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SCIENTIFIC AMERICAN Space & Physics

New Quantum Restraints on Reality

AN EXPERIMENTAL TWIST ON THE SCHRÖDINGER'S CAT PARADOX COULD OVERTURN CHERISHED ASSUMPTIONS IN METAPHYSICS

Plus:

HOW MANY ALIENS ARE REALLY OUT THERE?

MISSION TO MARS: PERSEVERANCE

TIME'S ARROW MAKES MUSIC

WITH COVERAGE FROM
nature

FROM THE EDITOR

LIZ TORMES

The Most Confused of the Scientific Branches

Quantum researchers seem to have more theories than they know what to do with. Of the handful of options, take, for example, the many-worlds view, which posits that when a quantum observation is made, reality splits into parallel universes, each representing all potential outcomes. Or there is the relatively new QBism camp, members of which argue that quantum mechanics is subjective to the individuals making predictions about how they will measure an experiment. On top of these conflicting theories, any new experimental data invariably support one possible explanation and contradict another. What to make of this confounding research situation? Where some see an impasse, others see opportunity. At the very end of this issue's cover story, Michele Reilly, co-founder of a quantum computing company based in New York City, tells our reporter that such confusion opens the door for novel experiments, of both the theoretical variety and the physical (see "This Twist on Schrödinger's Cat Paradox Has Major Implications for Quantum Theory"). If that's not a pure emblem of the scientific method, then I don't know what is.

Elsewhere in this issue, Anil Ananthaswamy examines the latest estimates of alien life in the universe—estimates that ride on 18th-century statistics (see "How Many Aliens Are in the Milky Way? Astronomers Turn to Statistics for Answers"). And Alexandra Witze gives a dazzling overview of NASA's latest rover project: Perseverance (see "NASA Has Launched the Most Ambitious Mars Rover Ever Built: Here's What Happens Next"). If any field needed the gumption to keep going for the long haul, it's space and physics. Enjoy!

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SPACE & PHYSICS

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On the Cover

An experimental twist on the Schrödinger's cat paradox could overturn cherished assumptions in metaphysics

ANDRZEJ WOJCICKI *Getty Images*

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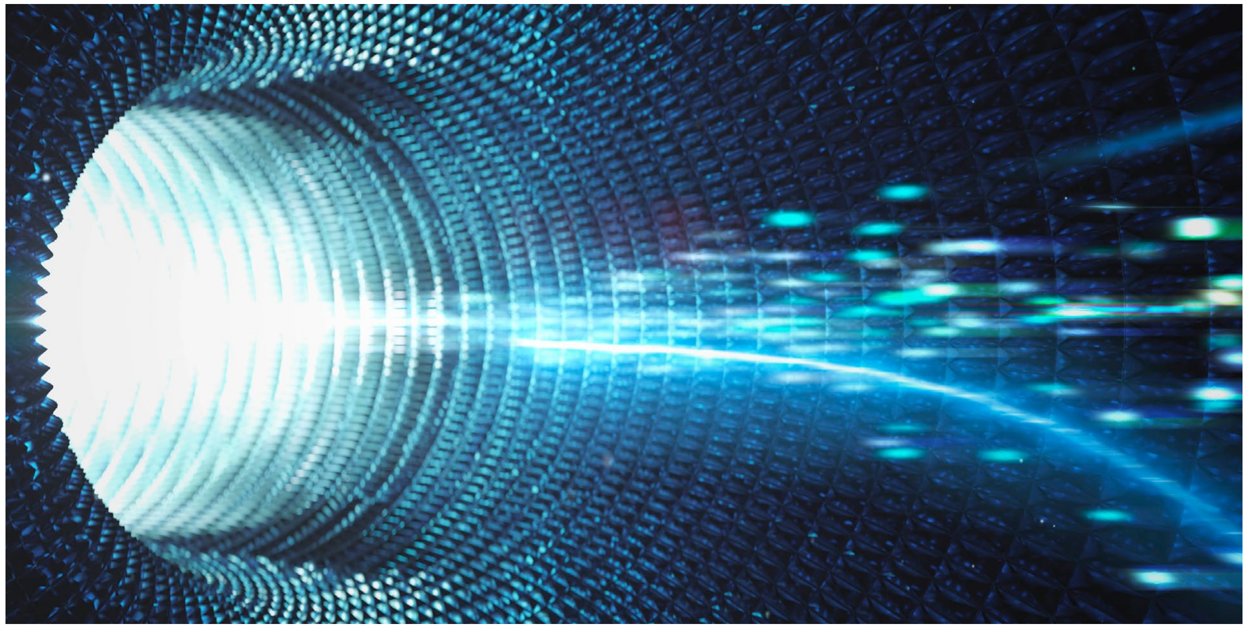

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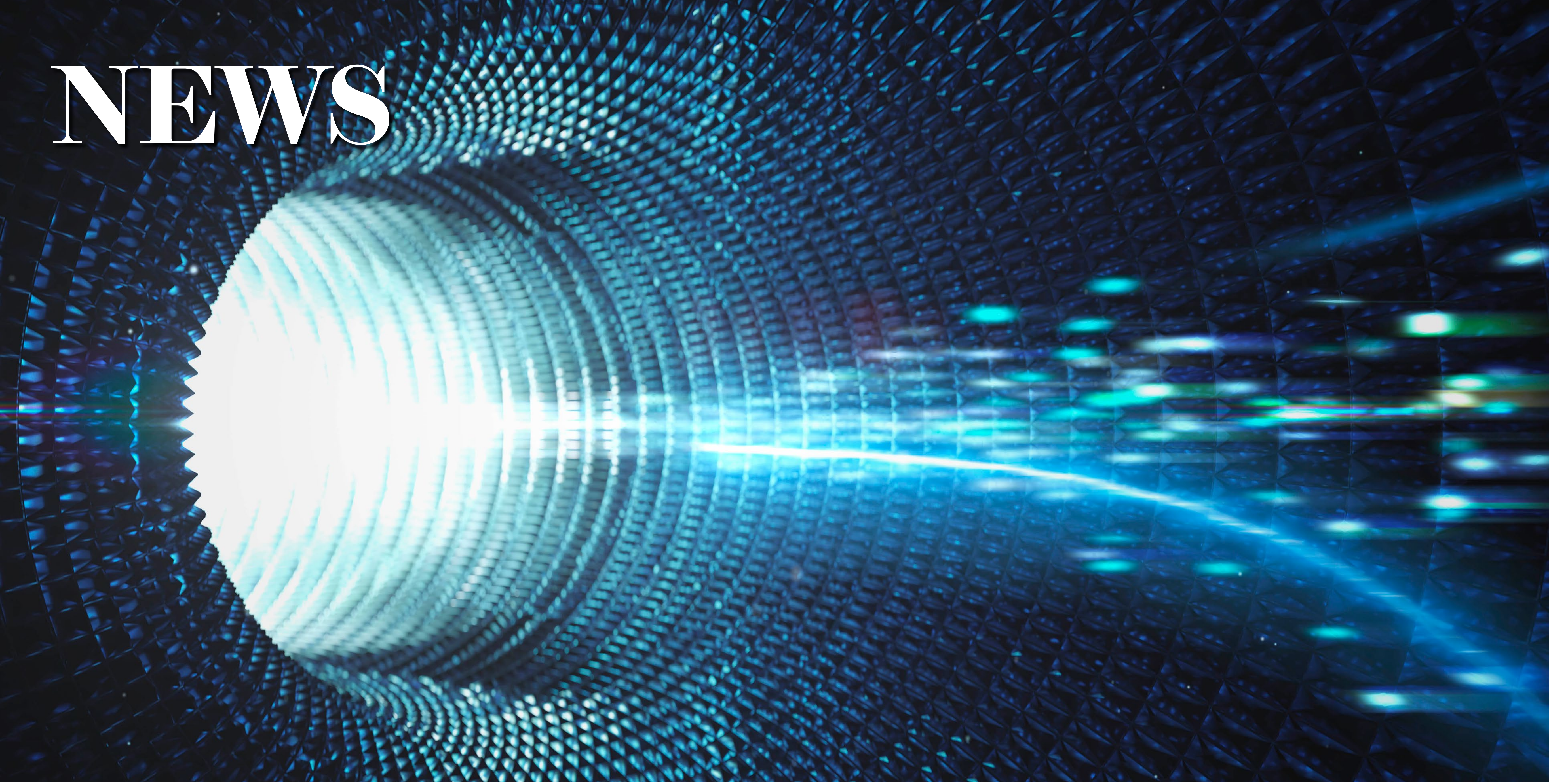


YUICHIRO CHINO *Getty Images*

Quantum Tunneling Is Not Instantaneous, Physicists Show

A new experiment tracks the transit time of particles burrowing through barriers, revealing previously unknown details of a deeply counterintuitive phenomenon

Although it would not get you past a brick wall and onto Platform 9 ¾ to catch the Hogwarts Express, quantum tunneling—in which a particle “tunnels” through a seemingly insurmountable barrier—remains a confounding, intuition-defying phenomenon. Now Toronto-based experimental physicists using rubidium atoms to study this effect have measured, for the first time, just how long these atoms spend in transit through a barrier. Their findings appeared in *Nature* on July 23.

The researchers have showed that quantum tunneling is not instantaneous—at least, in one way of thinking about the phenomenon—despite recent headlines that have suggested otherwise. “This is a beautiful experiment,” says Igor Litvinyuk of Griffith University in Australia, who works on quantum tunneling but was not part of this demonstration. “Just to do it is a heroic effort.”

To appreciate just how bizarre quantum tunneling is, consider a ball rolling on flat ground that encounters a small, rounded hillock. What happens next depends on the speed of the ball. Either it will reach the top and roll down the other side, or it will climb partway uphill and slide back down because it does not have enough energy to get over the top.

This situation, however, does not hold for particles in the quantum world. Even when a particle does not possess enough energy to go over the top of the hillock, sometimes it will still get to the opposite end. “It’s as though the particle dug a tunnel under the hill and appeared on the other side,” says study co-author Aephraim Steinberg of the University of Toronto.

Such weirdness is best understood by thinking of the particle in terms of its wave function, a mathematical representation of its quantum state. The wave function evolves and spreads. And its amplitude at any point in time and space lets you calculate the probability of finding the particle then and there—should you make a measurement. By definition, this probability can be nonzero in many places at once.

If the particle confronts an energy barrier, this encounter modifies the spread of the wave function, which starts to exponentially decay inside the barrier. Even so, some of it leaks through, and its amplitude does not go to zero on the barrier’s far side. Thus, there remains a finite probability, however small, of detecting the particle beyond the barrier.

Physicists have known about quantum tunneling since the late 1920s. Today the phenomenon is at the heart of devices such as tunneling diodes, scanning tunneling microscopes and superconducting qubits for quantum computing.

Ever since its discovery, experimentalists have strived for a clearer understanding of exactly what happens during tunneling. In 1993, for example, Steinberg, Paul Kwiat and Raymond Chiao, all then at the University of California, Berkeley, detected photons tunneling through an optical barrier (a special piece of glass that reflected 99 percent of the incident photons; 1 percent of them tunneled through). The tunneling photons arrived earlier, on average, than photons that traveled the exact same distance but were unimpeded by a barrier. The tunneling photons seemed to be traveling faster than the speed of light.

Careful analysis revealed that it was, mathematically speaking, the peak of the tunneling photons’ wave functions (the most likely place to find the particles) that was traveling at superluminal speed. The leading edges of the wave functions of both the unimpeded photon and the tunneling photon reach their detectors at the same time, however—so there is no violation of Einstein’s theories of relativity. “The peak of the wave function is allowed to be faster than light without information or energy traveling faster than light,” Steinberg says.

“This is a beautiful experiment. Just to do it is a heroic effort.”
—Igor Litvinyuk

Last year Litvinyuk and his colleagues published results showing that when electrons in hydrogen atoms are confined by an external electric field that acts like a barrier, they occasionally tunnel through it. As the external field oscillates in intensity, so does the number of tunneling electrons, as predicted by theory. The team established that the time delay between when the barrier reaches its minimum and when the maximum number of electrons tunnel through was, at most, 1.8 attoseconds (1.8×10^{-18} second). Even light, which travels at about 300,000 kilometers per second, can only travel over three ten-billionths of a meter, or about the size of a single atom, in one attosecond. “[The time delay] could be zero, or it would be some zeptoseconds [10^{-21} second],” Litvinyuk says.

Some media reports controversially claimed that the Griffith University experiment had shown tunneling to be instantaneous. The confusion has a lot to do with theoretical definitions of tunneling time. The type of delay the team measured was certainly almost zero, but that result was not the same as saying the electron spends no time in the barrier. Litvinyuk and his colleagues had not examined that aspect of quantum tunneling.

Steinberg’s new experiment claims to do just that. His team has measured how long, on average, rubidium atoms spend inside a barrier before they tunnel through it. The time is on the order of a millisecond—

nowhere close to instantaneous.

Steinberg and his colleagues started by cooling rubidium atoms down to about one nanokelvin before coaxing them with lasers to move slowly in a single direction. Then they blocked this path with another laser, creating an optical barrier that was about 1.3 microns thick. The trick was to measure how much time a particle spent in the barrier as it tunneled through.

To do so, the team built a version of a so-called Larmor clock using a complicated assemblage of lasers and magnetic fields to manipulate atomic state transitions. In principle, here is what happens: Imagine a particle whose spin points in a certain direction—think of it as a clock hand. The particle encounters a barrier, and inside it is a magnetic field that causes the clock hand to rotate. The longer the particle stays within the barrier, the more it interacts with the magnetic field, and the more the hand rotates. The amount of rotation is a measure of the time spent in the barrier.

Unfortunately, if the particle interacts with a magnetic field strong enough to correctly encode the elapsed time, its quantum state collapses. This collapse disrupts the tunneling process.

So Steinberg's team resorted to a technique known as weak measurement: An ensemble of identically prepared rubidium atoms approaches the barrier. Inside the barrier, the atoms encounter, and barely interact with, a weak magnetic field. This weak interaction does not perturb the tunneling. But it causes each atom's clock hand to move by an unpredictable amount, which can be measured once that atom exits the barrier. Take the average of the clock-hand positions of the ensemble, and you get a number that can be interpreted as representative of the correct value for a single atom—even though one can never do that kind of measurement for an individual atom. Based on such weak measurements, the researchers found that the atoms in their experiment were spending about 0.61 millisecond inside the barrier.

They also verified another strange prediction of quantum mechanics: the lower the energy, or slower the movement, of a tunneling particle, the less time it spends in the barrier. This result is counterintuitive because in our everyday notion of how the world works, a slower particle would be expected to remain in the barrier for a longer stretch of time.

Irfan Siddiqi, a quantum physicist at the University of California, Berkeley, is impressed by the technical sophistication of the experiment. "What we are witnessing now is quite amazing, in that we have the tools to test all of these philosophical musings [of] the last century," he says.

Satya Sainadh Undurti, a co-author of Litvinyuk's 2019 study, who is now at Technion–Israel Institute of Technology, agrees. "The Larmor clock is certainly the right way to go about asking tunneling time questions," he says. "The experimental setup in this paper is a clever and clean way to implement it."

Steinberg admits that his team's interpretation will be questioned by some quantum physicists, particularly those who think weak measurements are themselves suspect. Nevertheless, he thinks the experiment says something unequivocal about tunneling times. "If you use the right definitions, it's not really instantaneous. It may be remarkably fast," he says. "I think that's still an important distinction."

—Anil Ananthaswamy

Scientists Unveil First Ever Pictures of Multiple Planets around a Sunlike Star

The two giant worlds, each much larger than Jupiter, constitute only the third multiplanet system ever imaged

For the first time ever, scientists have managed to capture images of multiple planets twirling about another sunlike star. Yet despite its stellar host's resemblance to our own, the snapshots of this planetary system reveal it to be no place like home.

Named TYC 8998-760-1 and located about 300 light-years from Earth in the constellation Musca, the star is similar in mass to the sun. Its two known planets, however, are distinctly alien—orbiting their star at about 160 and 320 times the Earth-sun distance, respectively (spans that are about four and eight times greater than Pluto's separation from our sun). Both worlds are supersized compared with anything in our solar system. The outermost planet is some six times heavier than Jupiter, and the inner one tips the scales at 14 times Jupiter's mass. Each of the worlds appears as a small dot around the star in images produced by the Spectro-Polarimetric High-contrast Exoplanet Research instrument, or SPHERE, which operates on the European Southern Observatory's Very Large Telescope in northern Chile. The findings are detailed in a study published on July 20 in *Astrophysical Journal Letters*.

"The really fascinating thing about this work is that [it] continues to add to the vast diversity of what systems and planets are out there, orbiting all sorts of stars," says Rebecca Oppenheimer, an astrophysicist at the American Museum of Natural History in New York City, who was not involved with the study. "There is no single 'architecture' for a planetary system."

The new study marks only the third time that scientists have managed to take pictures of—or "directly image"—multiple worlds orbiting a single star. But those previously observed systems were around stars either much heavier or lighter than the sun, making them less comparable to our solar system. Direct imaging remains a rarity in the study of worlds beyond our planetary neighborhood. The vast majority of exoplanets in astronomers' catalogues are known solely through more indirect means: they betray their presence and most basic properties—mass, size and orbit—by periodically tugging on, or silhouetting against, their host stars, as seen from Earth. Directly imaging exoplanets is important, says study lead Alexander Bohn, an astrophysicist at Leiden University in the Netherlands, because by "receiving light from planets, we can better characterize the atmospheres—and elemental abundances of the atmospheres—and the composition." That information, in turn, allows researchers to make more educated guesses about what an alien world's environmental conditions could be—and whether or not it might, like Earth, harbor life.

No one is contemplating life on either of the two newly imaged worlds, however. In addition to being bloated gas giants in frigid orbits with no meaningful surfaces

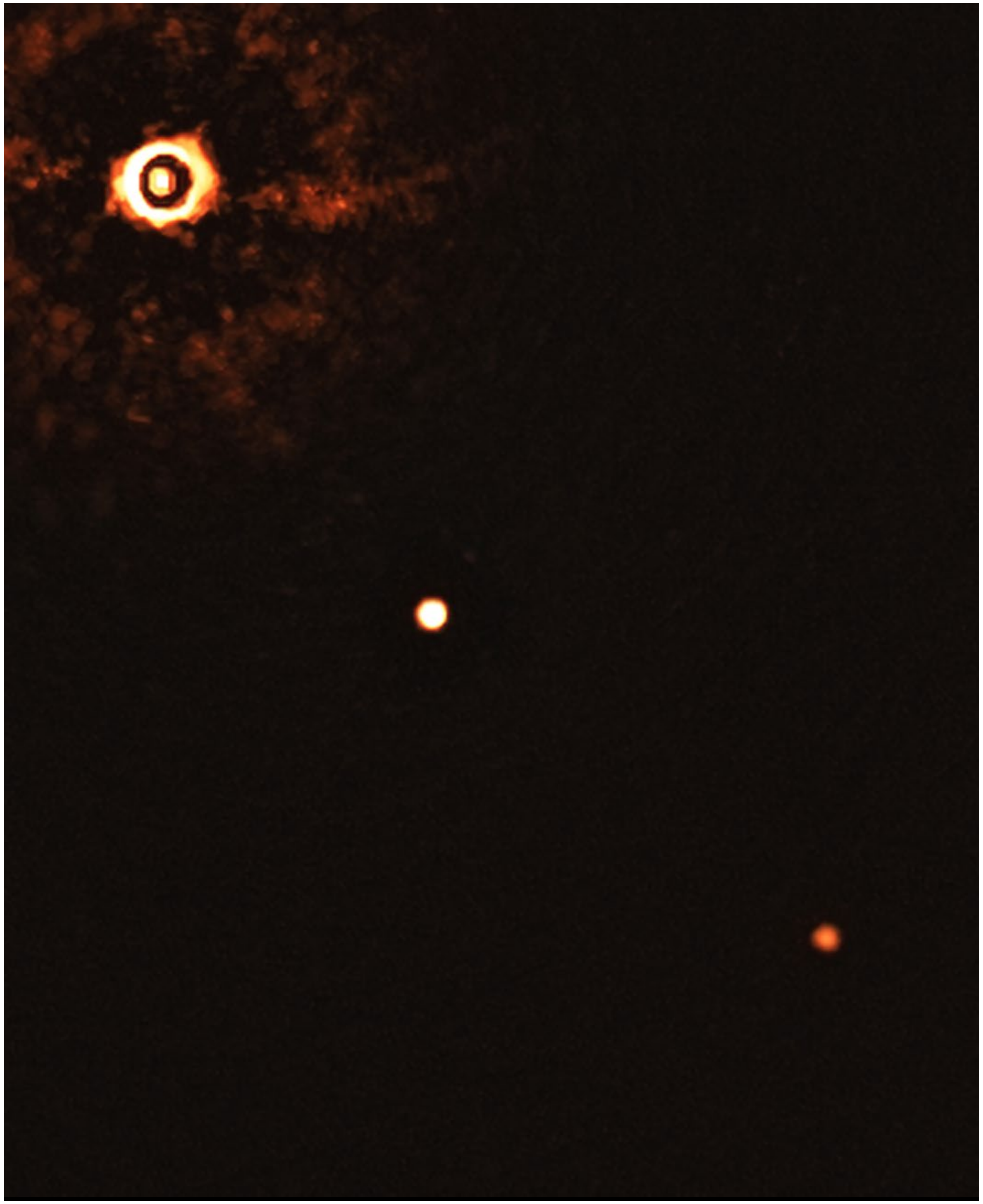


Image of the sunlike star TYC 8998-760-1 (*upper left*), accompanied by two giant exoplanets (*lower right*).

ESO/BOHN ET AL.

on which organisms could dwell, they and their star are far younger than our sun and the planets around it. "The system itself is 17 million years [old]," Bohn says. "And our solar system is 4.5 billion years [old]." Even if they did possess habitable conditions, each world's relatively newborn status would not offer much time for biology to arise from the vagaries of chemistry. And although their planets' size and youth make them poor candidates for life as we know it, these properties are precisely why astronomers can presently see them at all, because of the powerful infrared glow they emit as leftover energy from their formation. Smaller, older, more clement worlds that are closer in to their stars remain out of current planet imagers' reach. But they could eventually be revealed by more powerful instrumentation on gargantuan telescopes. Already three extremely large telescopes (ELTs)—ground-based observatories with mirrors on the order of 30 meters across—are approaching their final stages of development. And astronomers are vigorously lobbying for NASA or other space agencies to launch even more ambitious planet-imaging space telescopes in coming decades.

Even so, "we're an incredibly long way from taking pictures of Earth-sized planets," says Bruce Macintosh, an astrophysicist at Stanford University and principal investigator on the Gemini Planet Imager—another instrument that, along with SPHERE, represents the state of the art in exoplanetary picture taking. "With current technology, we can see a planet that is about one million times fainter than the star. That's amazing. But even Jupiter—the biggest world in our solar system—is a billion times fainter than the sun."

Whether a target planet next to a bright star is a giant gaseous orb or a more Earth-like rock, Bohn says, observing it is like viewing "a firefly right next to a lighthouse, which is maybe a meter away. You want to see this tiny firefly, and you are 500 kilometers away. This is basically the challenge we're dealing with." To gather the extremely faint light of a world, compared with that of its star, SPHERE and most other planet-imaging instruments use a device called a coronagraph, which blocks out almost all of the star's light—effectively dimming the glare from the "lighthouse" so that nearby planetary "fireflies" can be seen.

Besides more nuanced details of any given world, such images can reveal other wonders—and raise important new mysteries—that go to the heart of theorists' still nascent understanding of precisely how planetary systems emerge and evolve. In the newly imaged system, "both planets formed around the same star and are the same age, but one is twice as massive as the other," says Macintosh, who was not involved in the study. "Comparing their properties will help us see how the masses of planets affect their evolution." Further, he adds, subsequent images of the system could reveal more about the planets' orbits—and even the presence of as yet unseen worlds. "Are they aligned the same way planetary orbits in our solar system are aligned? Are they circular?" Macintosh asks. Learning the answers to such questions could show whether these planets formed in the same way as the worlds around our sun or via some other process—and thereby provide another hint as to whether planets and systems such as our own are common or rare. *—Karen Kwon*

Time's Arrow Flies through 500 Years of Classical Music, Physicists Say

A statistical study of more than 8,000 compositions shows how the flow of time distinguishes music from noise

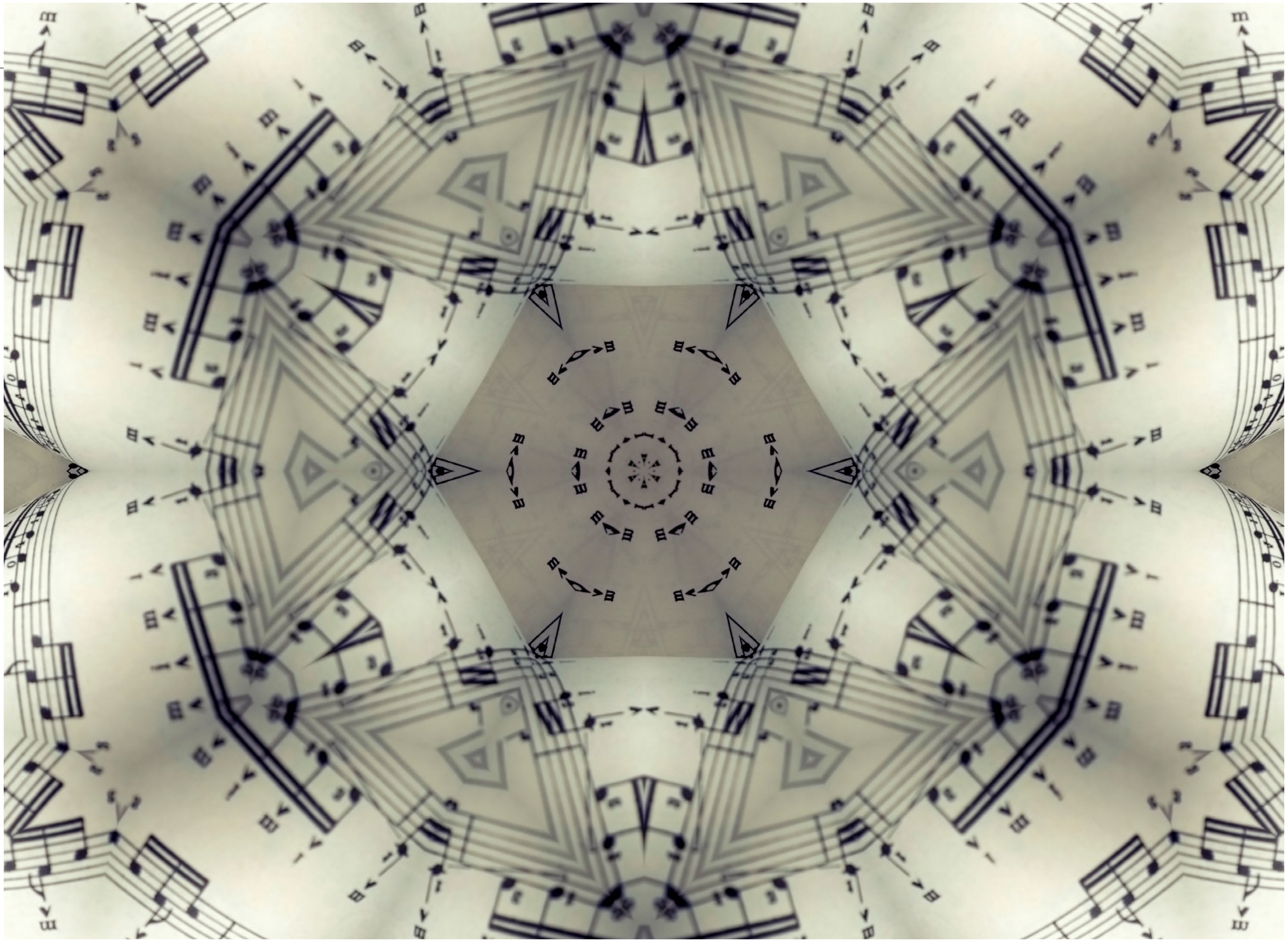
What, exactly, makes music to the ears? Time will tell, according to a new study of five centuries' worth of compositions.

Using techniques derived from statistical mechanics—typically used to study large groups of particles—a team of physicists has mathematically measured the "time irreversibility" of more than 8,000 pieces of Western classical music. Published in *Physical Review Research* in July, the study quantifies what many listeners intuit: noise can sound the same played forward or backward in time, but composed music sounds dramatically different in those two time directions.

Time irreversibility—the existence of an "arrow of time"—is a concept drawn from fundamental physics, first formulated in 1927 by British astronomer Arthur Eddington. But it is meaningful in many contexts, says Lucas Lacasa, a physicist at Queen Mary University of London and a co-author of the study. One can see it in action over breakfast: think of the implausibility of unscrambling an egg and returning it to a pristinely pieced-back-together shell. But until now, Lacasa says, time irreversibility "hasn't been measured at all in music." Lacasa became interested in analyzing music through conversations with co-authors Gustavo Martínez-Mekler of the National Autonomous University of Mexico and Alfredo González-Espinoza of the University of Pennsylvania, both of whom are physicists and musicians. By finding patterns across large bodies of composed music, they were hoping to find hints as to what makes a successful composer.

Compared with systems made of millions of particles, a typical musical composition consisting of thousands of notes is relatively short. Counterintuitively, that brevity makes statistically studying most music much harder, akin to determining the precise trajectory of a massive landslide based solely on the motions of a few tumbling grains of sand. For this study, however, Lacasa and his co-authors exploited and enhanced novel methods particularly successful at extracting patterns from small samples. By translating sequences of sounds from any given composition into specific types of diagrams or graphs, the researchers were able to marshal the power of graph theory to calculate time irreversibility.

This is far from the first statistical study of music. In his 1963 book *Formalized Music,* composer and music theorist Iannis Xenakis used matrices and differential equations to buttress arguments about the nature of music and musical composition. Boldly, he posed that "much like a god, a composer may ... invert Eddington's 'arrow of time.'" But con-



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firmation of this contention proved elusive. The new paper, however, validates the claim: most compositions the researchers studied were found to follow an arrow of time.

Systems that are time-reversible, under statistical analysis, seem the same when the arrow of time is flipped. The unstructured static hiss of white noise is one example. A different kind of noise prevalent in biological systems, dubbed "pink noise," is also time-reversible. And by certain statistical measures, it is almost indistinguishable from music. Specifically, when analyzing how much power each frequency component within a musical piece tends to have, scientists find the same distribution as in pink noise. Consequently, music has been accepted to be a type of pink noise.

The new study challenges this association, demonstrating that despite such basic similarities music has more structure than pink noise and that this structure is meaningful. "Irreversibility gives you an idea of change in time; it approaches the idea of a narrative," Martínez-Mekler says. Music being time-irreversible, then, might reflect a composer's effort to tell a story through the progression of notes.

Time irreversibility is related to a measure of disorder that, in physics, is called entropy. The composition having the most entropy would be a strictly random shuffle of sounds. It would also look the same—fully disordered—in all time directions, thus displaying no arrow of time. Conversely, the most time-irreversible composition would be the one that is the least random, possessing the least amount of entropy and the most structure. In this sense, measuring time irreversibility might reflect how singular a particular composer's style is—the difference, say, between the gaudy violinist Niccolò Paganini and the melancholy lutenist John Dowland.

González-Espinoza, Martínez-Mekler and Lacasa wondered whether the time-irreversibility score their analysis assigned to each composer could accurately reflect the aesthetic properties of that composer's music. Past studies of music as pink noise spurred similar questions. To be enjoyable, it seems, music must strike a balance of predictability and surprise—a property pink noise is considered to possess. "The ordered way in which we create music is sort of an optimization process," says Jesse Berezovsky, a physicist at Case Western Reserve University, who was not involved with the study. He has also used statistical mechanics methods to study music, finding that its rules emerge at the middle ground between dissonance and complexity. In a time-irreversible music piece, the sense of directionality in time may help the listener generate expectations. The most compelling compositions, then, would be those that balance between breaking those expectations and fulfilling them—a sentiment with which anyone anticipating a catchy tune's "hook" would agree.

At the same time, interpreting statistical results can be incredibly complicated. Elizabeth Hellmuth Margulis, director of the Music Cognition Lab at Princeton University, cautions that only melodies were considered in the study. She also raises the issue of cultural factors: listeners from different cultures perceive music differently. As Berezovsky explains, physicists often make simplifying assumptions to capture the essence of otherwise intractably complicated systems. This works well for studying the statistical mechanics of collections of atoms, but it may have limited use for music, which is, for many, more than just a collection of sounds. "Quantitative tools are essential" to statistical studies of music, Margulis says, but combining them with "sensitive cultural insight is more likely to produce useful results."

Martínez-Mekler is excited about how much more there is to learn. For one, the statistical tools he and his co-authors developed could be applied to a wealth of more contemporary and global compositions. Echoing Margulis, he would like to consider harmony and rhythm, in addition to melody, in future analyses.

"Music is a very complicated phenomenon that emerged from many different interactions or constructions in society," González-Espinoza says, acknowledging the complexities inherent to its study. But he trusts that structures we find pleasing in music reflect something about the way we hear our own thoughts play inside our head. This research has only just started to demonstrate that, through composition, great musicians translate some of the patterning of our minds into the orderliness of music.

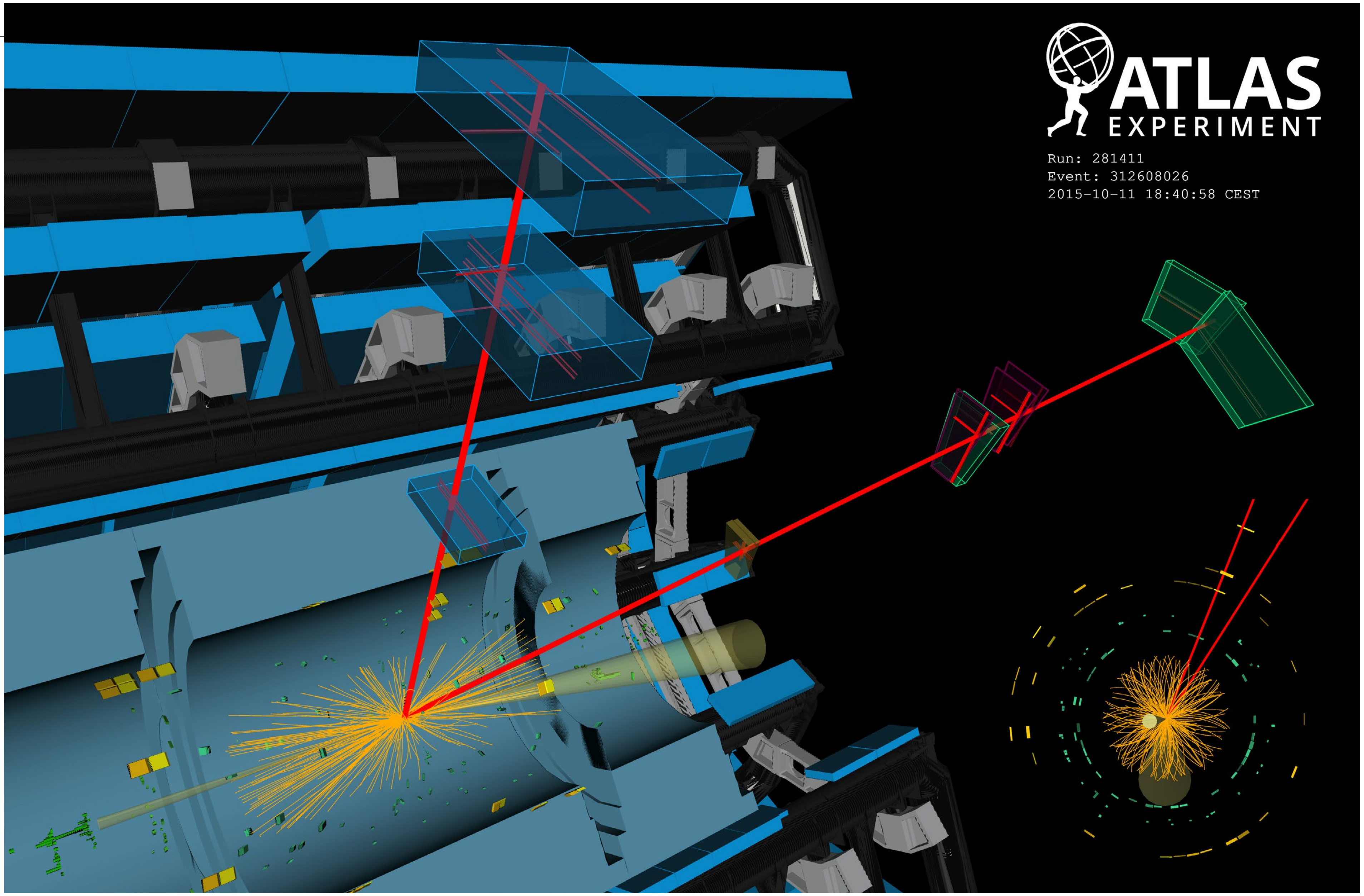
—Karmela Padavic-Callaghan

Higgs Boson Gives Next-Generation Particle Its Heft

Experiments at the Large Hadron Collider suggest that muons and other "second-generation particles" obtain their mass from interacting with the Higgs, further strengthening the Standard Model

In the periodic table, no element is more important than another one. But in the Standard Model—a theory that explains the smallest constituents of the universe and the forces that govern them, minus gravity—the Higgs boson is arguably central. Like other elementary bosons—such as photons, the particles of light—the Higgs is a "force carrier." Instead of carrying the electromagnetic, strong or weak force, it carries mass to all the elementary particles via the so-called Higgs field, which pervades the universe.

Particles that interact, or "couple," strongly with the Higgs field are massive. Those that couple with it weakly are lighter. Photons do not interact with the Higgs at all. And as a result, they have no mass.



Visualization of a collision event in the ATLAS detector containing two muons (*red*) with a mass compatible with that of the Higgs boson and two forward jets (*yellow cones*).

ATLAS COLLABORATION *CERN*

But experimentally proving that all the elementary particles that have mass get it through the Higgs field has remained difficult. Now particle physicists have, for the first time, found direct evidence that this field is the mechanism that gives mass to muons, the heavier cousins of electrons. Analyses from ATLAS and CMS, two experiments at the Large Hadron Collider (LHC) at CERN near Geneva, have shown that the Higgs boson can decay into two muons—which demonstrates that muons couple with the Higgs field, where they get their mass.

Particle physicists are not surprised by the outcome. The Standard Model, which has proved stubbornly accurate, predicts that the Higgs field gives mass to all elementary particles. But to actually confirm that idea, scientists need experimental evidence for each type of particle, says Stefania Gori, a theoretical physicist at the University of California, Santa Cruz, who was not involved with the research.

"Obviously, the Standard Model is a great theory," she says. "But seeing [the Higgs interact] in nature has a very different weight than just assuming it because of our theory."

When a new particle was discovered by ATLAS and CMS in 2012, it was initially dubbed "Higgs-like" because no one knew just how many properties it would share with the Higgs boson that had been postulated by a cohort of physicists in the early 1960s. "I don't think because in 1964 they wrote down something that immediately from one measurement all the other things follow," says Tristan du Pree, an experimental physicist at ATLAS. "That's why I think [a Higgs decaying into two muons] was still a very important test that could have gone and been something else."

As the Higgs boson has passed more tests and grown ever more "Higgs-like," the "like" qualifier has quietly been dropped. But the effort to understand the particle's properties has only grown.

> **"This was the first time there's ever been an interaction between the Higgs and the second generation."**
>
> ***—Marc Sher***

HOW TO FIND A HIGGS

To create a Higgs boson from scratch, physicists smash particles together like a subatomic car crash test. The LHC provides the necessary oomph: it accelerates protons to nearly the speed of light, giving each of them an energy of 6,500 giga-electron volts, or GeV (at rest, protons have an energy of roughly 1 GeV). These accelerated protons circulate through the LHC's 26.7-kilometer-long tunnel until they collide. Such encounters create a spray of particle debris—and, in rare cases, the elusive Higgs boson.

It is not possible to actually observe the Higgs boson, which lasts for about a sextillionth of a second. But scientists can see what particles it decays into. Initial evidence for the Higgs came from it decaying into its fellow bosons.

Particle decays are a matter of random chance described by so-called branching ratios. Each of the many possible decay processes is a "branch" with a certain probability, a bit like rolling a die to choose which road to take at an intersection with many forks. In general, the Higgs—which possesses an energy of 125 GeV—decays most easily into heavy rather than light particles. So, for instance, its decay will create a spray of 4-GeV bottom quarks 10 times more often than a shower of 1-GeV charm quarks. A Higgs boson decaying to two muons (which weigh in at 0.1057 GeV apiece) is relatively rare—it happens only once in 5,000 times. When such a decay does occur, ATLAS and CMS see two muons with a combined energy of 125 GeV flying off in opposite directions.

If combined, the measurement would be statistically significant to more than three sigma, which means there is less than a one-in-700 chance the result is a random fluke, assuming the Higgs does not decay to muons. Such evidence is strong but short of the five-sigma standard (a one-in-3.5-million chance) physicists prefer.

Previously, evidence that the Higgs ever decayed into two muons was so weak that theorists' efforts to come up with models in which the muon got its mass elsewhere were perfectly justified. One proposal by another physicist, which du Pree cheekily referred to as the "TRISTANdard Model," used three different varieties of the Higgs boson to give mass to each generation of particles.

Convention dictates that the 12 fermions (particles of matter) in the Standard Model are divided into three generations. The particles in one generation have counterparts in another that exhibit identical properties and behavior—so far as we can tell—except for their mass. Under this universality, taus are more massive versions of muons, which are merely more massive versions of electrons. And because what we call "mass" is just a result of how much a particle interacts with the Higgs field, the difference between two generations might only be how much each particle couples with the Higgs boson. But until now there was no evidence that the Higgs coupled with fermions outside of the third generation.

"This was the first time there's ever been an interaction between the Higgs and the second generation," says Marc Sher, a theoretical physicist at the College of William & Mary, who was not involved with the research. "It's really a special test of universality because if there was something different with the generations, this might be the first place you would see it."

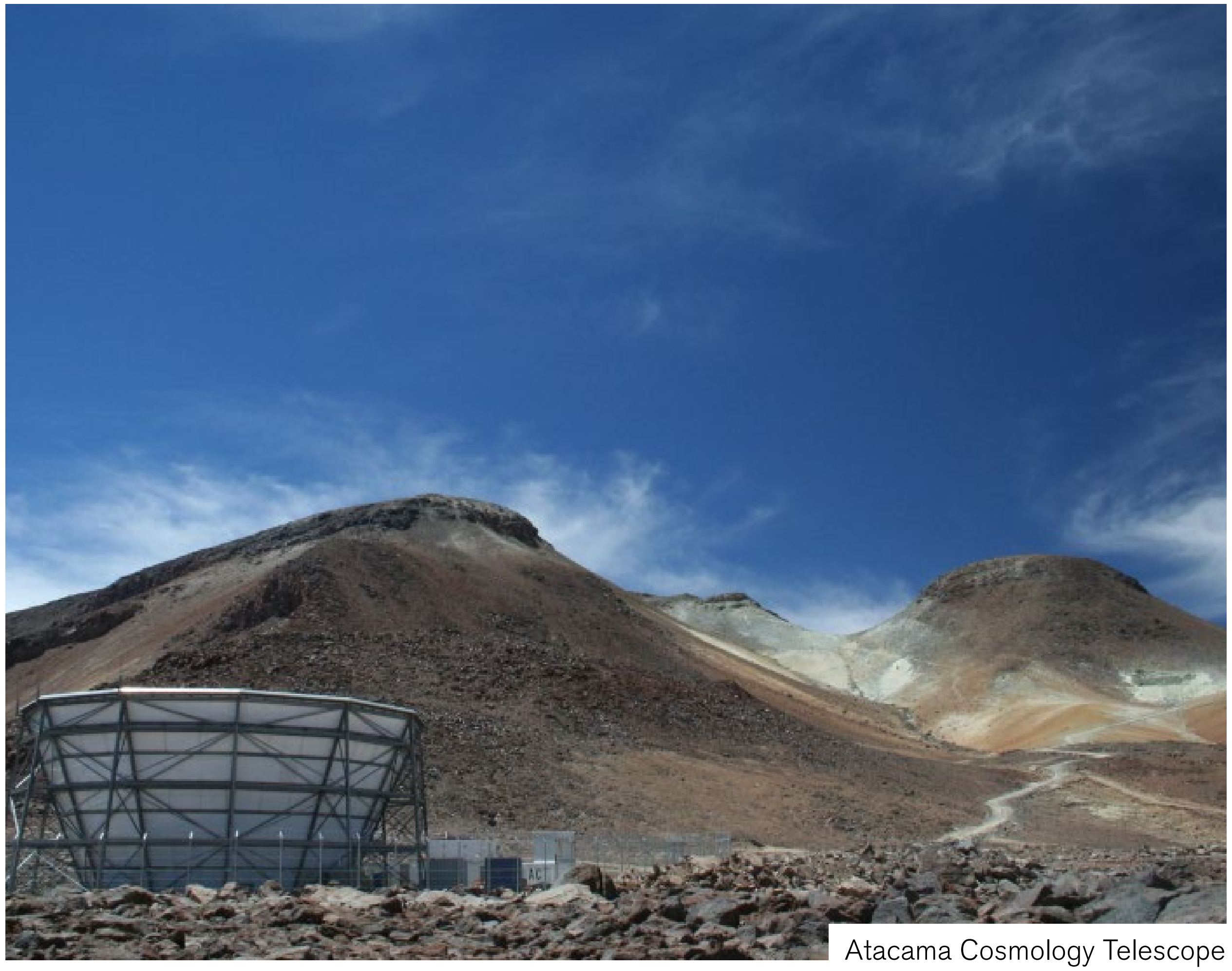
Unfortunately for physicists looking to depart from the predictions of the Standard Model, the muon seems to get its mass from the same place as the tau. But in many ways, the hunt for novel Higgs physics is only beginning.

In June the 2020 report from the European Strategy Group, a consortium of particle physicists who periodically convene to determine research priorities for Europe, stated that its highest-priority goals are investigating the properties of the Higgs. "The Higgs boson is a unique particle that raises profound questions about the fundamental laws of nature," the report states. "It also provides a powerful experimental tool to study these questions."

—Daniel Garisto

Mystery over Universe's Expansion Deepens with Fresh Data

A long-awaited map of the big bang's afterglow fails to settle a debate over how fast the universe is expanding



Atacama Cosmology Telescope

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A new map of the early universe has reinforced a long-running conundrum in astronomy over how fast the cosmos is expanding. The data—collected using a telescope in Chile's Atacama Desert—back up previous estimates of the universe's age, geometry and evolution. But the findings clash with measurements of how fast galaxies are flying apart from one another and predict that the universe should be expanding at a significantly slower pace than is currently observed.

The Atacama Cosmology Telescope (ACT) mapped the cosmic microwave background (CMB), the radiation "afterglow" of the big bang. The findings, based on data collected from 2013 to 2016, were posted on July 15 in two preprints on the arXiv repository.

CMB radiation comes from all directions of space, but it is not perfectly uniform: its variations across the sky reveal that regions of the early universe differed slightly in temperature, by less than 0.03 kelvin. Over the past two decades cosmologists have used those minute variations—together with an established theory they call the Standard Model—to calculate some of the key features of the universe's structure and evolution, including its age and the density of matter.

Cosmologists also use the variations to predict the rate at which the universe is currently expanding, a measure known as the Hubble constant after the U.S. astronomer Edwin Hubble.

The European Space Agency's Planck telescope mapped the entire CMB sky from 2009 to 2013 with unprecedented precision, and its observations are considered the gold standard of CMB cosmology. The ACT data now vindicate Planck's findings and produce a very similar value for the Hubble constant.

But neither result matches direct measurements of the Hubble constant—a discrepancy that has become known as the Hubble-constant tension. Astronomers who use the brightness of particular types of stars and supernova explosions, collectively called standard candles, to calculate the expansion rate find that galaxies rush away from one another roughly 10 percent faster than the CMB maps predict.

Many researchers had hoped that as techniques became more accurate, the gap would shrink. Instead narrowing error bars for each type of study have only made the inconsistency more significant.

The ACT is the first ground-based CMB experiment that could have challenged Planck's results, says Erminia Calabrese, a cosmologist at Cardiff University in Wales, who led the analysis of the data. The telescope's design and location, just inside the tropics, enable it to map more of the CMB sky than other ground-based or balloon-borne telescopes, which have typically been limited to smaller regions.

Mapping the sky on a large scale is crucial for calculating the key parameters of cosmic expansion, Calabrese says. Another strength of the ACT was that an upgrade in 2013 allowed it to make precise measurements of the polarization of the CMB radiation, says principal investigator Suzanne Staggs of Princeton University. Polarization data reveal how galaxies in the foreground affect how the CMB travels and help to make the cosmological measurements more precise.

"For the first time we have two data sets measured independently and with enough precision to make a comparison," Calabrese says. Having also been a member of the Planck team, she says it was a relief to find that the two experiments' Hubble-constant predictions agreed to within 0.3 percent.

This agreement between ACT and Planck on the Hubble constant is "a truly major milestone," says Paul Steinhardt, a theoretical physicist at Princeton. "I am very impressed by the quality of the new data and their analysis," he adds.

"It's always good to have independent checks, and I think this really provides it," says Wendy Freedman, an astronomer at the University of Chicago and a standard-candle pioneer. Adam Riess, an astronomer at Johns Hopkins University, who has led much of the cutting-edge work on standard candles, says that the ACT data's agreement with Planck is "reassuring" and "a testament to the quality of the experimenters' work and carefulness."

But the tension on the Hubble constant remains. Techniques developed by several teams, including one led by Freedman, could help to resolve it. Steinhardt thinks that the measurements will eventually converge as experimentalists perfect their methods.

But Riess says that perhaps it is cosmology's Standard Model that is wrong instead. "My gut feeling is that there's something interesting going on."

—Davide Castelvecchi

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This Photo of the Sun Is the Closest Ever Taken

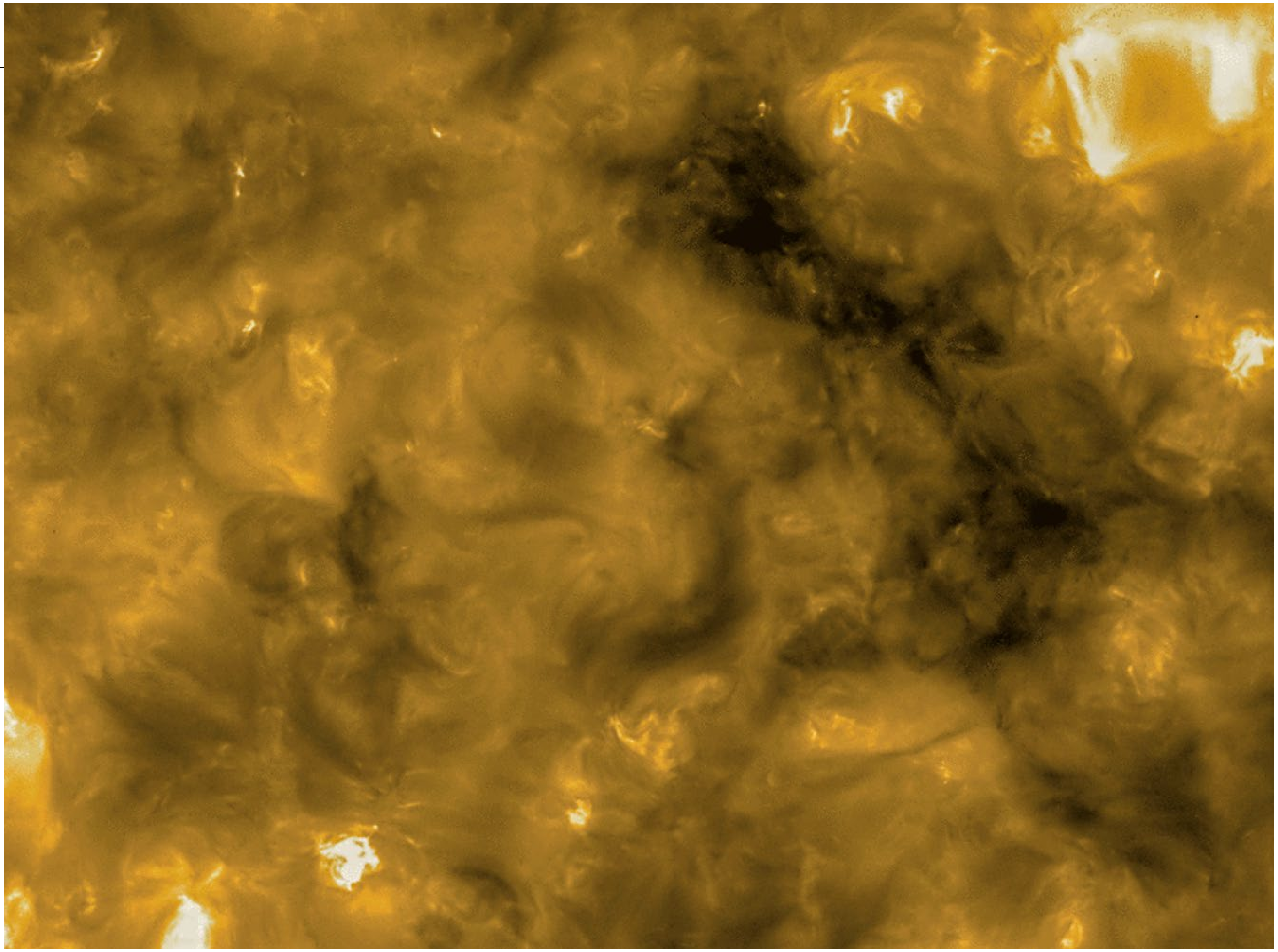
Close-up reveals a surface dancing with "campfires"

This image—the closest ever taken of the sun—shows the corona teeming with thousands of miniature solar flares, which scientists have dubbed "campfires." The pictures are the first released from the Solar Orbiter satellite mission, led by the European Space Agency.

"When the first images came in, my first thought was this is not possible; it can't be that good," David Berghmans, principal investigator for the orbiter's Extreme Ultraviolet Imager instrument, said in a press briefing on July 16. "It was much better than we dared to hope for."

"The sun might look quiet at the first glance, but when we look in detail, we can see those miniature flares everywhere we look," said Berghmans, a solar physicist at the Royal Observatory of Belgium, in a statement.

The fires are millions or billions of



SOLAR ORBITER/EUI TEAM (ESA & NASA); CSL, IAS, MPS, PMOD/WRC, ROB, UCL/MSSL

times smaller than solar flares that can be seen from Earth, which are energetic eruptions thought to be caused by interactions within the sun's magnetic fields. The mission team has yet to figure out whether the two phenomena are driven by the same process, but they speculate the combined effect of the many campfires could contribute to the searing heat of the sun's outer atmosphere, known as the corona. Why the corona is hundreds of times hotter than its surface is a longstanding mystery.

The images, taken by the ultraviolet imager on May 30 and released on July 16, were captured 77 million kilometers from the sun's surface (Earth is about 150 million kilometers from the sun). A daring NASA mission called the Parker Solar Probe has flown even closer and will get within just 6.2 million kilometers during its mission—inside the corona itself—but the environment is so harsh that it does not carry a camera facing the sun. Meanwhile from Earth, the Daniel K. Inoye Solar Telescope in Hawaii has taken higher-resolution images of the sun than the orbiter, but these do not fully capture the star's light because Earth's atmosphere filters out some ultraviolet and x-ray wavelengths.

Scientists are excited about the potential of the Solar Orbiter, an international collaboration that launched in February and carries 10 instruments to image the sun and study its environment. The spacecraft will eventually switch its orbit to study the sun's polar regions for the first time. "We've never been closer to the sun with a camera, and this is just the beginning of a long epic journey with Solar Orbiter, which will take us even closer to the sun in two years' time," said Daniel Müller, the mission's project scientist, at the briefing.

—Elizabeth Gibney

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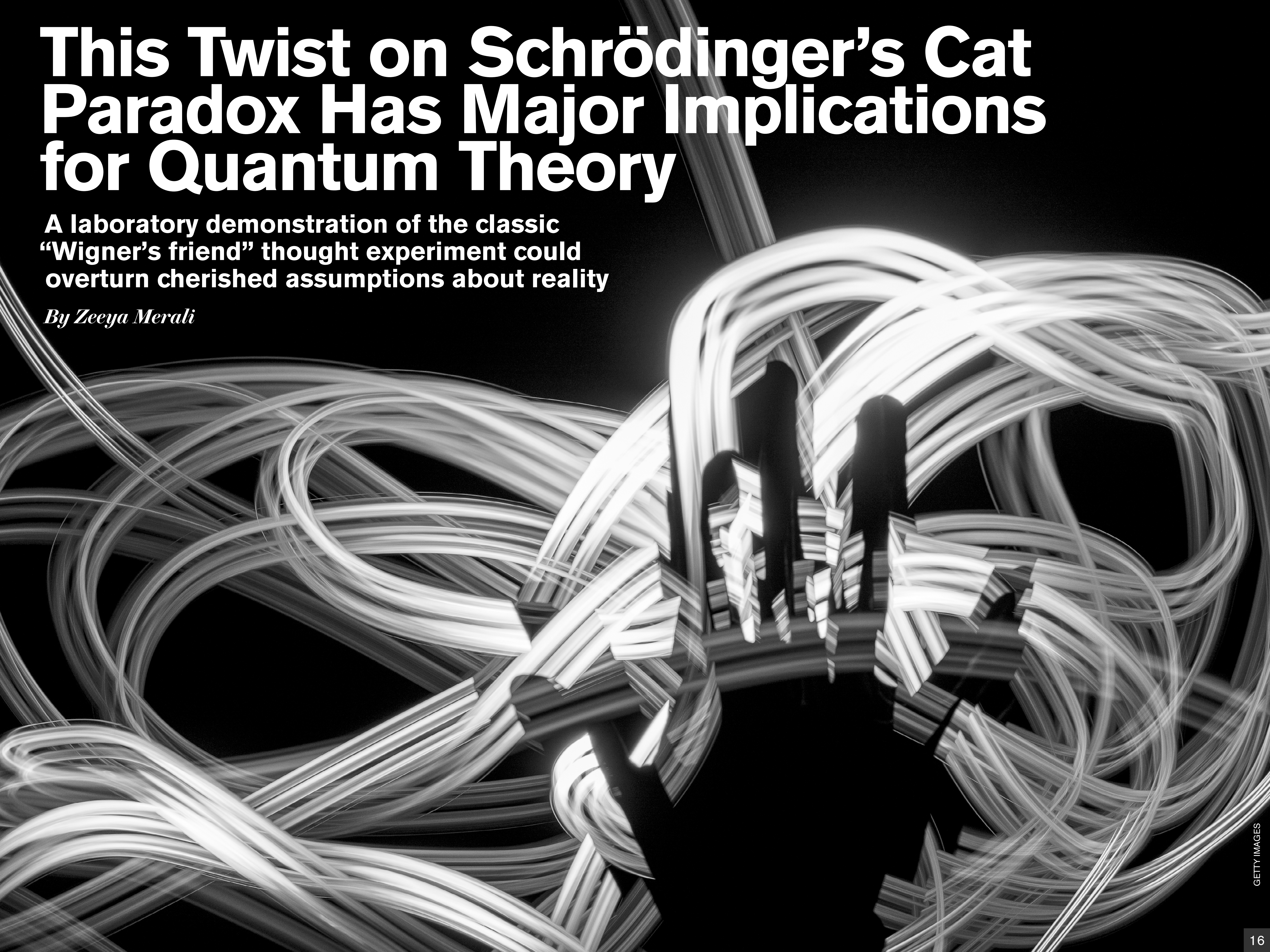
This Twist on Schrödinger’s Cat Paradox Has Major Implications for Quantum Theory

A laboratory demonstration of the classic “Wigner’s friend” thought experiment could overturn cherished assumptions about reality

By Zeeya Merali



GETTY IMAGES

Zeeya Merali is a freelance writer based in London and author of *A Big Bang in a Little Room.*

What does it feel like to be both alive and dead?

That question irked and inspired Hungarian-American physicist Eugene Wigner in the 1960s. He was frustrated by the paradoxes arising from the vagaries of quantum mechanics—the theory governing the microscopic realm that suggests, among many other counterintuitive things, that until a quantum system is observed, it does not necessarily have definite properties. Take his fellow physicist Erwin Schrödinger's famous thought experiment in which a cat is trapped in a box with poison that will be released if a radioactive atom decays. Radioactivity is a quantum process, so before the box is opened, the story goes, the atom has both decayed and not decayed, leaving the unfortunate cat in limbo—a so-called superposition between life and death. But does the cat experience being in superposition?

Wigner sharpened the paradox by imagining a (human) friend of his shut in a lab, measuring a quantum system. He argued it was absurd to say his friend exists in a superposition of having seen and not seen a decay unless and until Wigner opens the lab door. "The 'Wigner's friend' thought experiment shows that things can become very weird if the observer is also observed," says Nora Tischler, a quantum physicist at Griffith University in Brisbane, Australia.

Now Tischler and her colleagues have carried out a version of the Wigner's friend test. By combining the classic thought experiment with another quantum head-scratcher called entanglement—a phenomenon that links particles across vast distances—they have also derived a new theorem, which they claim puts the strongest constraints yet on the fundamental nature of reality. Their study, which appeared in *Nature Physics* on August 17, has implications for the role that consciousness might play in quantum physics—and even whether quantum theory must be replaced.

The new work is an "important step forward in the field of experimental metaphysics," says quantum physicist Aephraim Steinberg of the University of Toronto, who was not involved in the study. "It's the beginning of what I expect will be a huge program of research."

A MATTER OF TASTE

Until quantum physics came along in the 1920s, physicists expected their theories to be deterministic, generating predictions for the outcome of experiments with certainty. But quantum theory appears to be inherently probabilistic. The textbook version—sometimes called the Copenhagen interpretation—says that until a system's properties are measured, they can encompass myriad values. This superposition collapses into a single state only when the system is observed, and physicists can never precisely predict what that state will be. Wigner held the then popular view that consciousness somehow triggers a superposition to collapse. Thus, his hypothetical friend would discern a definite outcome when she or he made a measurement—and Wigner would never see her or him in superposition.

This view has since fallen out of favor. "People in the foundations of quantum mechanics rapidly dismiss Wigner's view as spooky and ill defined because it makes observers special," says David Chalmers, a philosopher and cognitive scientist at New York University. Today most physicists concur that inanimate objects can knock quantum systems out of superposition through a process known as decoherence. Certainly researchers attempting to manipulate complex quantum superpositions in the lab can find their hard work destroyed by speedy air particles colliding with their systems. So they carry out their tests at ultracold temperatures and try to isolate their apparatuses from vibrations.

Several competing quantum interpretations have sprung up over the decades that employ less mystical mechanisms, such as decoherence, to explain how superpositions break down without invoking consciousness. Other interpretations hold the even more radical position that there is no collapse at all. Each has its own weird and wonderful take on Wigner's test. The most exotic is the "many worlds" view, which says that whenever you make a quantum measurement, reality fractures, creating parallel universes to accommodate every possible outcome. Thus, Wigner's friend would split into two copies, and "with good enough supertechnology," he could indeed measure that person to be in superposition from outside the lab, says quantum physicist and many-worlds fan Lev Vaidman of Tel Aviv University.

> **"If you try and manipulate a classical observer—a human, say—and treat it as a quantum system, it would immediately collapse."**
> ***—Angelo Bassi***

The alternative "Bohmian" theory (named for physicist David Bohm) says that at the fundamental level, quantum systems do have definite properties; we just do not know enough about those systems to precisely predict their behavior. In that case, the friend has a single experience, but Wigner may still measure that individual to be in superposition because of his own ignorance. In contrast, a relative newcomer on the block called the QBism interpretation embraces the probabilistic element of quantum theory wholeheartedly. (QBism, pronounced "cubism," is actually short for quantum Bayesianism, a reference to 18th-century mathematician Thomas Bayes's work on probability.) QBists argue that a person can use quantum mechanics only to calculate how to calibrate his or her beliefs about what he or she will measure in an experiment. "Measurement outcomes must be regarded as personal to the agent who makes the measurement," says Ruediger Schack of Royal Holloway, University of London, who is one of QBism's founders. According to QBism's tenets, quantum theory cannot tell you anything about the underlying state of reality, nor can Wigner use it to speculate on his friend's experiences.

Another intriguing interpretation, called retrocausality, allows events in the future to influence the past. "In a retrocausal account, Wigner's friend absolutely does experience something," says Ken Wharton, a physicist at San Jose State University, who is an advocate for this time-twisting view. But that "something" the friend experiences at the point of measurement can depend on Wigner's choice of how to observe that person later.

The trouble is that each interpretation is equally good—or bad—at predicting the outcome of quantum tests, so choosing between them comes down to taste. "No one knows what the solution is," Steinberg says. "We don't even know if the list of potential solutions we have is exhaustive."

Other models, called collapse theories, do make testable predictions. These models tack on a mechanism that forces a quantum system to collapse when it gets too big—explaining why cats, people and other macroscopic objects cannot be in superposition. Experiments are underway to hunt for signatures of such collapses, but as yet they have not found anything. Quantum physicists are also placing ever larger objects into superposition: last year a team in Vienna reported doing so with a 2,000-atom molecule. Most quantum interpretations say there is no reason why these efforts to supersize superpositions should not continue upward forever, presuming researchers can devise the right experiments in pristine lab conditions so that decoherence can be avoided. Collapse theories, however, posit that a limit will one day be reached, regardless of how carefully experiments are prepared. "If you try and manipulate a classical observer—a human, say—and treat it as a quantum system, it would immediately collapse," says Angelo Bassi, a quantum physicist and proponent of collapse theories at the University of Trieste in Italy.

A WAY TO WATCH WIGNER'S FRIEND

Tischler and her colleagues believed that analyzing and performing a Wigner's friend experiment could shed light on the limits of quantum theory. They were inspired by a new wave of theoretical and experimental papers that have investigated the role of the observer in quantum theory by bringing entanglement into Wigner's classic setup. Say you take two particles of light, or photons, that are polarized so that they can vibrate horizontally or vertically. The photons can also be placed in a superposition of vibrating both horizontally and vertically at the same time, just as Schrödinger's paradoxical cat can be both alive and dead before it is observed.

Such pairs of photons can be prepared together—entangled—so that their polarizations are always found to be in the opposite direction when observed. That may not seem strange—unless you remember that these properties are not fixed until they are measured. Even if one photon is given to a physicist called Alice in Australia while the other is transported to her colleague Bob in a lab in Vienna, entanglement ensures that as soon as Alice observes her photon and, for instance, finds its polarization to be horizontal, the polarization of Bob's photon instantly syncs to vibrating vertically. Because the two photons appear to communicate faster than the speed of light—something prohibited by his theories of relativity—this phenomenon deeply troubled Albert Einstein, who dubbed it "spooky action at a distance."

These concerns remained theoretical until the 1960s, when physicist John Bell devised a way to test if reality is truly spooky—or if there could be a more mundane explanation behind the correlations between entangled partners. Bell imagined a commonsense theory that was local—that is, one in which influences could not travel between particles instantly. It was also deterministic rather than inherently probabilistic, so experimental results could, in principle, be predicted with certainty only if physicists understood more about the system's hidden properties. And it was realistic, which, to a quantum theorist, means that systems would have these definite properties even if nobody looked at them. Then Bell calculated the maximum level of correlations between a series of entangled particles that such a local, deterministic and realistic theory could support. If that threshold was violated in an experiment, then one of the assumptions behind the theory must be false.

Such "Bell tests" have since been carried out, with a series of watertight versions performed in 2015, and they have confirmed reality's spookiness. "Quantum foundations is a field that was really started experimentally by Bell's [theorem]—now more than 50 years old. And we've spent a lot of time reimplementing those experiments and discussing what they mean," Steinberg says. "It's very rare that people are able to come up with a new test that moves beyond Bell."

The Brisbane team's aim was to derive and test a new theorem that would do just that, providing even stricter constraints—"local friendliness" bounds—on the nature of reality. Like Bell's theory, the researchers' imaginary one is local. They also explicitly ban "superdeterminism"—that is, they insist that experimenters are free to choose what to measure without being influenced by events in the future or the distant past. (Bell implicitly assumed that experimenters can make free choices, too.) Finally, the team prescribes that when an observer makes a measurement, the outcome is a real, single event in the world—it is not relative to anyone or anything.

Testing local friendliness requires a cunning setup involving two "superobservers," Alice and Bob (who play the role of Wigner), watching their friends Charlie and Debbie. Alice and Bob each have their own interferometer—an apparatus used to manipulate beams of photons. Before being measured, the photons' polarizations are in a superposition of being both horizontal and vertical. Pairs of entangled photons are prepared such that if the polarization of one is measured to be horizontal, the polarization of its partner should immediately flip to be vertical. One photon from each entangled pair is sent into Alice's interferometer, and its partner is sent to Bob's. Charlie and Debbie are not actually human friends in this test. Rather they are beam displacers at the front of each interferometer. When Alice's photon hits the displacer, its polarization is effectively measured, and it swerves either left or right, depending on the direction of the polarization it snaps into. This action plays the role of Alice's friend Charlie "measuring" the polarization. (Debbie similarly resides in Bob's interferometer.)

Alice then has to make a choice: She can measure the photon's new deviated path immediately, which would be the equivalent of opening the lab door and asking Charlie what he saw. Or she can allow the photon to continue on its journey, passing through a second beam displacer that recombines the left and right paths—the equivalent of keeping the lab door closed. Alice can then directly measure her photon's polarization as it exits the interferometer. Throughout the experiment, Alice and Bob independently choose which measurement choices to make and then compare notes to calculate the correlations seen across a series of entangled pairs.

Tischler and her colleagues carried out 90,000 runs of the experiment. As expected, the correlations violated Bell's original bounds—and, crucially, they also violated the new local-friendliness threshold. The team could also modify the setup to tune down the degree of entanglement between the photons by sending one of the pair on a detour before it entered its interferometer, gently perturbing the perfect harmony between the partners. When the researchers ran the experiment with this slightly lower level of entanglement, they found a point where the correlations still violated Bell's bound but not local friendliness. This result proved that the two sets of bounds are not equivalent and that the new local-friendliness constraints are stronger, Tischler says. "If you violate them, you learn more about reality," she adds. Namely, if your theory says that "friends" can be treated as quantum systems, then you must give up locality, accept that measurements do not have a single result that observers must agree on or allow superdeterminism. Each of these options has profound—and, to some physicists, distinctly distasteful—implications.

RECONSIDERING REALITY

"The paper is an important philosophical study," says Michele Reilly, co-founder of Turing, a quantum-computing company based in New York City, who was not involved in the work. She notes that physicists studying quantum foundations have often struggled to come up with a feasible test to back up their big ideas. "I am thrilled to see an experiment behind philosophical studies," Reilly says. Steinberg calls the experiment "extremely elegant" and praises the team for tackling the mystery of the observer's role in measurement head-on.

Although it is no surprise that quantum mechanics forces us to give up a commonsense assumption—physicists knew that from Bell—"the advance here is that we are narrowing in on which of those assumptions it is," says Wharton, who was also not part of the study. Still, he notes, proponents of most quantum interpretations will not lose any sleep. Fans of retrocausality, such as himself, have already made peace with superdeterminism: in their view, it is not shocking that future measurements affect past results. Meanwhile QBists and many-worlds adherents long ago threw out the requirement that quantum mechanics prescribe a single outcome that every observer must agree on.

And both Bohmian mechanics and spontaneous collapse models already happily ditched locality in response to Bell. Furthermore, collapse models say that a real macroscopic friend cannot be manipulated as a quantum system in the first place.

Vaidman, who was also not involved in the new work, is less enthused by it, however, and criticizes the identification of Wigner's friend with a photon. The methods used in the paper "are ridiculous; the friend has to be macroscopic," he says. Philosopher of physics Tim Maudlin of New York University, who was not part of the study, agrees. "Nobody thinks a photon is an observer, unless you are a panpsychic," he says. Because no physicist questions whether a photon can be put into superposition, Maudlin feels the experiment lacks bite. "It rules something out—just something that nobody ever proposed," he says.

Tischler accepts the criticism. "We don't want to overclaim what we have done," she says. The key for future experiments will be scaling up the size of the "friend," adds team member Howard Wiseman, a physicist at Griffith University. The most dramatic result, he says, would involve using an artificial intelligence, embodied on a quantum computer, as the friend. Some philosophers have mused that such a machine could have humanlike experiences, a position known as the strong AI hypothesis, Wiseman notes, although nobody yet knows whether that idea will turn out to be true. But if the hypothesis holds, this quantum-based artificial general intelligence (AGI) would be microscopic. So from the point of view of spontaneous-collapse models, it would not trigger collapse because of its size. If such a test were run and the local-friendliness bound were not violated, that result would imply that an AGI's consciousness cannot be put into superposition. In turn, that conclusion would suggest that Wigner was right that consciousness causes collapse. "I don't think I will live to see an experiment like this," Wiseman says. "But that would be revolutionary."

> **"It's becoming conceivable that larger- and larger-scale computational devices could, in fact, be measured in a quantum way."**
>
> ***—Aephraim Steinberg***

Reilly, however, warns that physicists hoping that future AGI will help them home in on the fundamental description of reality are putting the cart before the horse. "It's not inconceivable to me that quantum computers will be the paradigm shift to get to us into AGI," she says. "Ultimately we need a theory of everything to build an AGI on a quantum computer, period, full stop."

That requirement may rule out more grandiose plans. But the team also suggests more modest intermediate tests involving machine-learning systems as friends, which appeals to Steinberg. That approach is "interesting and provocative," he says. "It's becoming conceivable that larger- and larger-scale computational devices could, in fact, be measured in a quantum way."

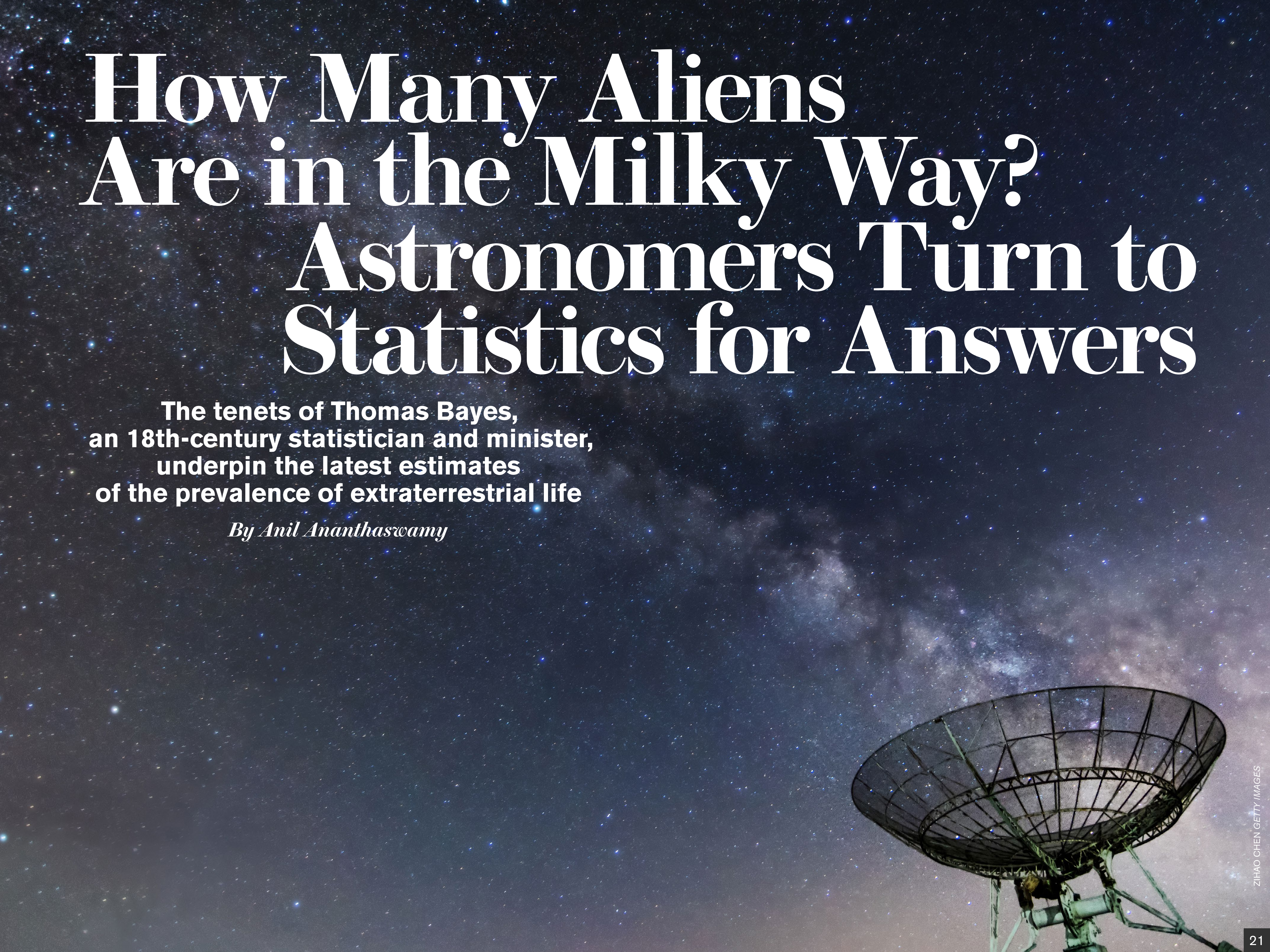
Renato Renner, a quantum physicist at the Swiss Federal Institute of Technology Zurich (ETH Zurich), makes an even stronger claim: regardless of whether future experiments can be carried out, he says, the new theorem tells us that quantum mechanics needs to be replaced. In 2018 Renner and his colleague Daniela Frauchiger, then at ETH Zurich, published a thought experiment based on Wigner's friend and used it to derive a new paradox. Their setup differs from that of the Brisbane team but also involves four observers whose measurements can become entangled. Renner and Frauchiger calculated that if the observers apply quantum laws to one another, they can end up inferring different results in the same experiment.

"The new paper is another confirmation that we have a problem with current quantum theory," says Renner, who was not involved in the work. He argues that none of today's quantum interpretations can worm their way out of the so-called Frauchiger-Renner paradox without proponents admitting they do not care whether quantum theory gives consistent results. QBists offer the most palatable means of escape because from the outset they say that quantum theory cannot be used to infer what other observers will measure, Renner says. "It still worries me, though: If everything is just personal to me, how can I say anything relevant to you?" he adds. Renner is now working on a new theory that provides a set of mathematical rules that would allow one observer to work out what another should see in a quantum experiment.

Still, those who strongly believe their favorite interpretation is right see little value in Tischler's study. "If you think quantum mechanics is unhealthy and it needs replacing, then this is useful because it tells you new constraints," Vaidman says. "But I don't agree that this is the case—many worlds explains everything."

For now physicists will have to continue to agree to disagree about which interpretation is best or if an entirely new theory is needed. "That's where we left off in the early 20th century—we're genuinely confused about this," Reilly says. "But these studies are exactly the right thing to do to think through it."

Disclaimer: The author frequently writes for the Foundational Questions Institute, which sponsors research in physics and cosmology and partially funded the Brisbane team's study.



How Many Aliens Are in the Milky Way? Astronomers Turn to Statistics for Answers

The tenets of Thomas Bayes, an 18th-century statistician and minister, underpin the latest estimates of the prevalence of extraterrestrial life

By Anil Ananthaswamy

ZIHAO CHEN *GETTY IMAGES*

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.*

IN THE 12TH EPISODE OF *COSMOS,* WHICH AIRED ON DECEMBER 14, 1980, the program's co-creator and host Carl Sagan introduced television viewers to astronomer Frank Drake's eponymous equation. Using it, he calculated the potential number of advanced civilizations in the Milky Way that could contact us using the extraterrestrial equivalent of our modern radio-communications technology. Sagan's estimate ranged from "a pitiful few" to millions. "If civilizations do not always destroy themselves shortly after discovering radio astronomy, then the sky may be softly humming with messages from the stars," Sagan intoned in his inimitable way.

Sagan was pessimistic about civilizations being able to survive their own technological "adolescence"—the transitional period when a culture's development of, say, nuclear power, bioengineering or a myriad of other powerful capabilities could easily lead to self-annihilation. In essentially all other ways, he was an optimist about the prospects for pangalactic life and intelligence. But the scientific basis for his beliefs was shaky at best. Sagan and others suspected the emergence of life on clement worlds must be a cosmic inevitability because geologic evidence suggested it arose shockingly quickly on Earth: in excess of four billion years ago, practically as soon as our planet had sufficiently cooled from its fiery formation. And if, just as on our world, life on other planets emerged quickly and evolved to become ever more complex over time, perhaps intelligence and technology, too, could be common throughout the universe.

In recent years, however, some skeptical astronomers have tried to put more empirical heft behind such pronouncements using a sophisticated form of analysis called Bayesian statistics. They have focused on two great unknowns: the odds of life arising on Earth-like planets from abiotic conditions—a process called abiogenesis—and, from there, the odds of intelligence emerging. Even with such estimates in hand, astronomers disagree about what they mean for life elsewhere in the cosmos. That lack of consensus is because even the best Bayesian analysis can do only so much when hard evidence for extraterrestrial life and intelligence is thin on the ground.

The Drake equation, which the astronomer introduced in 1961, calculates the number of civilizations in our galaxy that can transmit—or receive—interstellar messages via radio waves. It relies on multiplying a number of factors, each of which quantifies some aspect of our knowledge about our galaxy, planets, life and intelligence. These factors include f_p, the fraction of stars with extrasolar planets; n_e, the number of habitable planets in an extrasolar system; f_l, the fraction of habitable planets on which life emerges; and so on.

"At the time Drake wrote [the equation] down—or even 25 years ago—almost any of those factors could have been the ones that make life very rare," says Edwin Turner, an astrophysicist at Princeton University. Now we know that worlds around stars are the norm and that those similar to Earth in the most basic terms of size, mass and insolation are common as well. In short, there appears to be no shortage of galactic real estate that life could occupy. Yet "one of the biggest uncertainties in the whole chain of factors is the probability that life would ever get started—that you would make that leap from chemistry to life, even given suitable conditions," Turner says.

Ignoring this uncertainty can lead astronomers to make rather bold claims. For example, in June, Tom Westby and Christopher Conselice, both at the University of Nottingham in England, made headlines when they calculated that there should be at least 36 intelligent civilizations in our galaxy capable of communicating with us. The estimate was based on an assumption that intelligent life emerges on other habitable Earth-like planets about 4.5 billion to 5.5 billion years after their formation.

"That's just a very specific and strong assumption," says astronomer David Kipping of Columbia University. "I don't see any evidence that that's a safe bet to be making."

Answering questions about the likelihood of abiogenesis and the emergence of intelligence is difficult because scientists have just a single piece of information: life on Earth. "We don't even really have one full data point," Kipping says. "We don't know when life emerged, for instance, on Earth. Even that is subject to uncertainty."

Yet another problem with making assumptions based on what we locally observe is so-called selection bias. Imagine buying lottery tickets and hitting the jackpot on your 100th attempt. Reasonably, you might then assign a 1 percent probability to winning the lottery. This incorrect conclusion is, of course, a selection bias that arises if you poll only the winners and none of the failures (that is, the tens of millions of people who purchased tickets but never won the lottery). When it comes to calculating the odds of abiogenesis, "we don't have access to the failures," Kipping says. "So this is why we're in a very challenging position when it comes to this problem."

> **"We still struggle to define what we mean by a living system."**
> ***—Caleb Scharf***

Enter Bayesian analysis. The technique uses Bayes's theorem, named after Thomas Bayes, an 18th-century English statistician and minister. To calculate the odds of some event, such as abiogenesis, occurring, astronomers first come up with a likely probability distribution of it—a best guess, if you will. For example, one can assume that abiogenesis is as likely between 100 million to 200 million years after Earth formed as it is between 200 million to 300 million years after that time or in any other 100-million-year chunk of our planet's history. Such assumptions are called Bayesian priors, and they are made explicit. Then the statisticians collect data or evidence. Finally, they combine the prior and the evidence to calculate what is called a posterior probability. In the case of abiogenesis, that probability would be the odds of the emergence of life on an Earth-like planet, given our prior assumptions and evidence. The posterior is not a single number but rather a probability distribution that quantifies any uncertainty. It may show, for instance, that abiogenesis becomes more or less likely with time rather than having a uniform probability distribution suggested by the prior.

In 2012 Turner and his colleague David Spiegel, then at the Institute for Advanced Study in Princeton, N.J., were the first to rigorously apply Bayesian analysis to abiogenesis. In their approach, life on an Earth-like planet around a sunlike star does not emerge until some minimum number of years, t_{min}, after that world's formation. If life does not arise before some maximum time, t_{max}, then as its star ages (and eventually dies), conditions on the planet become too hostile for abiogenesis to ever occur. Between t_{min} and t_{max}, Turner and Spiegel's intent was to calculate the probability of abiogenesis.

The researchers worked with a few different prior distributions for this probability. They also assumed that intelligence took some fixed amount of time to appear after abiogenesis.

Given such assumptions, the geophysical and paleontological evidence of life's genesis on Earth and what evolutionary theory says about the emergence of intelligent life, Turner and Spiegel were able to calculate different posterior probability distributions for abiogenesis. Although the evidence that life appeared early on Earth may indeed suggest that abiogenesis is fairly easy, the posteriors did not place any lower bound on the probability. The calculation "doesn't rule out very low probabilities, which is really sort of common sense with statistics of one," Turner says. Despite life's rapid emergence on Earth, abiogenesis could nonetheless be an extremely rare process.

Turner and Spiegel's effort was the "first really serious Bayesian attack on this problem," Kipping says. "I think what was appealing is that they broke this default, naive interpretation of the early emergence of life."

Even so, Kipping thought the researchers' work was not without its weaknesses, and he has now sought to correct it with a more elaborate Bayesian analysis of his own. For instance, Kipping questions the assumption that intelligence emerged at some fixed time after abiogenesis. This prior, he says, could be another instance of selection bias—a notion influenced by the evolutionary pathway by which our own intelligence emerged. "In the spirit of encoding all of your ignorance, why not just admit that you don't know that number either?" Kipping says. "If you're trying to infer how long it takes life to emerge, then why not just also do intelligence at the same time?"

That suggestion is exactly what Kipping attempted, estimating both the probability of abiogenesis and the emergence of intelligence. For a prior, he chose something called the Jeffreys prior, which was designed by another English statistician and astronomer, Harold Jeffreys. It is said to be maximally uninformative. Because the Jeffreys prior does not bake in massive assumptions, it places more weight on the evidence. Turner and Spiegel had also tried to find an uninformative prior. "If you want to know what the data are telling you and not what you thought about them previously, then you want an uninformative prior," Turner says. In their 2012 analysis, the researchers employed three priors, one of which was the least informative, but they fell short of using Jeffreys prior, despite being aware of it.

In Kipping's calculation, that prior focused attention on what he calls the "four corners" of the parameter space: life is common, and intelligence is common; life is common, and intelligence is rare; life is rare, and intelligence is common; and life is rare, and intelligence is rare. All four corners were equally likely before the Bayesian analysis began.

Turner agrees that using the Jeffreys prior is a significant advance. “It’s the best way that we have, really, to just ask what the data are trying to tell you,” he says.

Combining the Jeffreys prior with the sparse evidence of the emergence and intelligence of life on Earth, Kipping obtained a posterior probability distribution, which allowed him to calculate new odds for the four corners. He found, for instance, that the “life is common, and intelligence is rare” scenario is nine times more likely than both life and intelligence being rare. And even if intelligence is not rare, the life-is-common scenario has a minimum odds ratio of 9 to 1. Those odds are not the kind that one would bet the house on, Kipping says: “You could easily lose the bet.”

Still, that calculation is “a positive sign that life should be out there,” he says. “It is, at least, a suggestive hint that life is not a difficult process.”

Not all Bayesian statisticians would agree. Turner, for one, interprets the results differently. Yes, Kipping’s analysis suggests that life’s apparent early arrival on Earth favors a model in which abiogenesis is common, with a specific odds ratio of 9:1. But this calculation does not mean that model is nine times more likely to be true than the one that says abiogenesis is rare, Turner says, adding that Kipping’s interpretation is “a little bit overly optimistic.”

According to Turner, who applauds Kipping’s work, even the most sophisticated Bayesian analysis will still leave room for the rarity of both life and intelligence in the universe. “What we know about life on Earth doesn’t rule out those possibilities,” he says.

And it is not just Bayesian statisticians who may have a beef with Kipping’s interpretation. Anyone interested in questions about the origin of life would be skeptical about claimed answers, given that any such analysis is beholden to geologic, geophysical, paleontological, archaeological and biological evidence for life on Earth—none of which is unequivocal about the time lines for abiogenesis and the appearance of intelligence.

“We still struggle to define what we mean by a living system,” says Caleb Scharf, an astronomer and astrobiologist at Columbia. “It is a slippery beast in terms of scientific definition. That’s problematic for making a statement [about] when abiogenesis happens—or even statements about the evolution of intelligence.”

If we did have rigorous definitions, problems would persist. “We don’t know whether or not life started up, stopped, restarted. We also don’t know whether life can only be constructed one way or not,” Scharf says. When did Earth become hospitable to life? And when it did, were the first molecules of this “life” amino acids, RNAs or lipid membranes? And after life first came about, was it snuffed out by some cataclysmic event early in Earth’s history only to restart in a potentially different manner? “There’s an awful lot of uncertainty,” Scharf says.

All this sketchy evidence makes even Bayesian analysis difficult. But as a technique, it remains the best-suited method for handling more evidence—say, the discovery of signs of life existing on Mars in the past or within one of Jupiter’s ice-covered, ocean-bearing moons at the present.

“The moment we have another data point to play with, assuming that happens, [the Bayesian models] are the ways to best utilize that extra datum. Suddenly the uncertainties shrink dramatically,” Scharf says. “We don’t necessarily have to survey every star in our galaxy to figure out how likely it is for any given place to harbor life. One or two more data points, and suddenly we know about, essentially, the universe in terms of its propensity for producing life or possibly intelligence. And that’s rather powerful.”

NASA's Perseverance rover sits aboard an Atlas V rocket before launching from Cape Canaveral Air Force Station in Florida.

JOEL KOWSKY *NASA*

NASA Has Launched the Most Ambitious Mars Rover Ever Built: Here's What Happens Next

Perseverance will stow away rocks for eventual delivery to Earth and will listen for Martian sounds for the first time

By Alexandra Witze

Alexandra Witze works for *Nature* magazine.

THE BIGGEST, MOST COMPLEX ROVER EVER SENT TO MARS IS NOW ON its way. NASA's Perseverance rover launched successfully on July 30, the third of three Mars missions to launch in the space of just 10 days. The rover will be the first mission ever to attempt to collect rock samples for return to Earth; it will also search for signs of ancient alien life, launch the first helicopter on the Red Planet and use microphones to capture Mars's sounds for the first time.

The rover blasted into the skies above Cape Canaveral, Fla., aboard an Atlas V rocket at 7:50 A.M. local time. The launch follows the United Arab Emirates' Mars Hope orbiter, which took off on July 20, and China's Tianwen-1 rover, which launched three days after that. All three capitalized on a favorable alignment between the orbits of Earth and Mars for a fuel-efficient journey.

Now Perseverance will cruise through space for nearly seven months, aiming to land in Mars's Jezero Crater on February 18, 2021. If it reaches the surface safely, the $2.7-billion, plutonium-powered, 1,025-kilogram rover will spend at least one Mars year—nearly two Earth years—exploring a landscape where an ancient river flowed into a lake that might have hosted Martian life.

As well as searching the riverbed and lakeshore for signs of fossilized life, Perseverance will test whether astronauts could produce oxygen from the Red Planet's atmosphere. But most important, it will fill tubes with Martian rock and soil that a yet-to-be-built spacecraft might one day fly back to Earth—in what would be the first sample return from Mars.

"Perseverance is going to do so much for us," says Kennda Lynch, an astrobiologist at the Lunar and Planetary Institute in Houston, Tex.

NEXT-GENERATION EXPLORER

The machine is a beefed-up version of the Curiosity rover, which gripped the world when it landed on Mars eight years ago in a nail-biting seven-minute maneuver. After a journey of roughly 500 million kilometers, Perseverance will hit the Martian atmosphere traveling at around 19,500 kilometers per hour. It will deploy a parachute and then a "sky crane" system—similar to that used by Curiosity—that will fire retrorockets to slow it down as it approaches the planet's surface. Unlike Curiosity, the spacecraft has an autopiloting system to detect obstacles such as big rocks and to guide it to a safe location.

Once Perseverance touches down, engineers will spend around 90 days remotely checking all its systems to make sure they are in working order. The rover probably will not begin rolling in earnest until May, when it will strike out on its six wheels to explore Jezero Crater, which lies about 3,750 kilometers from Curiosity's landing site.

Jezero means "lake" in several Slavic languages. More than 3.8 billion years ago a river flowed into the 45-kilometer-wide crater, and lake waters filled it. Images suggest that along the crater's rim, carbonate minerals settled out and hardened into rock. That is exciting because on Earth ancient carbonate rocks hold some of the oldest known evidence of life, including fossilized bacterial mats known as stromatolites.

If Martian life ever existed, Jezero's carbonates are a good place to look for it. "We've not explored an environment like this before," says Tanja Bosak, a geobiologist at the Massachusetts Institute of Technology, who is working on the mission. Evidence of life could come in the form of actual fossils or in chemical or geologic signatures of organisms that once lived in the rocks.

TOOLS OF THE TRADE

The rover is loaded with instruments that make it a true field geologist—and truly international. They include a pair of zoomable cameras that can spot a fly from the other side of a sports field; a Spanish-built weather station; a Norwegian-built radar to scan layers of soil and rock underneath the planet's surface; and an advanced version of a laser instrument carried on Curiosity, which will probe rocks to study their chemical makeup. "Who

> **“Returning samples will be the first time we will have done a round trip to Mars. That’s important because it’s a metaphor for human spaceflight. Most astronauts who go to Mars are going to want to come back.”**
> ***—John Grunsfeld***

doesn’t love a camera with a laser that zaps rocks?” says John Grunsfeld, a former NASA astronaut who led the development of Perseverance when he ran the agency’s science office from 2012 to 2016.

Perseverance is also pioneering because it carries two microphones, which will not only reveal the winds and other sounds of Mars for the first time but also be able to listen for engineering problems in the motors or wheels, Grunsfeld says. And it has a 1.8-kilogram helicopter named Ingenuity, which it can deploy to scout ahead for places where the rover could roll. If the mission is successful, Ingenuity will be the first craft to make a controlled flight on another planet.

But the workhorse of Perseverance is its robotic arm, which can stretch to scrutinize rocks up close and then drill out samples to be stored in tubes in the rover’s belly. The mission will stash these samples until a future spacecraft can retrieve them and bring them back to Earth. Perseverance carries 43 tubes, “and we will use them all in the pursuit of something like 30 or 35 really good samples,” says Ken Farley, a geologist at the California Institute of Technology and the mission’s project scientist. NASA and the European Space Agency plan to bring those rocks back to Earth by 2031 so that scientists can study them in sophisticated laboratories—although only a small part of the funding has yet been committed.

THERE AND BACK AGAIN

“Returning samples will be the first time we will have done a round trip to Mars,” Grunsfeld says. “That’s important because it’s a metaphor for human spaceflight. Most astronauts who go to Mars are going to want to come back.”

As a step toward that long-term exploration, the rover will use one of its instruments to attempt to produce oxygen from Mars’s carbon dioxide atmosphere. Future human astronauts might be able to do the same to make oxygen to breathe or to produce rocket fuel to get home.

The COVID-19 pandemic has not made Perseverance’s past few months on Earth easy. In March, when the pandemic hit the U.S., the spacecraft was in Florida being prepared for launch—but most of its engineers were in California, at the Jet Propulsion Laboratory. When staff needed to travel to Florida to help with final arrangements, NASA used some of its agency aircraft to transport them so they would not have to risk exposure to the coronavirus by flying commercially.

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POLICY & ETHICS

Unidentified Aerial Phenomena, Better Known as UFOs, Deserve Scientific Investigation

UAP are a scientifically interesting problem. Interdisciplinary teams of scientists should study them

People gather in Dexter, Mich., to watch for UFOs in 1966.

GETTY IMAGES

UFOs have been back in the news because of videos, initially leaked and later confirmed by the U.S. Navy and officially released by the Pentagon, that purportedly show "unidentified aerial phenomena" (UAP) in our skies. Speculations about their nature have run the gamut from mundane objects such as birds or balloons to visitors from outer space.

It is difficult, if not impossible, to say what these actually are, however, without context. What happened before and after these video snippets? Were there any simultaneous observations from other instruments or sightings by pilots?

A judgment on the nature of these objects (and these seem to be "objects," as confirmed by the navy) needs a coherent explanation that should accommodate and connect all the facts of the events. And this is where interdisciplinary scientific investigation is needed.

The proposal to scientifically study UAP is not new. The problem of understanding such unexplained UAP cases drew interest from scientists during the 1960s, which resulted in the U.S. Air

Force funding a group at the University of Colorado, headed by physicist Edward Condon, to study UAP from 1966 to 1968. The resulting Condon Report concluded that further study of UAP was unlikely to be scientifically interesting—a conclusion that drew mixed reactions from scientists and the public.

Concerns over the inadequacy of the methods used for the Condon Report culminated in a congressional hearing in 1968, as well as a debate sponsored by the American Association for the Advancement of Science (AAAS) in 1969, with participation by scholars such as Carl Sagan, J. Allen Hynek, James McDonald, Robert Hall and Robert Baker. Hynek was an astronomy professor at the Ohio State University and led the Project Blue Book investigation. McDonald, who was a well-known meteorologist and a member of the National Academy of Sciences and the AAAS, performed a thorough investigation of UAP. Sagan, a professor of astronomy at Cornell University, was one of the organizers of the AAAS debate. He dismissed the extraterrestrial hypothesis as unlikely but still considered the UAP subject worthy of scientific inquiry.

Recent UAP sightings, however, have so far failed to generate similar interest among the scientific community. Part of the reason could be the apparent taboo around UAP, which connects them to the paranormal or pseudoscience while ignoring the history behind them. Sagan even wrote in the afterword of the 1969 debate proceedings about the "strong opposition" by other scientists who were "convinced that AAAS sponsorship would somehow lend credence to 'unscientific' ideas." As scientists, we must simply let scientific curiosity be the spearhead of understanding such phenomena. We should be cautious of outright dismissal by assuming that all UAP must be explainable.

Why should astronomers, meteorologists or planetary scientists care about these events? Shouldn't we just let image analysts or radar observation experts handle the problem? All good questions, and rightly so. Why should we care? Because we are scientists. Curiosity is the reason we became scientists. In the current interdisciplinary collaborative environment, if someone (especially a fellow scientist) approaches us with an unsolved problem beyond our area of expertise, we usually do our best to actually contact other experts within our professional network to try to get some outside perspective. The best-case outcome is that we work on a paper or a proposal with our colleague from another discipline; the worst case is that we learn something new from a colleague in another discipline. Either way, curiosity helps us to learn more and become scientists with broader perspectives.

So what should be the approach? If a scientific explanation is desired, one needs an interdisciplinary approach to address the combined observational characteristics of UAP rather than isolating one aspect of the event. Furthermore, UAP are not U.S.-specific events. They are a worldwide occurrence. Several other countries studied them. So shouldn't we as scientists choose to investigate and curb the speculation around them?

A systematic investigation is essential to bring the phenomena into mainstream science. The collection of hard data is paramount to establishing any credibility to the explanation of the phenomena. A rigorous scientific analysis is sorely needed, by multiple independent study groups, just as we do to evaluate other scientific discoveries. We, as scientists, cannot hastily dismiss any phenomenon without in-depth examination and then conclude the event itself is unscientific.

Such an approach would certainly not pass the "smell test" in our day-to-day science duties, so these kinds of arguments similarly should not suffice to explain UAP. We must insist on strict agnosticism. We suggest an approach that is purely rational: UAP represent observations that are puzzling and waiting to be explained—just like any other science discovery.

The transient nature of UAP events, and hence the unpredictability of when and where the next event will happen, is likely one of the main reasons that UAP have not been taken seriously in science circles. But how can one identify a pattern without systematically collecting the data in the first place? In astronomy, the observations (location and timing) of gamma-ray bursts (GRBs), supernovae and gravitational waves are similarly unpredictable. We now recognize them, however, as natural phenomena arising from stellar evolution.

How did we develop detailed and complex mathematical models that could explain these natural phenomena? By a concerted effort from scientists around the world who meticulously collected data from each occurrence of the event and systematically observed them. We still cannot predict when and where such astronomical events will occur in the sky.

But we understand to an extent the nature of GRBs, supernovae and gravitational waves. Why? Because we have not dismissed the phenomena or the people who observed them. We studied them. Astronomers have tools, so they can share the data they collect even if some question their claim. Similarly, we need tools to observe UAP; radar, thermal and visual observations will be immensely helpful. We must repeat here that this is a global phenomenon. Perhaps some, or even most, UAP events are simply classified military aircraft or strange weather formations or other misidentified but mundane phenomena. Yet there are still a number of truly puzzling cases that might be worth investigating.

Of course, not all scientists need to make UAP investigation a part of their research portfolio. For those who do, discarding the taboo surrounding these phenomena would help in developing interdisciplinary teams of motivated individuals who can begin genuine scientific inquiry.

A template to perform a thorough scientific investigation can be found in McDonald's paper "Science in Default." Although he entertains the conclusion that these events could be extraterrestrial (which we do not subscribe to), McDonald's methodology itself is a great example of objective scientific analysis. And this is exactly what we as scientists can do to study these events.

As Sagan concluded at the 1969 debate, "scientists are particularly bound to have open minds; this is the lifeblood of science." We do not know what UAP are, and this is precisely the reason that we as scientists should study them.

Caleb A. Scharf is director of astrobiology at Columbia University. He is author and co-author of more than 100 scientific research articles in astronomy and astrophysics. His work has been featured in publications such as *New Scientist, Scientific American, Science News, Cosmos Magazine, Physics Today* and *National Geographic.* For many years he wrote the Life, Unbounded blog for *Scientific American.*

SPACE

Could We Force the Universe to Crash?

If we're all living in a simulation, as some have suggested, it would be a good, albeit risky, way to find out for sure

These are the days of fever dreams, whether induced by an actual virus or by the slow-motion stresses of a world dealing with a pandemic. One kind of dream in particular that I know I have had has to do with discovering that this was all, well, a dream. Except when I really do wake up, I remember that there are ideas about the nature of reality that go beyond even this. The trickiest variant of these concepts is the simulation hypothesis, which is that we far more likely exist within a virtual reality than in a physical reality.

The proposition that the world is a sham is not new; it has been cropping up for thousands of years across different cultures, from China to ancient Greece, advocated by thinkers such as Descartes with his mind-body dualism. But this more recent version, based on computation—or at

CALEB SCHARF

least artificial reconstruction—bubbled up around 2003 with the publication of a paper entitled “Are You Living in a Computer Simulation?” by philosopher Nick Bostrom. In essence Bostrom makes the argument that if any extremely advanced civilizations developed the capacity to run “ancestor simulations” (to learn about their own pasts), the simulated ancestral entities would likely far outnumber actual sentient entities in the universe. With a little probabilistic hand waving, it is then possible to argue that we are most likely simulated.

> **The question is: How do you bring down a simulation of reality from inside it?**

All of which is good fun if you have had a few beers or spent a few too many hours cowering under your bedclothes. But whether you love or hate this hypothesis, the simple fact is that before judging it, we should really apply the criteria we use for assessing any hypothesis, and the first step in that process is to ask whether it can be assessed in any reasonable way.

Intriguingly, the simulation hypothesis might be testable, under certain assumptions. For example, we might suppose that a simulation has its limitations. The most obvious one, extrapolating from the current state of digital computation, is simply that a simulation will have to make approximations to save on information storage and calculation overheads. In other words, it would have limits on accuracy and precision.

One way that those limits could manifest themselves is in the discretization of the world, perhaps showing up in spatial and temporal resolution barriers. Although we do think that there are some absolute limits to what constitutes meaningful small distances or time intervals—the Planck scale and Planck time—that has to do with the limits of our current understanding of physics rather than the kind of resolution limits on your pixelated screen. Nevertheless, recent research suggests that the true limit of meaningful intervals of time might be orders of magnitude larger than the traditional Planck time (which is 10^{-43} second). Perhaps future physics experiments could reveal an unexpected chunkiness to time and space.

But the neatest test of the hypothesis would be to crash the system that runs our simulation. Naturally that sounds a bit ill-advised, but if we are all virtual entities anyway, does it really matter? Presumably a quick reboot and restore might bring us back online as if nothing had happened, but possibly we would be able to tell, or at the very least have a few microseconds of triumph, just before it all shuts down.

The question is: How do you bring down a simulation of reality from inside it? The most obvious strategy would be to try to cause the equivalent of a stack overflow—asking for more space in the active memory of a program than is available—by creating an infinitely, or at least excessively, recursive process. And the way to do that would be to build our own simulated realities, designed so that within those virtual worlds are entities creating their version of a simulated reality, which is in turn doing the same, and so on all the way down the rabbit hole. If all of this worked, the universe as we know it might crash, revealing itself as a mirage just as we winked out of existence.

You could argue that any species capable of simulating a reality (likely similar to its own) would surely anticipate this eventuality and build in some safeguards to prevent it from happening. For instance, we might discover that it is strangely and inexplicably impossible to actually make simulated universes of our own, no matter how powerful our computational systems are—whether generalized quantum computers or otherwise. That in itself could be a sign that we already exist inside a simulation. Of course, the original programmers might have anticipated that scenario, too, and found some way to trick us, perhaps just streaming us information from other simulation runs rather than letting us run our own.

But interventions like this risk undermining the reason for a species running such simulations in the first place, which would be to learn something deep about its own nature. Perhaps letting it all crash is simply the price to pay for the integrity of the results. Or perhaps they are simply running the simulation containing us to find out whether they themselves are within a fake reality.

Sweet dreams.

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 Center for Astrophysics | Harvard & Smithsonian. 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 author of *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth,* forthcoming from Houghton Mifflin Harcourt in January 2021.

SPACE

A Movie of the Evolving Universe Is Potentially Scary

The Vera C. Rubin Observatory will reveal all kinds of short-term changes in the cosmos—and some could have dire consequences for humanity

RUBIN OBSERVATORY, NSF AND AURA (CC BY 4.0)

After the COVID-19 rules about social distancing went into effect, I developed a morning routine of jogging through the woods near my home. During the first months, I focused on the green branches stretching upward toward the sky, but then I started to notice the debris of tree trunks lying on the ground. There are many such remnants being eaten by termites, rotting and ultimately dispersing into the underlying soil. A glimpse at the forest reveals a sequence of evolutionary phases in the history of trees that have lived or died at different times.

The phenomenon happens in other contexts. For example, I recently completed a nine-year term as chair of the astronomy department at Harvard University. And only now have I begun to notice the former chairs scattered around me, just like those tree trunks in the woods.

Entering a new stage of life can be humbling. We acquire a false sense of permanence from reviewing the frozen past, as if it were a statue that will never erode. But this view is shortsighted because each moment can also be seen as a new beginning, shaped by forces beyond our control and swirling on a grander scale.

Old-fashioned astronomy was also permeated by a false sense of permanence. Astronomers collected still images of the universe, creating the impression that nothing really changes under the sun—or above it, either. But just like the revelation from my stroll through the woods, these snapshots showed stars and galaxies of different ages at various evolutionary phases in their history. Computer simulations helped us patch together the full story by solving the equations of motion for matter, starting from the initial conditions imprinted on the cosmic microwave background at early cosmic times. By generating snapshots of an artificial cosmos similar to those captured by telescopes, these simulations unraveled our cosmic roots. The scientific insight that emerged is that the likely origins of our existence were quantum fluctuations in the early universe. Perhaps we should add "Quantum Mechanics Day" to our annual celebrations of Mother's Day and Father's Day.

There are some missing pages in the photo album made up of our observations, however: the period known as the cosmic dawn, for example, when the first stars and galaxies turned on. These missing pages will be filled in the coming decade by the next generation of telescopes, such as the James Webb Space Telescope (JWST), the ground-based "extremely large" telescopes and the Hydrogen Epoch of Reionization Array (HERA).

To reveal a more literal gap in the sky, the Event Horizon Telescope recently captured a still image of the silhouette of the black hole in the giant galaxy M87. The next goal is to obtain a sequence of images or a video showing the time variability of the accretion flow around the black hole.

The tradition of still images makes sense when dealing with systems like galaxies, which evolve on a timescale of billions of years. But the universe also exhibits transient fireworks that flare up and dim during a human lifetime. Observing them is the motivation behind the Legacy Survey of Space and Time (LSST) on the Vera C. Rubin Observatory, which will have its first light soon. LSST will be a filming project documenting nearly 1,000 deep multicolor images per patch of the southern sky over a decade and recording the most extensive video of the universe ever taken, with its plethora of transients in full glory.

Some of the LSST flares are expected to be the counterparts of gravitational-wave sources detected by LIGO/Virgo or LISA. Their discovery will usher in multimessenger astronomy based on both gravitational and electromagnetic waves emitted by the same sources, providing new insights about the central engines that power these transients. The related "standard sirens" could serve as new rulers for measuring precise distances in cosmology.

Within the Milky Way, transient events close to Earth could lead to catastrophe.

Within the Milky Way, transient events close to Earth could lead to catastrophe. A supernova explosion, for example, could cause a mass extinction on an unprecedented scale. If a meteor similar to the one that hit the unpopulated regions near Chelyabinsk in 2013 or Tunguska in 1908 hit New York City, it could cause a far larger death toll and more economic damage than COVID-19. Or consider the impact of a blob of hot gas from the sun, a so-called coronal mass ejection of the type that missed Earth in 2012. Such an event could shut off communication systems, disable satellites and damage power grids. Altogether, astronomical alerts about such celestial threats could be crucial for securing the longevity of our species.

Of greatest relevance for our long-term survival is identifying large objects on a collision course with Earth, similar to the Chicxulub asteroid that killed the dinosaurs 66 million years ago. In 2005 Congress passed a bill requiring NASA to find and track at least 90 percent of all near-Earth objects larger than 140 meters (enough to cause regional devastation) by 2020. Only a third of these objects have been identified in the sky so far. In a recent paper with my undergraduate student Amir Siraj, we explained some puzzling properties of the Chicxulub asteroid as a tidal breakup of a long-period comet that passed close to the sun. If future sky surveys alert us to another fragment whose apparent size grows rapidly against the sky, we had better have a contingency plan to deflect its trajectory—or else immediately call our realtor.

Keeping up with the challenge of precision cosmology for the next few decades can demonstrate that the Hubble constant, which describes the expansion rate of the universe, is not really a constant, in accordance with the expected Sandage-Loeb test. In the long run, the only thing that stays constant is change. The accelerated expansion of the universe under the influence of so-called dark energy will be the ultimate manifestation of extragalactic social distancing in the post-COVID-19 era, preventing any future contact between us and civilizations outside our galaxy.

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A Cosmic Crisis
AN EPIC DEBATE IS BREWING ABOUT HOW FAST THE UNIVERSE IS EXPANDING
Plus:
A NEW KIND OF NEUTRINO
Q&A WITH HAWKING'S FINAL CO-AUTHOR
GLITTERING DIAMOND DUST IN SPACE
WITH COVERAGE FROM nature