we'll get one," he says. And if it comes within a few times of the Earth-sun distance of our star, JWST should be able to study it—with Cordiner heading the campaign. "The aim," he says, "is to characterize the chemical composition," such as water and carbon dioxide, giving us a glimpse at material from another planetary system.

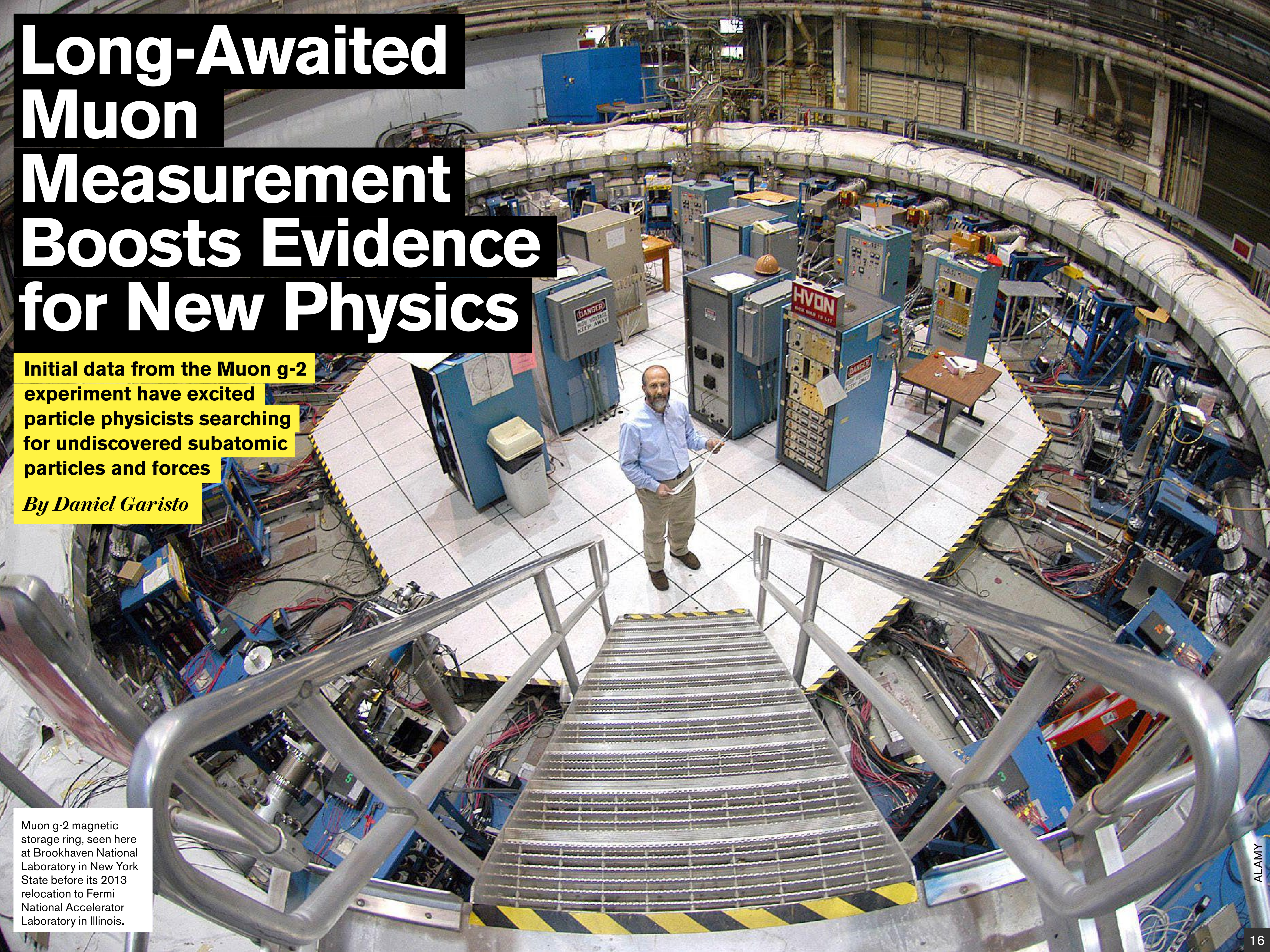
Such programs are just a small selection of the cornucopia of science JWST will unleash. But more than anything, they are an indicator of the transformative results researchers and the public should expect from this telescope. For now, though, the world must endure an anxious wait for JWST's successful launch and hope that every piece of machinery performs as expected to allow this fabulous window to the universe to open. "There will be several days of terror when all of these mechanisms are unfolding," says Günther Hasinger, ESA's director of science. And while many are eager to get the ball rolling as soon as possible, there will be no rush—jokes at JWST's expense be damned. "Be patient," Hasinger says, "and keep fingers crossed that we get this wonderful machine into orbit."

—Jonathan O'Callaghan

Long-Awaited Muon Measurement Boosts Evidence for New Physics

Initial data from the Muon g-2 experiment have excited particle physicists searching for undiscovered subatomic particles and forces

By Daniel Garisto



Muon g-2 magnetic storage ring, seen here at Brookhaven National Laboratory in New York State before its 2013 relocation to Fermi National Accelerator Laboratory in Illinois.

ALAMY

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

WHEN HUNDREDS OF PHYSICISTS GATHERED ON A ZOOM call in late February to discuss their experiment's results, none of them knew what they had found. Like doctors in a clinical trial, the researchers at the Muon g-2 experiment blinded their data, concealing a single variable that prevented them from being biased about or knowing—for years—what the information they were working with actually meant.

But when the data were unveiled over Zoom, the physicists knew the wait had been worth it: their results are further evidence that new physics is hiding in muons, the bulkier cousins of electrons. "That was the point at which we knew the results. Until then we had no idea," says Rebecca Chislett, a physicist at University College London, who is part of the Muon g-2 collaboration. "It was exciting and nerve-wracking and a bit of a relief."

Despite its remarkable success in explaining the fundamental particles and forces that make up the universe, the Standard Model's description remains woefully incomplete. It does not account for gravity, for one thing, and it is similarly silent about the nature of dark matter, dark energy and neutrino masses. To explain these phenomena and more, researchers have been hunting for new physics—physics beyond the Standard Model—by looking for anomalies in which experimental results diverge from theoretical predictions.

Muon g-2 is an experiment at Fermi National Laboratory in Batavia, Ill., that aims to precisely measure how magnetic muons are by watching them wobble in a magnetic field. If the experimental value of these particles' magnetic moment differs from the theoretical prediction—an anomaly—that deviation could be a sign of new physics, such as some subtle and unknown muon-influencing particle or force. The newly updated experimental value for muons, reported in April in *Physical Review Letters,* deviates from theory by only a minuscule value (0.00000000251) and has a statistical significance of 4.2 sigma.* But even that tiny amount could profoundly shift the direction of particle physics.

"My first impression is 'Wow,'" says Gordan Krnjaic, a theoretical physicist at Fermilab, who was not involved in the research. "It's almost the best possible case scenario for speculators like us.… I'm thinking much more that it's possibly new physics, and it has implications for future experiments and for possible connections to dark matter."

Not everyone is as sanguine. Numerous anomalies have cropped up only to disappear, leaving the Standard Model victorious and physicists jaded about the prospects of breakthrough discoveries.

"My feeling is that there's nothing new under the sun," says Tommaso Dorigo, an experimental physicist at the University of Padua in Italy, who was also not involved with the new study. "I think that this is still more likely to be a theoretical miscalculation.… But it is certainly the most important thing that we have to look into at present."

Muons are almost identical to electrons. The two particles have the same electric charge and other quantum properties, such as spin. But muons are some 200 times heavier than electrons, which causes them to have a short lifetime and to decay into lighter particles. As a result, muons cannot play electrons' pivotal role in forming structures: molecules and mountains alike—indeed, essentially all chemical bonds among atoms—endure thanks to electrons' stability.

When German physicist Paul Kunze first observed the muon in 1933, he wasn't sure what to make of it. "He showed this track that was neither an electron nor a proton, which he called—my translation—'a particle of uncertain nature,'" says Lee Roberts, a physicist at Boston University and an experimentalist at Muon g-2. The newfound particle was a curious complication to the otherwise limited cast of subatomic particles, which led physicist Isidor Isaac Rabi to famously wonder, "Consider the muon. Who ever ordered that?" The ensuing deluge of exotic particles discovered in the decades that followed showed that the muon was actually part of a larger ensemble, but history has nonetheless been kind to Rabi's befuddlement: it turns out there might indeed be something strange about the muon.

In 2001 the E821 experiment at Brookhaven National Laboratory in New York State, found hints that muons' magnetic moment diverged from theory. At the time, the finding was not robust enough because it had a statistical significance of only 3.3 sigma: that is, if there were no new physics, then scientists would still expect to see a difference that large once out of 1,000 runs of an experiment because of pure chance. The result was short of five sigma—a one-in-3.5-million fluke—but enough to pique researchers' interest for future experiments.

With a statistical significance of 4.2 sigma, researchers cannot yet say they have made a discovery. But the evidence for new physics in muons—in conjunction with anomalies recently observed at the Large Hadron Collider Beauty (LHCb) experiment at CERN near Geneva—is tantalizing.

> **"My feeling is that there's nothing new under the sun. I think that this is still more likely to be a theoretical miscalculation…. But it is certainly the most important thing that we have to look into at present."**
>
> ***—Tommaso Dorigo***

MOVING MUONS

Most physics experiments reuse parts. For example, the Large Hadron Collider is based in the tunnel designed for, and previously occupied by, its predecessor, the Large Electron-Positron Collider. But the experimentalists behind Muon g-2 took matters further than most when, instead of building a new magnet, they shipped the 50-foot ring from Brookhaven on a 900-mile trip to its new home at Fermilab.

The magnet occupies a central place in Muon g-2. A beam of positive pions—lightweight particles made from an up quark and a down antiquark—decay into muons and muon neutrinos. The muons are collected and channeled into an orderly circular path around the magnet, which they will circle, at most, a few thousand times before they decay into positrons. By detecting the direction of muon decays, physicists can extract information about how the particles interacted with the magnet.

How does this process work? Imagine each muon as a tiny analog clock. As the particle circles the magnet, its hour hand goes around and around at a rate predicted by theory. When the muon's time is up, it decays into a positron that is emitted in the direction of the hour hand. But if that hand turns at a rate different from theory—say, a tick too fast—the positron decay will end up pointing in a slightly different direction. (In this analogy, the hour hand corresponds to the muon's spin, a quantum property that determines the direction of the muon decay.) Detect enough deviating positrons, and you have an anomaly.

What an anomaly implies is ambiguous. There might be something not accounted for by the Standard Model, and it could be a difference between electrons and muons. Or there could be a similar effect in electrons that is too small to currently see. (The mass of a particle is related to how much it can interact with heavier unknown particles, so muons, which have about 200 times the mass of electrons, are much more sensitive.)

Muon g-2 began collecting data for its first run in 2017, but the results did not come out until now because processing that information was an arduous task. "Although people might have wanted to see the result come out early, this just reflects a long period of doing our due diligence to understand things," says Brendan Kiburg, a Fermilab physicist, who is part of the collaboration.

Alone, Muon g-2's experimental value does not indicate much. To have meaning, it has to be compared against the latest theoretical prediction, which itself was the work of about 130 physicists.

The necessity for all that brainpower comes down to this: When a muon travels through space, that space is not really empty. Instead it is a sizzling and swarming soup of an infinite number of virtual particles that can pop in and out of existence. The muon has some small chance of interacting with these particles, which tug on it, influencing how it behaves. Calculating the virtual particles' effect on the muon's spin—the rate at which its hour hand turns—requires a series of equally arduous and incredibly precise theoretical determinations.

All of this means the theoretical prediction for muons has its own uncertainty, which theorists have been trying to whittle down. One way is via lattice quantum chromodynamics (QCD), a technique that relies on massive computational power to numerically solve the effects of the virtual particles on muons. According to Aida X. El-Khadra, a physicist at the University of Illinois at Urbana-Champaign, who was not involved with the experimental result, about half a dozen groups are all in hot pursuit of the problem.

GETTING PHYSICAL

The fun is just beginning. In the coming days and weeks, a torrent of theoretical papers will attempt to make more sense of the new result. Models that introduce new particles such as the *Z′* boson and the leptoquark will be updated in light of the new information. While some physicists speculate about what, exactly, the muon anomaly could mean, the effort to reduce uncertainties and push the anomaly above five sigma is ongoing.

Data from Muon g-2's second and third runs are expected in about 18 months, according to Kiburg and Chislett, and that information could push the anomaly past the five-sigma threshold—or decrease its significance. If it is not decisive, researchers at J-PARC (Japan Proton Accelerator Research Complex), a physics lab in Tokai, Japan, may have an answer. They plan to independently corroborate the Muon g-2 result using a slightly different method to observe muon behavior. Meanwhile theorists will continue to refine their predictions to reduce the uncertainty of their own measurements.

Even if all of these efforts confirm that there is new physics at work in muons, however, they will not be able to reveal what, exactly, that new physics is. The needed tool to reveal its nature may be a new collider—something many physicists are clamoring for via proposals such as the International Linear Collider and the High-Luminosity LHC. In the past few months, interest has surged around a muon collider, which multiple papers predict would guarantee physicists the ability to determine the properties of the unknown particle or force affecting the muon.

Even those who are skeptical about the significance of the new result cannot help but find a silver lining. "It is good for particle physics," Dorigo says, "because particle physics has been dead for a little while."

**Editor's Note: The author of this article is related to Robert Garisto, a handling editor at* Physical Review Letters, *but they had no communications about the paper prior to its publication.*

Quantum Astronomy Could Create Telescopes Hundreds of Kilometers Wide

Astronomers hope to use innovations from the subatomic world to construct breathtakingly large arrays of optical observatories

By Anil Ananthaswamy

Composed of four 8.2-meter telescopes that can act as one, the European Southern Observatory's Very Large Telescope in northern Chile is the world's premier astronomical facility for optical interferometry. New approaches from the quantum world, however, could allow astronomers to make far larger and more capable optical interferometers.

JUAN CARLOS MUÑOZ-MATEOS/ESO

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

A FEW YEARS AGO RESEARCHERS USING THE RADIO-BASED EVENT HORIZON TELESCOPE (EHT) PERFORMED AN EXTRAORDINARY observation, the likes of which remains a dream for most other astronomers. The EHT team announced in April 2019 that it had successfully imaged the shadow of a supermassive black hole in a nearby galaxy by combining observations from eight different radio telescopes spread across our planet. This technique, called interferometry, effectively gave the EHT the resolution, or the ability to distinguish sources in the sky, of an Earth-sized telescope. At the optical wavelengths underpinning the gorgeous pictures from the Hubble Space Telescope and many other famed facilities, today's interferometers can only combine light from instruments that are a few hundred meters apart at most. That may be set to change as astronomers turn to quantum physicists for help to start connecting optical telescopes that are tens, even hundreds, of kilometers away from one another.

Such optical interferometers would rely on advances being made in the field of quantum communications—particularly the development of devices that store the delicate quantum states of photons collected at each telescope. Called quantum hard drives (QHDs), these devices would be physically transported to a centralized location where the data from each telescope would be retrieved and combined with the others to collectively reveal details about some distant celestial object.

This technique is reminiscent of the iconic double-slit experiment, first performed by physicist Thomas Young in 1801, in which light falls on an opaque barrier that has two slits through which it can pass. The light recombines on the other side of the barrier, creating an interference pattern of bright and dark stripes, also known as an interferogram. This works even if individual photons trickle through the slits one by one: over time, the interference pattern will still emerge.

"If we have two telescopes that can be made to behave like Young's slits, and we are able to get an interferogram on a source of light, like a star on the sky, the interferogram tells you a lot of things about the source," says astronomer Jonathan Bland-Hawthorn of the University of Sydney, whose team is proposing the use of quantum hard drives to build optical interferometers. Such instruments could one day help astronomers measure the sizes and intrinsic motions of stars and galaxies with greater precision, a crucial ingredient in our understanding of the evolution of the cosmos.

Although radio astronomers have already built impressive interferometers such as the EHT, that is mainly because interferometry is easier to achieve in radio than at optical frequencies in three important ways: First, radio antennas are cheaper to build than optical telescopes, so one can construct large numbers of them (to increase the signal collecting area and hence sensitivity) and spread them apart (to increase resolution). Second, astronomical objects emit powerful radio waves, making it simpler to record these signals at individual antennas for subsequent correlation. Optical sources, however, are usually much, much fainter—so faint, in fact, that telescopes often must accumulate a celestial target's light literally one photon at a time, turning interference into a quantum-mechanical phenomenon. Third, Earth's atmosphere distorts optical light, leaving telescopes little time in which to collect the photons before the overlying layers of turbulent air disrupt their phase or coherence.

Such constraints have limited the baselines of optical interferometers—that is, the longest separations between any linked telescopes. For example, the Center for High Angular Resolution Astronomy (CHARA) is an array of six one-meter optical telescopes operating at Mount Wilson Observatory in California, and it boasts a maximum baseline of 330 meters. And the European Southern Observatory's GRAVITY interferometer, which connects four 8.2-meter telescopes at Paranal Observatory in Chile, has a maximum baseline of 130 meters. "The most impressive interferometer of any kind in the world is the ESO Gravity instrument," Bland-Hawthorn says. "Now imagine ESO Gravity [with a baseline of] over a kilometer, three kilometers or 10 kilometers."

With conventional optics technology, such concepts would remain elusive. The photons collected by each telescope have to be sent via optical fibers to some location where they can be combined. Also, photons from some telescopes may have to be kept in abeyance in "delay lines," often involving optical fibers, to ensure that the light from all telescopes has traveled the same distance. If the transmission or delay lines get too long—which occurs well short of kilometer scales—the photons are eventually absorbed or scattered, making interference impossible.

It is impossible, at least, without a helping hand from quantum physics. In 2011 Daniel Gottesman of the Perimeter Institute for Theoretical Physics in Ontario and his colleagues suggested putting a source of entangled photons midway between two distant telescopes. The source sends one of a pair of entangled photons to each telescope, where the particles are made to interfere with another photon received from a celestial target. The interference measurements in each telescope can be recorded and later used to reconstruct an interferogram. Although this may sound simple in principle, longer baselines for optical interferometry would require quantum repeaters—expensive and complex custom-built devices for distributing entanglement over great distances that are the antithesis of off-the-shelf tech.

Now Bland-Hawthorn has teamed up with quantum technologist John Bartholomew of the University of Sydney and Matthew Sellars of the Australian National University in Canberra to design optical interferometers that avoid the use of entangled photons and quantum repeaters. The basic idea is simple: Consider two eight-meter telescopes separated by tens of kilometers. The quantum states of the photons collected by each telescope—meaning the amplitude and phase of light as a function of time—are stored in quantum hard drives. Astronomers would physically transport these QHDs—by road, rail or air—to one location, where the quantum states would be read out and made to interfere, generating an interferogram.

Bartholomew and his colleagues have been working together on QHDs that could one day be used to build such an interferometer. In 2015 the group argued that photonic states could be stored in the nuclear spin states of certain ions in a crystal of europium-doped yttrium orthosilicate (or, more simply, Eu:YSO). In theory, in a crystal kept at a frosty temperature of two kelvins, the spin states should remain coherent for up to a month and a half, Bartholomew says. In a lab-based demonstration, his team managed a more modest but still impressive result, showing it could keep the spin states coherent for six hours. "We used to joke about putting the memory system in the back of a Toyota Corolla and driving down the highway," he says. "You'd be able to go quite a distance."

But the 2015 experiment did not store photonic states in the spin states and retrieve them later. It merely demonstrated that the spin states remained coherent for hours. In a December 2020 preprint study, Chuan-Feng Li of the University of Science and Technology of China and his colleagues reported using Eu:YSO crystals to store the coherent states of photons and retrieve them after an hour, verifying their fidelity via interference experiments. "It is a great idea to connect distant optical telescopes via QHDs," Li says. "It should be feasible to do so using the quantum memories based on Eu:YSO that we are working on. The QHD can be transported by trucks and helicopters."

Nora Tischler, a quantum physicist at Free University Berlin, who was not involved with any of this work, is also impressed by the idea of using QHDs to build optical interferometers. "Even though the proposal is technically very demanding, it is worth noting that this can take advantage of already (and independently) existing developments and efforts," she says. "The quantum community is working hard to optimize quantum memories as part of the effort to build future quantum networks." These memories could form the basis of quantum hard drives.

Bartholomew says that the next step is to ensure that QHDs are resilient against the vibrations and accelerations they would experience during transport. "The impact of those forces on the quantum storage needs to be characterized," he says. "But the reason for optimism is that these nuclear spin states are very insensitive to those types of perturbations."

Even so, there is no guarantee the technique will be a practical success. And it has a competitor. In 2019 Johannes Borregaard, now at Delft University of Technology in the Netherlands, and his colleagues augmented Gottesman's 2011 solution by designing a method to compress the information being received by telescopes, keeping only the relevant photons and discarding the rest. This would then require interactions with far fewer entangled photon pairs, which are difficult to produce at rates necessary for interferometry if the incoming information at the telescopes is not first compressed. And even with compression, longer baselines would still warrant quantum repeaters. Borregaard says it is still unclear whether QHDs or a combination of entangled photons and quantum repeaters will be the first to solve the problem of optical interferometry. "Both of them are challenging," he says.

Even if the quantum side of the equation can be solved, astronomer John Monnier, an expert in optical and infrared interferometry at the University of Michigan, is circumspect. Optical interferometers with longer and longer baselines will be observing smaller and fainter objects, meaning fewer photons per unit of time. To counter the atmosphere's deleterious effects, astronomers always have the very expensive option of making telescopes bigger—or the extraordinarily expensive one of putting them in space, where there is no atmosphere at all. Alternatively, they can use adaptive optics, which involves using the light of a bright reference object that is close in the sky to the star or galaxy being observed to correct for the atmosphere's blurring effects. But unlike in radio astronomy, where luminous sources are relatively abundant, in optical wavelengths, "it's super rare to find a bright object [close to] whatever you want to study," Monnier says.

It is possible that in the future, optical interferometers with large baselines will also employ the kind of adaptive optics used by individual telescopes today, which involves firing powerful lasers to create artificial reference stars, or guide stars, in the sky. But today's laser guide stars are not suitable for interferometers with baselines of tens of kilometers. Given such constraints, building optical interferometers is going to require more than QHDs, Monnier says. "[QHDs] could be a very interesting piece of a future that also involves some kind of new laser guide star for interferometers or large telescopes."

If that future comes to pass, Bland-Hawthorn says that a whole new era of optical astronomy will open up, particularly with interferometers using 30- and 39-meter telescopes that are being built in Hawaii and Chile, respectively.

Bland-Hawthorn also envisages being able to resolve white dwarfs such as Sirius B and binary systems into their component stars, measure stars' size and their intrinsic speed across the sky (also called proper motion) with greater precision and resolve, in finer detail, the stars moving around the black hole at our galactic center. "Tracking the stars around the black hole will allow us to probe the general theory of relativity in new ways," Bland-Hawthorn says.

Outside the Milky Way, he thinks 40-meter-class telescopes connected by QHDs will resolve stars in galaxies out to the Virgo cluster and also measure the proper motions of these galaxies. "This last experiment has key implications for the study of how large-scale structure evolves with cosmic time because of the underlying dark matter and the emergence of dark energy," Bland-Hawthorn says.

Even tiny pieces of space debris can have catastrophic effects. This image shows the result of a lab-test impact between a block of aluminum and a small aluminum sphere traveling at nearly seven kilometers per second.

ESA

Space Junk Removal Is Not Going Smoothly

Despite promising technology demonstrations, there is no one-size-fits-all solution for the growing problem of taking out the orbital trash

By Leonard David

Leonard David is a veteran space journalist and author of *Moon Rush: The New Space Race*, published by *National Geographic* in May 2019.

A SPACE AGE "TRAGEDY of the commons" is unfolding right under our nose—or, really, right over our head—and no consensus yet exists on how to stop it. For more than half a century, humans have been hurling objects into low-Earth orbit in ever growing numbers. And with few meaningful limitations on further launches into that increasingly congested realm, the prevailing attitude has been persistently permissive: in orbit, it seems, there is always room for one more.

After so many decades of the buildup of high-speed clutter in the form of spent rocket stages, stray bolts and paint chips, solid-rocket-motor slag, dead or dying satellites, and the scattered fragments from antisatellite tests—all of which could individually damage or destroy other assets—low-Earth orbit is finally on the verge of becoming too crowded for comfort. And the problem is now poised to get much worse because of the rise of satellite "mega constellations" requiring thousands of spacecraft, such as SpaceX's Starlink, a broadband Internet network. Starlink is but one of many similar projects: Another mega constellation from a company called OneWeb is already being deployed. And Amazon's Project Kuiper is seeking to create a mega constellation of up to 3,200 satellites in the near future.

As the congestion has grown, so, too, have close calls between orbiting assets. The International Space Station, for instance, regularly tweaks its orbit to avoid potentially hazardous debris. Worse yet, there has been an uptick in the threat of full-on collisions that generate menacing refuse that exacerbates the already bad situation. Consider the February 2009 run-in between a dead Russian Cosmos satellite and a commercial Iridium spacecraft, which produced an enormous amount of debris.

Finding ways to remove at least some of all that space junk should be a top global priority, says Donald Kessler, a retired NASA senior scientist for orbital debris research. In the late 1970s he foretold the possibility of a scenario that has been dubbed the Kessler syndrome: as the density of space rubbish increases, a cascading, self-sustaining runaway cycle of debris-generating collisions can arise that might ultimately make low-Earth orbit too hazardous to support most space activities.

"There is now agreement within the community that the debris environment has reached a 'tipping point' where debris would continue to increase even if all launches were stopped," Kessler says. "It takes an Iridium-Cosmos-type collision to get everyone's attention. That's what it boils down to.... And we're overdue for something like that to happen."

As for the Kessler syndrome, "it has already started," the debris expert says. "There are collisions taking place all the time—less dramatic and not at the large-size scale," Kessler adds.

UP AND OUT

Kessler's nightmare scenario has yielded no shortage of possible debris-flushing fixes: nets, laser blasts, harpoons, giant foam balls, puffs of air, tethers and solar sails—as well as garbage-gathering robotic arms and tentacles—have all been proposed as solutions for taking out our orbital trash.

A new entrant in grappling with this worrisome state of affairs is the just launched End-of-Life Services by Astroscale Demonstration (ELSA-d) mission. ELSA-d is a two-satellite mission developed by Astroscale, a Japan-based satellite services company: it consists of a "servicer" satellite designed to safely remove debris from orbit and a "client" one that doubles as an object of interest. The project aims to showcase a magnetic system that can capture stable and even tumbling objects, whether for disposal or servicing in orbit. Following a multiphase test agenda, the servicer and client will then deorbit together, disintegrating during their fiery plunge into Earth's atmosphere.

ELSA-d is now circling in Earth orbit. The mission was lofted on March 22 via a Russian Soyuz rocket that tossed scads of other hitchhiking satellites into space. Following the liftoff, Astroscale's founder and CEO Nobu Okada said ELSA-d will prove out debris-removal capabilities and "propel regulatory developments and advance the business case for end-of-life and active debris removal services." The launch is a step toward realizing "safe and sustainable development of space for the benefit of future generations," he said.

Although ELSA-d and other technology demonstrations of its ilk are unquestionably positive developments for clearing orbital debris, they should not be mistaken for cure-alls. Despite their modest successes, such missions are falling short of addressing the dynamic dilemma at hand, and the proliferation of space junk continues essentially unabated.

ONE-SIZE-FITS-ALL SOLUTION?

“From my perspective, the best solution to dealing with space debris is not to generate it in the first place,” says T. S. Kelso, a scientist at CelesTrak, an analytic group that keeps an eye on Earth-orbiting objects. “Like any environmental issue, it is easier and far less expensive to prevent pollution than to clean it up later. Stop leaving things in orbit after they have completed their mission.”

There simply is no “one-size-fits-all solution” to the problem of space junk, Kelso says. Removing large rocket bodies is a significantly different task than removing the equivalent mass of a lot more smaller objects, which are in a wide range of orbits, he observes. Meanwhile innovations by companies such as SpaceX are dramatically lowering launch costs, opening the floodgates for far more satellites to reach low-Earth orbit, where some will inevitably fail and become drifting, debris-generating hazards (unless they are removed by ELSA-d-like space tugs). “Many of these operators are starting to understand the difficulty and complexity of continuing to dodge the growing number of debris.”

Space junk ranges from nanoparticles to whole spacecraft such as the European Space Agency’s Envisat, which is the size of a double-decker bus and at the top of everyone's removal hit list, says Alice Gorman, a space archaeologist and space junk expert at Flinders University in Australia.

There are also objects such as despin weights, which are solid lumps of metal, and thermal blankets, which are paper-thin. “They’ll cause different types of damage and may need different strategies to remove. There is no way that a one-size-fits-all approach is going to do it,” Gorman says.

The most serious risks, she says, come from debris particles between one and 10 centimeters in size. “There’s far more of them than whole defunct spacecraft, and there is a far greater probability of collision,” Gorman says. “While debris this size might not cause a catastrophic breakup, collision with it can certainly damage working satellites and create new debris particles.”

Turning her attention to satellite mega constellations, Gorman worries about their effects in a low-Earth orbital environment that is already congested. “We also know that orbital dynamics can be unpredictable,” she says. “I want to see some of these mega constellation operators releasing their long-term modeling for collisions as more and more satellites are launched.”

There is no doubt that active orbital debris removal is technically challenging, Gorman says. “However, the big issue is that any successful technology that can remove an existing piece of debris can also be used as an antisatellite weapon,” she says. “This is a whole other can of worms that requires diplomacy and negotiation and, most important, trust at the international level.”

Indeed, the ability to cozy up to spacecraft in orbit and perform servicing or sabotage has spurred considerable interest from military planners in recent years, says Mariel Borowitz, an associate professor at the Georgia Institute of Technology’s Sam Nunn School of International Affairs. “These rapidly advancing technologies have the potential to be used for peaceful space activities or for warfare in space,” she says. “Given the dual-use nature of their capabilities, it’s impossible to know for sure in advance how they’ll be used on any given day.”

TAKING UP SPACE

For now, according to Moriba Jah, an orbital debris expert at the University of Texas at Austin, the business case for space debris removal is not monetizable and is more a “PowerPoint talk” than a real marketplace.

“I think people are hoping that government basically comes to some common sense to help create and establish a marketplace for industries to engage in these sorts of activities,” Jah says. For that to happen, he believes that spacefaring nations have to agree that near-Earth space is an ecosystem like land, air and the ocean. “It’s not infinite, so we need environmental protection,” he says.

Jah has in mind space sustainability metrics akin to a carbon footprint. “Let’s call it a ‘space traffic’ footprint,” he says. “We need a way we can quantify at what point an ‘orbital highway’ gets saturated with traffic so that it’s not usable. Then you can assign a bounty for objects and talk about nonconsensual debris removal. Maybe there is a penalty to the sovereign owner of their dead asset that’s taking up capacity of an orbit. This could definitely create a marketplace where space-object-removal technologies can thrive.”

A classification scheme for objects in space is also needed. Having such a taxonomy, Jah says, would help sort out what types of technologies are required for removing different pedigrees of orbital clutter.

As for the big picture, Jah says it is a simple numbers game: the rate of launches exceeds the rate of space objects reentering Earth’s atmosphere. “That’s not a great kind of energy balance,” he adds.

Alas, Jah says, policy makers are still sluggish in their reactions to the problem. After all, although events such as the 2009 Cosmos-Iridium collision generate massive amounts of debris, they are still quite rare—for now.

“In my view, that 2009 collision was equivalent to passengers on the *Titanic* feeling that bump from an iceberg, and then there’s a band playing on deck,” Jah says. “In terms of hazardous orbital debris, things are already going a detrimental way because we haven’t changed our behavior.”

Sabine Hossenfelder is a physicist and research fellow at the Frankfurt Institute for Advanced Studies in Germany. She is author of the book *Lost in Math: How Beauty Leads Physics Astray* (Basic Books, 2018) and creator of the YouTube channel Science without the Gobbledygook.

PHYSICS

Is the Standard Model of Physics Now Broken?

The discrepancy between the theoretical prediction and the experimentally determined value of the muon's magnetic moment has become slightly stronger with a new result from Fermilab. But what does it mean?

Muon g-2 magnetic storage ring, seen here during its relocation from Brookhaven National Laboratory on Long Island to the Fermi National Accelerator Laboratory in Batavia, Ill., is a central component of the project's quest for new physics.

ALAMY

The so-called muon anomaly, first seen in an experiment at Brookhaven National Laboratory in 2001, hasn't budged. For 20 years, this slight discrepancy between the calculated value of the muon's magnetic moment and its experimentally determined one has lingered at a significance of about 3.7 sigma. That is a confidence level of 99.98 percent, or about a one-in-4,500 chance the discrepancy is a random fluctuation. With the recently announced results from the Muon g-2 experiment at Fermi National Laboratory in Batavia, Ill., the significance has increased to 4.2 sigma. That is a confidence level of about 99.997 percent, or about a one-in-40,000 chance for the observed deviation to be a coincidence. By itself, the new Fermilab measurement has only 3.3 sigma significance, but because it reproduces the earlier finding from Brookhaven, the combined significance has risen to 4.2 sigma. Still, the latter falls short of particle physicists' five-sigma discovery threshold.

The result has been long-awaited because of its potential to finally break the Standard Model of particle physics, a collection of the so far known fundamental constituents of matter that has been in place for about 50 years. This model currently contains a couple of dozen particles, but most of them are unstable and therefore can't be found just by looking at the matter that normally surrounds us. The unstable particles are, however, naturally produced in highly energetic events, such as when cosmic rays hit the upper atmosphere. They are also made in lab-created particle collisions, such as those used in the Fermilab experiments to measure the muon's magnetic moment.

What does the persistence of the anomaly mean? High-precision experiments at low energy, such as this one, complement high-energy experiments. They can provide similar information because, in principle, all the contributions from high energies are also present at low energies.

The muon was one of the first unstable particles known, with its discovery dating back to 1936. It is a heavier version of the electron, and like the latter particle, it is electrically charged. The muon has a lifetime of about two microseconds. For particle physicists, that's a long time, which is why the particle lends itself to precision measurements. The muon's magnetic moment determines how fast the particle's spin axis orbits around magnetic field lines. To measure it at Fermilab, physicists create muons and keep them going in a circle of about 15 meters in diameter with powerful magnets. The muons eventually decay, and from the distribution of the decay products, one can infer the their magnetic moment.

The result is usually quoted as the "g-2," where "g" is the magnetic moment. The "2" is included because the value is close to two—and in the deviations from two are the quantum contributions that physicists are interested in. These contributions come from vacuum fluctuations that contain all particles, albeit in virtual form: they only appear briefly before disappearing again. This means that if there are more particles than those in the Standard Model, they should contribute to the muon g-2—hence its relevance. A deviation from the Standard Model prediction could therefore mean that there are more particles than those that are currently known—or that there is some other new physics, such as additional dimensions of space.

So how are we to gauge the 4.2-sigma discrepancy between the Standard Model's prediction and the new measurement? First of all, it is helpful to remember the reason that particle physicists use the five-sigma standard to begin with. The reason is not so much that particle physics is somehow intrinsically more precise than other areas of science or that particle physicists are so much better at doing experiments. It's primarily that particle physicists have a lot of data. And the more data you have, the more likely you are to find random fluctuations that coincidentally look like a signal. Particle physicists began to commonly use the five-sigma criterion in the mid-1990s to save themselves from the embarrassment of having too many "discoveries" that later turn out to be mere statistical fluctuations.

But of course, five sigma is an entirely arbitrary cut, and particle physicists also discuss anomalies well below that limit. Indeed, quite a few three- and four-sigma anomalies have come and gone over the years. The Higgs boson, for example, was already "discovered" in 1996, when a signal of about four sigma appeared at the Large Electron-Positron Collider (LEP) at CERN near Geneva—and then disappeared again. (The Higgs was conclusively detected in 2012 by LEP's successor, the Large Hadron Collider, or LHC.) Also in 1996 quark substructures were found at around three sigma. They, too, disappeared.

In 2003 signs of supersymmetry—a conjectured extension of the Standard Model that introduces new particles—were seen at LEP, also at around three sigma. But soon they were gone. At the LHC in 2015, we saw the diphoton anomaly, which lingered around four sigma before it vanished. There have also been some stunning six-sigma discoveries that were not confirmed, such as the 1998 "superjets" at Fermilab's

Tevatron (even now no one really knows what they were) or the 2004 pentaquark sighting at the Hadron-Electron Ring Accelerator (HERA) accelerator in Germany (pentaquarks weren't actually detected until 2015).

This history should help you gauge how seriously to take any particle physics claim with a statistical significance of 4.2 sigma. But of course, the g-2 anomaly has in its favor the fact that its significance has gotten stronger rather than weaker.

What does the persistence of the anomaly mean? High-precision experiments at low energy, such as this one, complement high-energy experiments. They can provide similar information because, in principle, all the contributions from high energies are also present at low energies. It's just that they are very small—we're talking about a discrepancy between experiment and theory at the 11th digit after the decimal point.

In practice, this means that the calculations for the predictions have to exactly account for a lot of tiny contributions to reach the required precision. In particle physics, these calculations are done using Feynman diagrams—little graphs with nodes and links that denote particles and their interactions. They are a mathematical tool to keep track of which integrals must be calculated.

These calculations become more involved with higher precision because there are more and bigger diagrams. For the muon g-2, physicists had to calculate more than 15,000 diagrams. Although computers help greatly in the task, these calculations remain quite challenging.

A particular headache is the hadronic contribution. Hadrons are composite particles made of several quarks held together by gluons. Calculating these hadronic contributions to the g-2 value is notoriously difficult, and it is currently the largest source of error on the theoretical side. There are of course also various cross-measurements that play a role, such as the predictions that depend on the values of other constants, including the masses of leptons and coupling constants.

Thus, the discrepancy could rather mundanely mean that there's something wrong with the Standard Model calculation, with the hadronic contributions as the primary suspect. But there is also the possibility that the shortcoming lies within the Standard Model itself and not our calculation.

Maybe the discrepancy comes from new particles—supersymmetric particles are the most popular candidates. The problem with this explanation is that supersymmetry isn't a model—instead it's a property of a large number of models, with different models from that greater whole each yielding different predictions. Among other things, the g-2 contributions depend on the masses of the hypothetical supersymmetric particles, which are unknown. So for now it's impossible to attribute the discrepancy to supersymmetry in particular.

Fermilab's new high-precision measurement of the magnetic moment is a remarkable experimental achievement. But it's too soon to declare the Standard Model broken.

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Sarah Tuttle is an assistant professor of astronomy at the University of Washington.
Lucianne Walkowicz is an astronomer at the Adler Planetarium in Chicago and co-founder of the JustSpace Alliance.
Brian Nord is a scientist at Fermi National Accelerator Laboratory and the University of Chicago.

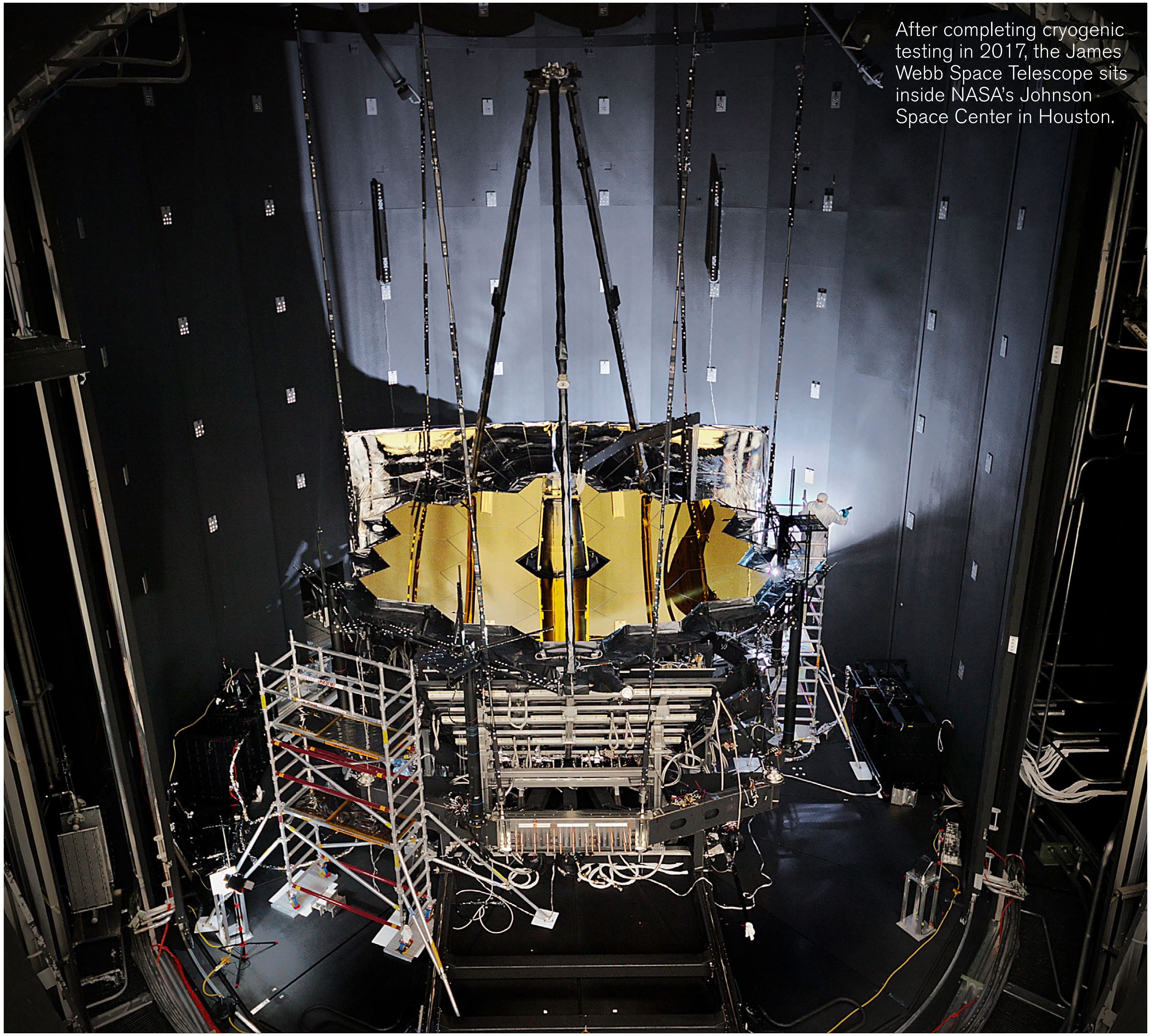
POLICY & ETHICS

The James Webb Space Telescope Needs to Be Renamed

The successor to the Hubble currently honors a man who acquiesced to homophobic government policies during the 1950s and 1960s

Because of its ability to see more deeply into spacetime than any instrument before it, the Hubble Space Telescope has completely transformed the way we see the universe—and ourselves. The James Webb Space Telescope (JWST), often called "the next Hubble," promises to do even better. Slated to launch later this year, JWST will peer farther into the universe than any optical or infrared telescope before it and could show us galaxies in their infancy, probe potentially habitable worlds and explore the mysteries of dark energy. These kinds of data not only provide insight into the universe but also help us humans situate our earthly concerns in context.

It is unfortunate, therefore, that NASA's current



After completing cryogenic testing in 2017, the James Webb Space Telescope sits inside NASA's Johnson Space Center in Houston.

CHRIS GUNN NASA

plan is to launch this incredible instrument into space carrying the name of a man whose legacy at best is complicated and at worst reflects complicity in homophobic discrimination in the federal government.

James Webb, who died in 1992, was a career civil servant whose time at the U.S. Department of State under President Harry S. Truman included advancing the development of psychological warfare as a cold war tool. He later oversaw the Apollo program as NASA administrator. When he arrived at NASA in 1961, his leadership role meant he was in part responsible for implementing what was by then federal policy: the purging of LGBT individuals from the workforce. When he was at State, this policy was enforced by those who worked under him. As early as 1950, he was aware of this policy, which was a forerunner to the antigay witch hunt known today as the lavender scare. Historian David K. Johnson's 2004 book on the subject, *The Lavender Scare,* discusses archival evidence indicating that Webb, along with others in State Department leadership, was involved in Senate discussions that ultimately kicked off a devastating series of federal policies.

Many astronomers feel a debt of gratitude for Webb's work as NASA administrator and are appreciative of and nostalgic for the time during the Apollo program when the space agency thrived. But while appreciation and nostalgia are important, they are not sufficient. Webb might have played a positive role at NASA, but his greater legacy beyond the agency is also relevant. Now that we know of Webb's silence at State and his actions at NASA, we think it is time to rename JWST. The name of such an important mission, which promises to live in the popular and scientific psyche for decades, should be a reflection of our highest values.

The allegations of Webb's complicity in persecution received broader public attention about six years ago. Although some astronomers reacted with dismay at the time, many in the community believed the opportunity to rename the telescope had passed. More recently, an astronomer attempted to refute Webb's negative image in an unreviewed blog post, including by highlighting the fact that a homophobic quote was misattributed to Webb on his Wikipedia page. Astronomers on social media began to argue that in the absence of this specific quote, there was little to prove that Webb was responsible for homophobic policies.

But that correction changes nothing. Webb was in leadership as the lavender scare unfolded. Additional archival evidence, easily found by Columbia University astronomer Adrian Lucy, underlines Webb's role as a facilitator of homophobic policy discussions with members of the Senate. In particular, in 1950 assistant secretary of state Carlisle Humelsine submitted a set of memos to Webb that included “objectives and methods of operation of the Senate Committee established to look into the problem,” which Webb then shared during a meeting with Senator Clyde Hoey of North Carolina. The records clearly show that Webb planned and participated in meetings during which he handed over homophobic material. There is no record of him choosing to stand up for the humanity of those being persecuted.

As someone in management, Webb bore responsibility for policies enacted under his leadership, including homophobic ones that were in place when he became NASA administrator. Some argue that if Webb was complicit, so was everyone working in the agency's administration at the time. We agree. But NASA is not launching a telescope named after its entire administration.

Some might be tempted to see the proposal to rename JWST as an attempt to litigate decades-old history. In fact, discrimination against queer people, including scientists, still affects their lives and careers. In 2016 the American Physical Society released the LGBT Climate in Physics report. Its core conclusion was that many queer scientists fundamentally do not feel safe in their workplaces. The climate is exclusionary, and physicists who identify as more than one minority, including LGBT+ physicists of color, experience the most harassment and exclusion. Astrophysicists who are LGBTQIA+ (lesbian, gay, bisexual, transgender, queer, intersex and asexual and/or ally, plus nonstraight identities not explicitly listed) exist and are marginalized. A 2021 study published in *Science Advances* found similar outcomes.

These practices are a continuation of history that dates back to Webb's era. Frank Kameny was an astronomer who was hired by the U.S. Army Map Service in 1957. When he was unwilling to provide information about his sexual orientation, he was investigated and subsequently fired. He could not find justice through the courts at that time, but he did spend the rest of his life as an activist. Kameny's case is a clear example of homophobic injustice during the era when Webb was active.

The same hypermasculinist fears that characterized the lavender scare and other ideological purges during the cold war continue to animate the incarnation of far-right movements across the globe. So what signal does it send to current and future generations of scientists when we prioritize the legacies of complicit government officials over the dreams of the next generation? With the launch of JWST just a few months away and a new presidential administration (and new NASA administrator) taking the helm, NASA has an opportunity to choose a new namesake that will embrace a future of freedom and inspiration for all.

This struggle is not limited to science or to the past: Just a few months ago Representative Joaquin Castro of Texas introduced the LOVE Act of 2020, which "requires the State Department to set up an independent commission to review the cases of individuals who were fired since the 1950s as a result of their sexual orientation, receive testimony, and correct employment records." Passage of the act would not only prompt an apology from Congress for its past complicity in the lavender scare but also provide protections for queer diplomats at home and abroad.

James Webb's legacy is the antithesis of the dreaming and sense of freedom inspired by the exploration of deep time and distant space. We will use this new telescope to learn about the origins of galaxies, the atmospheres of exoplanets and the nature of dark energy, which will offer insight into the fate the universe holds for us. We hope we have already learned some lessons about how humanity will move toward the future here on Earth rather than repeating mistakes of the past. There will always be complications in naming monuments or facilities after individuals. No hero is perfect.

Yet we can honor the incredible heroes who worked tirelessly to liberate others. Before she became a conductor on the Underground Railroad, a disabled and enslaved Harriet Tubman almost certainly used the North Star, just as it is documented that others did, to navigate her way to freedom. Naming the next Hubble the Harriet Tubman Space Telescope (HTST) would ensure that her memory lives always in the heavens that gave her and so many others hope. It could also serve as a reminder that the night sky is a shared heritage that belongs to all of us, including LGBTQIA+ people.

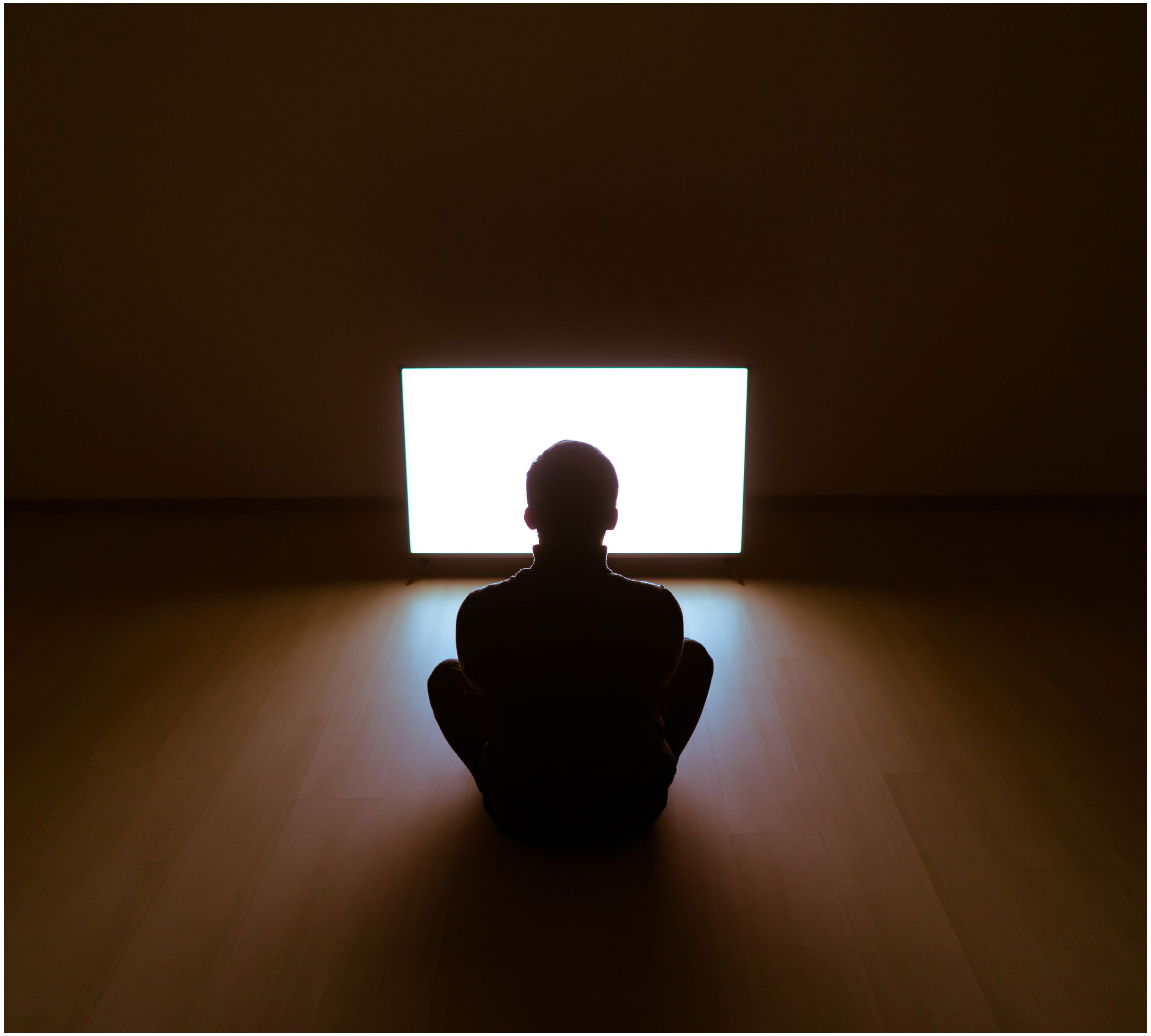
The time for lionizing leaders who acquiesced in a history of harm is over. We should name telescopes out of love for those who came before us and led the way to freedom—and out of love for those who are coming up after.

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 immensely popular blog Cross Check for *Scientific American.*

PHYSICS

Quantum Mechanics, the Chinese Room Experiment and the Limits of Understanding

All of us, even physicists, often process information without really knowing what we're doing



ARTEM PERETIATKO *GETTY IMAGES*

Like great art, great thought experiments have implications unintended by their creators. Take philosopher John Searle's Chinese room experiment. Searle concocted it to convince us that computers don't really "think" as we do; they manipulate symbols mindlessly, without understanding what they are doing.

Searle meant to make a point about the limits of machine cognition. Recently, however, the Chinese room experiment has goaded me into dwelling on the limits of human cognition. We humans can be pretty mindless, too, even when engaged in a pursuit as lofty as quantum physics.

Some background. Searle first proposed the Chinese room experiment in 1980. At the time, artificial-intelligence researchers, who have always been prone to mood swings, were cocky. Some claimed that machines would soon pass the Turing test, a means of determining whether a machine "thinks."

Computer pioneer Alan Turing proposed in 1950 that questions be fed to a machine and a human. If we cannot distinguish the machine's answers from the human's, then we must grant that the machine does indeed think. Thinking, after all, is just the manipulation of symbols, such as numbers or words, toward a certain end.

Some AI enthusiasts insisted that "thinking," whether carried out by neurons or transistors, entails conscious understanding. Marvin Minsky espoused this "strong AI" viewpoint when I interviewed him in 1993. After defining consciousness as a record-keeping system, Minsky asserted that LISP software, which tracks its own computations, is "extremely conscious," much more so than humans. When I expressed skepticism, Minsky called me "racist."

Back to Searle, who found strong AI annoying and wanted to rebut it. He asks us to imagine a man who doesn't understand Chinese sitting in a room. The room contains a manual that tells the man how to respond to a string of Chinese characters with another string of characters. Someone outside the room slips a sheet of paper with Chinese characters on it under the door. The man finds the right response in the manual, copies it onto a sheet of paper and slips it back under the door.

Computer pioneer Alan Turing proposed in 1950 that questions be fed to a machine and a human. If we cannot distinguish the machine's answers from the human's, then we must grant that the machine does indeed think.

Unknown to the man, he is replying to a question, like "What is your favorite color?," with an appropriate answer, like "blue." In this way, he mimics someone who understands Chinese even though he doesn't know a word. That's what computers do, too, according to Searle. They process symbols in ways that simulate human thinking, but they are actually mindless automatons.

Searle's thought experiment has provoked countless objections. Here's mine. The Chinese room experiment is a splendid case of begging the question (not in the sense of raising a question, which is what most people mean by the phrase nowadays, but in the original sense of circular reasoning). The meta-question posed by the Chinese room experiment is this: How do we know whether any entity, biological or nonbiological, has a subjective, conscious experience?

When you ask this question, you are bumping into what I call the solipsism problem. No conscious being has direct access to the conscious experience of any other conscious being. I cannot be absolutely sure that you or any other person is conscious, let alone that a jellyfish or smartphone is conscious. I can only make inferences based on the behavior of the person, jellyfish or smartphone.

Now, I assume that most humans, including those of you reading these words, are conscious, as I am. I also suspect that Searle is probably right and that an "intelligent" program like Siri only mimics understanding of English. It doesn't feel like anything to be Siri, which manipulates bits mindlessly. That's my guess, but I can't know for sure because of the solipsism problem.

Nor can I know what it's like to be the man in the Chinese room. He may or may not understand Chinese; he may or may not be conscious. There is no way of knowing, again, because of the solipsism problem. Searle's argument assumes that we can know what's going on, or not going on, in the man's mind and, hence by implication, what's going on or not in a machine. His flawed initial assumption leads to his flawed, question-begging conclusion.

That doesn't mean the Chinese room experiment has no value. Far from it. The *Stanford Encyclopedia of Philosophy* calls it "the most widely discussed philosophical argument in cognitive science to appear since the Turing Test." Searle's thought experiment continues to pop up in my thoughts. Recently, for example, it nudged me toward a disturbing conclusion about quantum mechanics, which I've been struggling to learn over the last year or so.

Physicists emphasize that you cannot understand quantum mechanics without understanding its underlying mathematics. You should have, at a minimum, a grounding in logarithms, trigonometry, calculus (differential and integral), and linear algebra. Knowing Fourier transforms wouldn't hurt.

That's a lot of math, especially for a geezer and former literature major like me. I was thus relieved to discover *Q Is for Quantum* by physicist Terry Rudolph. He explains superposition, entanglement and other key quantum concepts with a relatively simple mathematical system, which involves arithmetic, a little algebra, and lots of diagrams with black and white balls falling into and out of boxes.

Rudolph emphasizes, however, that some math is essential. Trying to grasp quantum mechanics without any math, he says, is like "having van Gogh's *Starry Night* described in words to you by someone who has only seen a black-and-white photograph. One that a dog chewed."

But here's the irony. Mastering the mathematics of quantum mechanics doesn't make it easier to understand and might even make it harder. Rudolph, who teaches quantum mechanics and co-founded a quantum-computer company, says he feels "cognitive dissonance" when he tries to connect quantum formulas to sensible physical phenomena.

Indeed, some physicists and philosophers worry that physics education focuses too narrowly on formulas and not enough on what they mean. Philosopher Tim Maudlin complains in *Philosophy of Physics: Quantum Theory* that most physics textbooks and courses do not present quantum mechanics as a theory, that is, a description of the world; instead they present it as a "recipe," or set of mathematical procedures, for accomplishing certain tasks.

Learning the recipe can help you predict the results of experiments and design microchips, Maudlin acknowledges. But if a physics student "happens to be unsatisfied with just learning these mathematical techniques for making predictions and asks instead what the theory claims about the physical world, she or he is likely to be met with a canonical response: Shut up and calculate!"

In his book, Maudlin presents several attempts to make sense of quantum mechanics, including the pilot-wave and many-worlds models. His goal is to show that we can translate the Schrödinger equation and other formulas into intelligible accounts of what's happening in, say, the double-slit experiment. But to my mind, Maudlin's ruthless examination of the quantum models subverts his intention. Each model seems preposterous in its own way.

Pondering the plight of physicists, I'm reminded of an argument advanced by philosopher Daniel Dennett in *From Bacteria to Bach and Back: The Evolution of Minds.* Dennett elaborates on his long-standing claim that consciousness is overrated, at least when it comes to doing what we need to do to get through a typical day. We carry out most tasks with little or no conscious attention.

Dennett calls this "competence without comprehension." Adding insult to injury, he suggests that we are virtual "zombies." When philosophers refer to zombies, they mean not the clumsy, grunting cannibals of *The Walking Dead* but creatures that walk and talk like sentient humans but lack inner awareness.

When I reviewed Dennett's book, I slammed him for downplaying consciousness and overstating the significance of unconscious cognition. Competence without comprehension may apply to menial tasks like brushing your teeth or driving a car but certainly not to science and other lofty intellectual pursuits. Maybe Dennett is a zombie, but I'm not! That, more or less, was my reaction.

But lately I've been haunted by the ubiquity of competence without comprehension. Quantum physicists, for example, manipulate differential equations and matrices with impressive competence—enough to build quantum computers!—but no real understanding of what the math means. If physicists end up like information-processing automatons, what hope is there for the rest of us? After all, our minds are habituation machines, designed to turn even complex tasks—like being a parent, husband or teacher—into routines that we perform by rote, with minimal cognitive effort.

The Chinese room experiment serves as a metaphor not only for physics but also for the human condition. Each of us sits alone within the cell of our subjective awareness. Now and then we receive cryptic messages from the outside world. Only dimly comprehending what we are doing, we compose responses, which we slip under the door. In this way, we manage to survive, even though we never really know what the hell is happening.

Avi Loeb is former chair (2011–2020) of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the Board on Physics and Astronomy of the National Academies and the advisory board for the Breakthrough Starshot project and is a member of the President's Council of Advisors on Science and Technology. Loeb is the bestselling author of *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth* (Houghton Mifflin Harcourt, 2021).

SPACE

When Did Life First Emerge in the Universe?

We don't know, but we could try to find out by searching for it on planets orbiting the very oldest stars

About 15 million years after the big bang, the entire universe had cooled to the point where the electromagnetic radiation left over from its hot beginning was at about room temperature. In a 2013 paper, I labeled this phase as the "habitable epoch of the early universe." If we had lived at that time, we wouldn't have needed the sun to keep us warm; that cosmic radiation background would have sufficed.

Did life start that early? Probably not. The hot, dense conditions in the first 20 minutes after the big bang produced only hydrogen and helium, along with a tiny trace of lithium (one in 10 billion atoms) and a negligible abundance of heavier elements. But life as we know it requires water and organic compounds, whose existence had to wait until the first stars fused hydrogen and helium into oxygen and carbon in their

Artist's conception of GN-z11, the earliest known galaxy in the universe.

PABLO CARLOS BUDASSI *WIKIMEDIA* (CC BY-SA 4.0)

interiors about 50 million years later. The initial bottleneck for life was not a suitable temperature, as it is today, but rather the production of the essential elements.

Given the limited initial supply of heavy elements, how early did life actually start? Most stars in the universe formed billions of years before the sun. Based on the cosmic star formation history, I showed in collaboration with Rafael Batista and David Sloan that life near sunlike stars most likely began over the most recent few billion years in cosmic history. In the future, however, it might continue to emerge on planets orbiting dwarf stars, like our nearest neighbor, Proxima Centauri, which will endure hundreds of times longer than the sun's. Ultimately it would be desirable for humanity to relocate to a habitable planet around a dwarf star like Proxima Centauri b, where it could keep itself warm near a natural nuclear furnace for up to 10 trillion years into the future (stars are merely fusion reactors confined by gravity, with the benefit of being more stable and durable than the magnetically confined versions that we produce in our laboratories).

As far as we know, water is the only liquid that can support the chemistry of life—but there is much we don't know. Could alternative liquids have existed in the early universe as a result of warming by the cosmic radiation background alone? In a new paper with Manasvi Lingam, we show that ammonia, methanol and hydrogen sulfide could exist as liquids just after the first stars formed and that ethane and propane might be liquids somewhat later. The relevance of these substances to life is unknown, but they can be studied experimentally. If we ever succeed in creating synthetic life, as is being attempted in Jack Szostak's laboratory at Harvard University, we could check whether life can emerge in liquids other than water.

One way to determine how early life started in the cosmos is to examine whether it formed on planets around the oldest stars. Such stars are expected to be deficient in elements heavier than helium, which astrophysicists call "metals." (In our language, unlike that of most people, oxygen, for example, is considered a metal.) Indeed, metal-poor stars have been discovered in the periphery of the Milky Way and have been recognized as potential members of the earliest generation of stars in the universe. These stars often exhibit an enhanced abundance of carbon, making them "carbon-enhanced metal-poor" (CEMP) stars. My former student Natalie Mashian and I suggested that planets around CEMP stars might be made mostly of carbon, so their surfaces could provide a rich foundation for nourishing early life.

We could therefore search for planets that transit, or pass in front of, CEMP stars and show biosignatures in their atmospheric composition. This would allow us to determine observationally how far back in time life may have started in the cosmos, based on the ages of these stars. Similarly, we could estimate the age of interstellar technological equipment that we might discover floating near Earth (or which might have crashed on the moon), based on long-lived radioactive elements or the extent of scars from impacts of dust particles on its surface.

A complementary strategy is to search for technological signals from early distant civilizations that harnessed enough energy to make them detectable across the vast cosmic scale. One possible signal would be a flash of light from a collimated light beam generated to propel light sails. Others could be associated with cosmic engineering projects, such as moving stars around. Communication signals are not expected to be detectable across the universe, because the signal travel time would require billions of years in each direction and no participant would be patient enough to engage in such a slow exchange of information.

But life's signatures will not last forever. The prospects for life in the distant future are gloomy. The dark and frigid conditions that will result from the accelerated expansion of the universe by dark energy will likely extinguish all forms of life 10 trillion years from now. Until then, we could cherish the temporary gifts that nature has blessed us with. Our actions will be a source of pride for our descendants if they sustain a civilization intelligent enough to endure for trillions of years. Here's hoping that we will act wisely enough to be remembered favorably in their "big history" books.

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