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SCIENTIFIC AMERICAN Space & Physics

The Sun, Solved

Neutrinos detected emanating from our star's core confirm decades-old predictions about what fuels its fusion

Plus:

STANDARD MODEL OF PHYSICS UNDER SCRUTINY

HOMING IN ON FAST RADIO BURSTS

NEXT-GEN DARK MATTER DETECTORS

WITH COVERAGE FROM
nature

FROM THE EDITOR

LIZ TORMES

The Scientific Question Machine

The title of this issue is a bit misleading. A fully explanatory and complete title would have gone something like: "Scientists Confirm Long-Standing Theory of Sun's Power, but As with All Science, Many Questions Remain and New Ones Are Revealed." Exhaustive, yes. Catchy? No. Though when it comes to attention-grabbing-if-slightly-truncated headlines, this one still holds water. As reporter Davide Castelvecchi reports, astrophysicists have long hypothesized that a small amount of the sun's energy is generated by a particular reaction involving carbon and nitrogen in the star's core, and can be detected by neutrino emissions (see "Neutrinos Reveal Final Secret of Sun's Nuclear Fusion"). It's always extremely satisfying when a scientific explanation is finally confirmed by direct evidence. In this case, the way that evidence was collected is fascinating, as are some of the further questions relevant to this research: What are the precise composition and temperature of the sun? What was our star like before the rest of the solar system formed? In science, it often goes that as soon as you've answered one question, you inadvertently have asked a dozen more. Call that frustrating or intriguing as you will.

Conflicting evidence about the weight of the cosmos is fueling a growing debate among physicists over the formation of the universe (see "How Heavy Is the Universe? Conflicting Answers Hint at New Physics"). And the surprise detection of radio bursts from within our own galaxy may help us resolve a larger cosmological phenomenon (see "'Magnetic Star' Radio Waves Could Solve the Mystery of Fast Radio Bursts"). But, you guessed it, this discovery is inciting a host of new questions waiting to be answered. I, for one, am intrigued.

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SPACE
& PHYSICS

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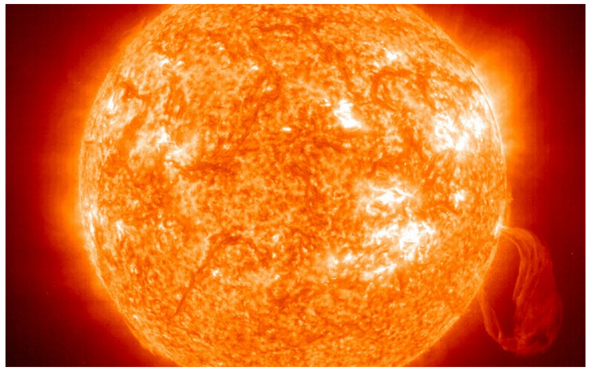

On the Cover

Our sun, as seen by NASA's Solar and Heliospheric Observatory

SOHO (ESA & NASA)

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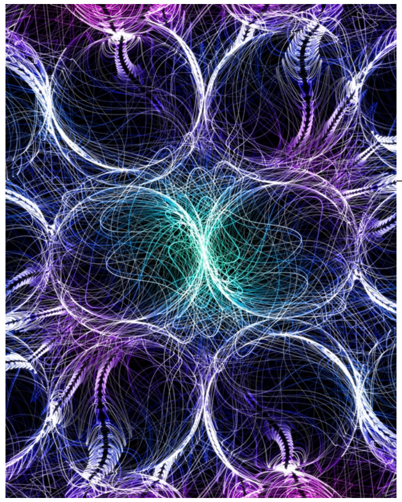

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ESO/L. CALÇADA

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Planet Nine Could Be a Mirage

Mysterious patterns in orbits of small bodies in the outer solar system could arise from the gravity of a massive disk of icy debris rather than an undiscovered giant world

Artist's illustration of a small icy object at the outskirts of our solar system. In sufficient numbers, such objects could explain mysterious orbital patterns otherwise attributed to an undiscovered world far from the sun.

NASA, ESA, AND G. BACON (STSCI)

Some four years ago, when Ann-Marie Madigan first encountered the idea that there might be an undetected massive planet lurking beyond Pluto's orbit, she felt excited but skeptical. The evidence for such a world was then—and remains—circumstantial: strange patterns in the orbits of small objects at the outskirts of the known solar system. Proponents of "Planet Nine" (Pluto no longer counts in the solar system's planetary tally) say such patterns could be produced by that world's hefty gravitational influence. But Madigan, an astrophysicist now at the University of Colorado Boulder, wondered whether some other, more prosaic explanation could suffice. At the time, she was studying how stars can jostle one another into different orbits as they whirl around supermassive black holes. And she saw no reason why her work could not also apply to tinier things orbiting our sun.

Today, from those modest beginnings, Madigan and a few of her collaborators have developed a totally different theory to explain the strangeness in the outer solar system: the "collective gravity" of a diffuse, sprawling (and so far largely hypothetical) disk of icy debris far beyond Pluto could alter the orbits of the far distant objects we readily see in a way that resembles the effect of a large planet. Such a disk would be composed of millions of small bodies, most of them left over from the solar system's formation long ago.

"What we're doing is taking the gravitational forces between all these small bodies into account," Madigan says. “Including those gravitational forces turns out to be really important.” Provided the putative disk possessed sufficient mass—several times that of Earth—over a billion years or so, the tiny gravitational interactions between and from its constituent members could sculpt the trans-Plutonian outer solar system in ways otherwise explained by Planet Nine, she maintains. The effect would be a bit like the proverbial butterfly flapping its wings to eventually set a distant storm in motion.

Madigan and her graduate student Alexander Zderic have now advanced their theory in two new studies posted on the preprint server arXiv.org. In one, submitted to the *Astronomical Journal,* they show how collective gravity can produce the same kinds of tilted and clumped orbits seen in about a dozen objects at a distance 250 times that between Earth and the sun—an observation others had attributed to a possible Planet Nine. In the other paper, under review at *Astrophysical Journal Letters,* they argue that given enough time, collective gravity can also explain how certain objects in far-out orbits can shift as they twirl around the sun, which had been taken as evidence for an unseen planet as well.

From this work by Madigan and her team, an alternative picture of the solar system’s plausible history is beginning to emerge. In the early days, Jupiter, Saturn, Uranus and Neptune coalesced in compact, orderly orbits somewhat closer to our star, which migrated outward later because of gravitational interactions. Back then those worlds were surrounded by a swarm of leftover chunks of debris that never found their way to planethood—icy bodies that the giant planets eventually kicked outward. Most were left ostracized in what Madigan calls a “primordial scattered disk” beyond the territory of present-day Pluto. And she suggests that there may be much more mass in the disk than other researchers have usually considered. The icy bodies were propelled into that ring with orbits far from circular, making up an unstable system—much like a wobbly, precariously spinning top. This system exerted gravitational effects while it gradually settled into a more stable configuration, with some orbits sharing similar planes and orientations. That configuration would, of course, essentially mirror what one would expect from the hidden gravitational hand of an undiscovered large outer planet.

“The fact that collective gravity can give you all the key observational features means that you don’t need anything new. I think Occam’s razor would lead you to believe that it’s the simpler solution” than Planet Nine, Madigan says.

California Institute of Technology astrophysicists Mike Brown and Konstantin Batygin have been two of the foremost proponents of the Planet Nine hypothesis since they released a sensational study on the subject in early 2016, and they have also been honing their arguments for the world’s existence. To match the latest observations, the researchers argue that Planet Nine’s mass must be between five and 10 times that of Earth and that its distance from the sun must be between 400 and 800 times that of our planet—slightly smaller and closer than what they first proposed.

Batygin says he is intrigued by Madigan’s idea of a remote ring of debris. But he thinks that is not what the solar system looks like. “If there were such a ring parked far away [from our sun], you run into the problem of its stability in the early solar system, since the solar system formed in a cluster of stars,” he says. “Perturbations from passing stars will mess up this ring. They’re going to destroy its coherence and disperse it.”

Madigan resolves this problem in her new simulations with careful tweaks to timing: if the scattered disk assembled after the young solar system left its stellar nursery and the giant planets formed, it could endure for eons. Such tweaks are not trivial: accurately modeling the collective gravity of a debris disk requires tracking the motions and interactions of thousands of particles or more floating and whipping around in computer models for the equivalent of hundreds of millions of years. That task is far more arduous than modeling the effects of a single planet, Madigan says—which is, in part, why she and her team so often seem to be one step behind the pro–Planet Nine contingent.

To date, Madigan’s idea has not gotten much attention in the scientific community compared with Planet Nine. But as telescopic searches for the planet continue to come up empty, that situation may be about to change. “We’re in a minority, but we're growing," she says. "In the solar system, collective gravity just hasn't really been studied. The field is just starting to take off."

At least two other research groups have also begun investigating various gravitational effects and dynamics as an alternative to Planet Nine. They similarly involve either a disk of rocky bodies or a smaller number of larger ones whose gravitational influences, billions of years ago, also could have shaken up the early solar system to create the peculiar orbits of post-Plutonian debris.

"The attraction of what Madigan is doing is that it's a radically different way of trying to explain what's going on with these distant orbits," says Scott Tremaine, an astrophysicist at the Institute for Advanced Study in Princeton, N.J. He points out a challenge for Madigan's proposal, however: Her collective gravity hypothesis requires the scattered disk to have so many icy bodies that they add up to a rather large mass. Unless at some point the disk had a combined mass that was about 20 times Earth's and a location around a few hundred times our planet's distance from the sun, it would lack the heft to sufficiently reconfigure the outer solar system to reflect what astronomers currently see. By following the orbits of comets, astronomers have already gained a fuzzy idea of how much mass must be out there. And a disk big enough to make Madigan's idea work lies at the upper end of what appears possible.

In the contest to explain astronomers' observations of the anomalous clustering in the outer solar system, there is another candidate—a dark horse—in addition to collective gravity and Planet Nine: Perhaps both hypotheses are wrong. Perhaps, in fact, there is no clustering at all. Biases in astronomers' methods of searching for small bodies and in the statistics used to study them en masse can lead to markedly different conclusions—some of which dismiss the observed clustering as illusory.

"With the Outer Solar System Origins Survey, we don't have strong evidence for clustering," says Michele Bannister, an astronomer at the University of Canterbury in New Zealand and a member of that collaboration. The survey's design made it possible for her and her colleagues to spot extremely faint bodies that were not seen before and to more systematically assess whether they are clustered in an unlikely configuration. The distant objects they found could simply be part of a larger population that is evenly spread out. New findings by members of the Dark Energy Survey point to a similar conclusion, but they, too, have discovered only a handful of objects.

The reality of small-number statistics, of seeing only a few glimmers of patterns and structures in the vast darkness, is what makes it extremely difficult to test ideas about the outer solar system—including searches for a concealed planet or for a disk of scattered bodies. Everything spotted there so far is faint, dark and small. Many are so remote that they take millennia to complete a single revolution around the sun, making it far harder for astronomers to efficiently determine the properties of their orbits.

In addition to explaining observations that have already been made, Madigan and her colleagues have begun making predictions. If they are right, there should be a huge gap in the distant objects' orbits: a region almost entirely swept free of debris and approximately centered at a point 50 times Earth's distance from the sun. If Planet Nine exists instead, there should not be such a wide gap. "I'm delighted to see that as the depths of the solar system get mapped out, it's creating this kind of theoretical enthusiasm and innovation," Bannister says, referring to both collective gravity and Planet Nine.

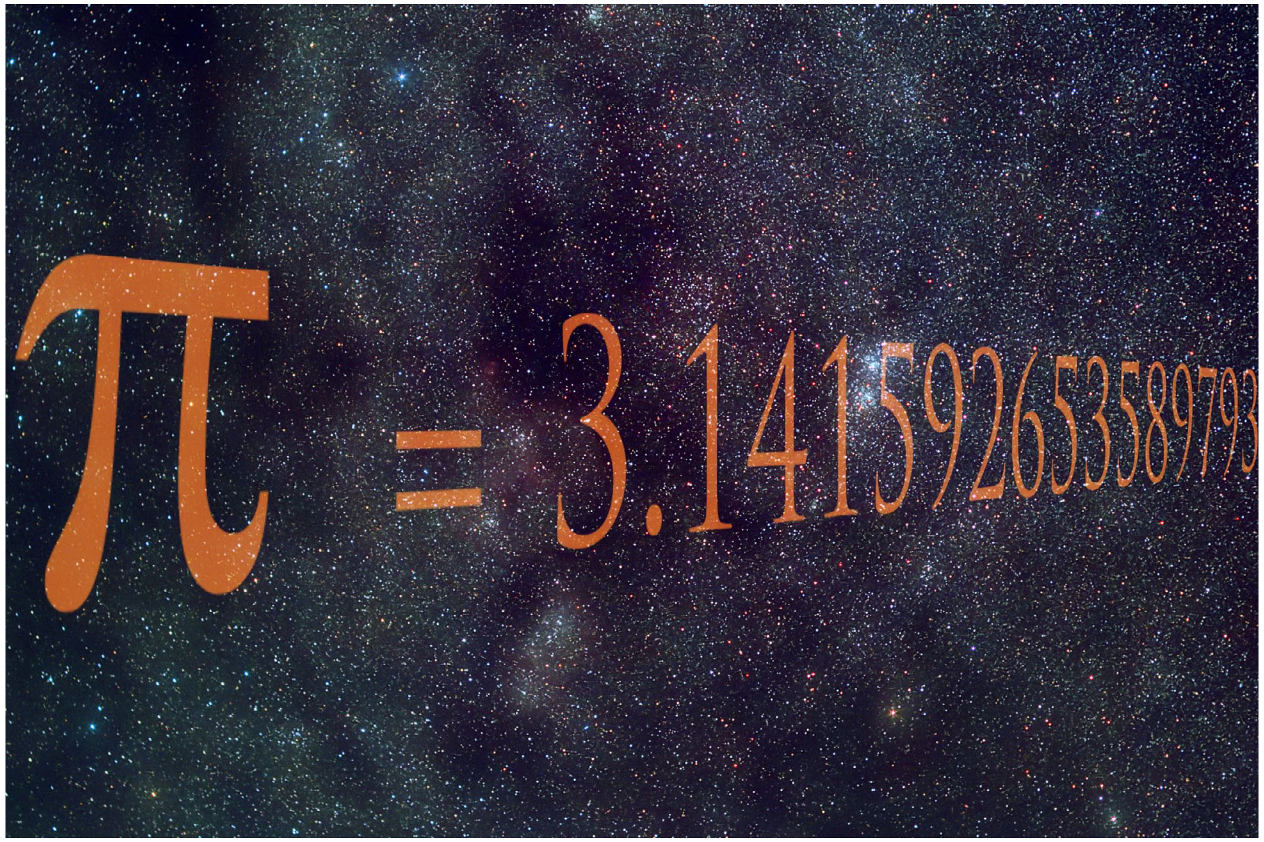
While Madigan, Batygin and other astrophysicists marshal additional pieces of indirect evidence to make their case and look for new predictions to test, they are also waiting for observations from more sensitive upcoming telescopes in the hope of directly settling the debate. The Vera C. Rubin Observatory, being built atop a desert mountain in northern Chile, will map small objects in the outer solar system to much greater depth and precision than before. And the telescope will see "first light" as early as fall 2021.

"Something really odd is going on in the outer solar system, and there has to be more mass out there. If [our hypothesized disk] is not observed with the Rubin Observatory, it's not there—and then it's Planet Nine," Madigan says. "It has to be one or the other."

—Ramin Skibba

Pi in the Sky: General Relativity Passes the Ratio’s Test

Using gravitational waves to approximate pi, physicists see no problem with Einstein’s theory



IGOR SOKALSKI *Getty Images*

At least 3,700 years ago, Babylonian mathematicians approximated the ratio of a circle’s circumference to its diameter. They inscribed their answer, the first discovered value of pi, on a humble clay tablet: 25/8, or 3.125. Now Carl-Johan Haster, a theoretical astrophysicist at the Massachusetts Institute of Technology, has managed to do almost as well: in a study uploaded to the preprint server arXiv.org, he measured pi as about 3.115.

In the intervening years, researchers have calculated the true value of the ratio to a modest 50 trillion decimal places with the aid of powerful computers (you probably know how it starts: 3.141592653 ... and on into infinity). Haster’s approximation of it may be a couple of millennia behind in terms of accuracy, but that fact is of little relevance to his real goal: testing Einstein’s general theory of relativity, which links gravity to the dynamics of space and time.

Information about the laws of physics is effectively baked into gravitational waves, the ripples in spacetime created when massive objects such as black holes spiral into one another. Haster, a member of the Laser Interferometer Gravitational-wave Observatory (LIGO) Scientific Collaboration, noticed that pi appeared in several terms of an equation describing the waves’ propagation.

“What Carl did was say, ‘Look, all of these coefficients depend on pi. So let’s change pi, and let’s check whether the measurements are consistent [with general relativity],’ ” says theoretical physicist Emanuele Berti of Johns Hopkins University, who was not involved in the new study and who is not part of the LIGO collaboration.

Haster realized that he could treat pi as a variable instead of a constant. Then he could check the equation for gravitational waves against LIGO’s experimental measurements of them. Einstein’s theory should have matched the measurements if and only if Haster used values of pi close to that already determined by other methods. If general relativity matched LIGO’s measurements when pi was not close to its true figure, that would be a sign that the theory was only half-baked. By trying values of pi from −20 to 20, Haster checked more than 20 observed candidate gravitational-wave events and found that the figure that matched theory to experiment was about 3.115. So Einstein’s recipe does not seem to need any tweaking just yet. “In my head, at least, [the study] has a nice mix of being both kind of cute and amusing and also actually producing a valid and fairly strong test of general relativity,” Haster says.

Pi seems to pop up all the time—not just explicitly in circles but in the hydrogen atom and in the way needles fall across lines. The reason a factor of pi appears in an equation for gravitational waves is a little headier, however: the waves interact with themselves.

“When a gravitational wave is traveling out, it sees the curvature of spacetime, including the energy that was generated by the gravitational waves produced in the past,” Berti says. The first stone you drop into a calm pond sends out smooth ripples across the surface. If you drop another stone immediately after, the surface is no longer smooth—leftover ripples from the first stone will interfere with new ripples from the second one. Gravitational waves work similarly, but the medium is spacetime itself, not water.

The equation describing this self-interacting effect contains factors of pi as a piece of several numerical terms. A previous examination of Einstein's theory by LIGO in 2016 varied individual terms instead of slicing out a common factor across several terms such as pi. Although this approach sufficed as a test of general relativity, physicists have wanted to see all the terms changing together, and Haster's method using pi offers a way of doing just that.

But it remains far from transcendental as a test of the theory. One issue is the relative uncertainty of Haster's figures: his approximation of pi currently ranges from 3.027 to 3.163. Significantly sharpening it will require observing mergers of lighter objects such as neutron stars, which create drawn-out gravitational waves that can last 300 times longer than those from a colliding pair of massive black holes. Like trying to identify an unknown song, the more one can listen, the better. Currently there are only two recorded confirmed neutron star mergers in the available data. And until LIGO—which is shut down because of COVID-19—resumes operations, that number will not change.

Not everyone is worried about the flakiness of this pi-scrying technique, though. "Many people have been discussing the fact that we could maybe change Pi Day (March 14) into 'Pi Two Weeks' (March 2 to March 15) to account for current uncertainty," jokes Christopher Berry, an astrophysicist at Northwestern University, who was not involved in the new study and is part of the LIGO collaboration.

This proposal would, of course, likely increase the number of pastries for a pi-loving physicist to consume. But Berry maintains that the calorie increase would not be altogether a bad thing. A fortnight of feasting, he says, would eventually give researchers another way to approximate pi: measuring their own rotund circumference.

—Daniel Garisto

Astronomers May Have Found the Closest Black Hole to Earth

At just 1,000 light-years away, an object in a nearby star system could be our nearest known black hole—but not everyone is convinced

Black holes might be black, but they are not necessarily invisible. They come in a variety of sizes, from minuscule to supermassive, with a key common feature: a boundary known as the event horizon, beyond which light cannot escape. Black holes near an object such as a star, however, can brighten when they feed, flaring as superheated dust and gas swirl down to oblivion. Those without such a companion are much more difficult to spot, black as they are, but they can still be indirectly detected via their gravitational effects on other nearby objects.

In a paper published in the journal *Astronomy & Astrophysics*, researchers say they have made just such an observation—unveiling what may be the closest known black hole to Earth. Their investigation of HR 6819, an otherwise inconspicuous star system that is faintly visible to the naked eye in the southern constellation of Telescopium, revealed that one of its two known stars appeared to be orbiting an unseen object once every 40 days. Closer inspection, the team says, showed this unseen object to be a black hole with a mass estimated at 4.2 times that of our sun. A star of comparable mass in HR 6819 would likely be bright enough to easily see, the researchers say. A black hole is therefore the most probable explanation.

"We initially thought [HR 6819] was a binary [system]," says Thomas Rivinius of the European Southern Observatory (ESO), who is the study's lead author. "But when we looked closer, we saw it was not a binary; it was actually three [objects]."

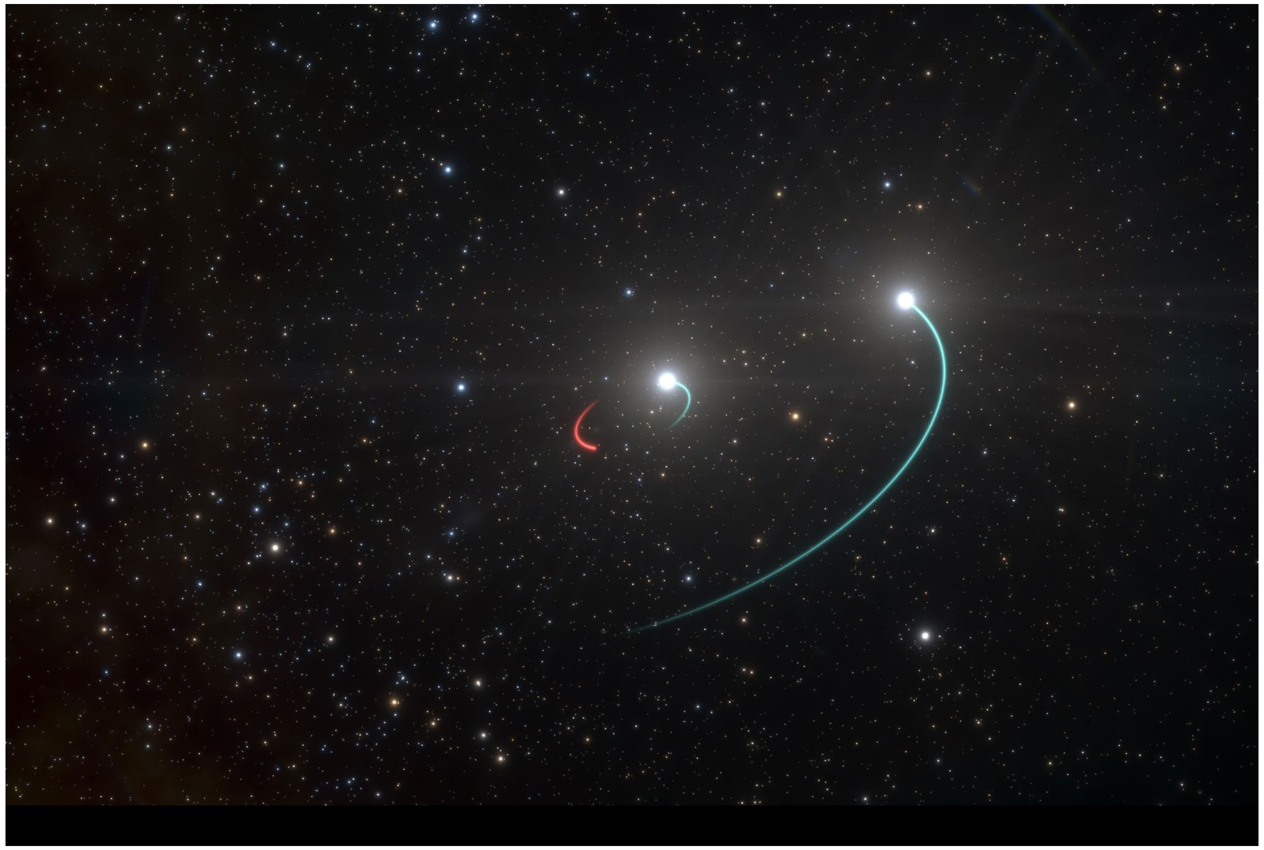
The astronomers used a 2.2-meter telescope at the ESO's La Silla Observatory in Chile to make the discovery. But this detection was not a recent one: the observations enabling the discovery were actually performed over several months back in 2004. Last year, however, the announcement of a possible black hole in a similar system called LB-1, which caused some debate, prompted Rivinius and his team to reexamine their archival data. “It looked exactly the same,” he says. “I thought, Wait a second. I have something in my drawer of unused data that looks pretty much like [LB-1].”

The team believes the black hole in the HR 6819 system is the result of a star there exploding as a supernova tens of millions of years ago, based on the supposed ages of the system’s two remaining stars. It was not noticed until now because its orbital separation from its companion stars is sufficient to currently prevent it from feeding on them. In contrast, other known black holes in binary systems are the companion of a star that they feast from and are surrounded by glowing disks of material emitting copious x-rays. Astronomers have found only a few dozen of these “x-ray binaries” among the hundreds of billions of stars in our galaxy.

If it indeed hosts a black hole, HR 6819 has some interesting implications. For starters, supernovae are expected to give any nearby stars a gravitational “kick,” potentially disrupting their orbit and sending them flying off into interstellar space. “The fact that this triple system still exists tells us there cannot have been a strong kick, if at all,” Rivinius says. “So that [would be] something new learned about supernovae—that black holes can form without kicks.”

Another implication is that quiescent black holes like this could be much more common than thought, suggesting there are many more to be discovered. It may even be that LB-1 is another example of this heretofore unknown class of black hole systems. Being more distant and fainter, however, it is much harder—though not impossible—to observe. “We have proposed to” study LB-1 as well, Rivinius says.

HR 6819 would also provide some tantalizing hints for how black hole binaries that produce gravitational waves are formed. Such systems, be they two black holes or a black hole and a neutron star, are known to produce these ripples in spacetime when they merge. But how they came to be before merging remains a topic of intense debate in astrophysics. “It’s really unknown,” says Laura Nuttal of the University of Portsmouth in England, who was not involved in the study. “There’s still no clear indication [of] exactly what the formation channel is.”



Artist’s impression of the orbits of objects in the HR 6819 triple system. Besides two stars (*orbits shown in blue*), the system also contains a quiescent stellar-mass black hole (*orbit shown in red*).

ESO/L. CALÇADA

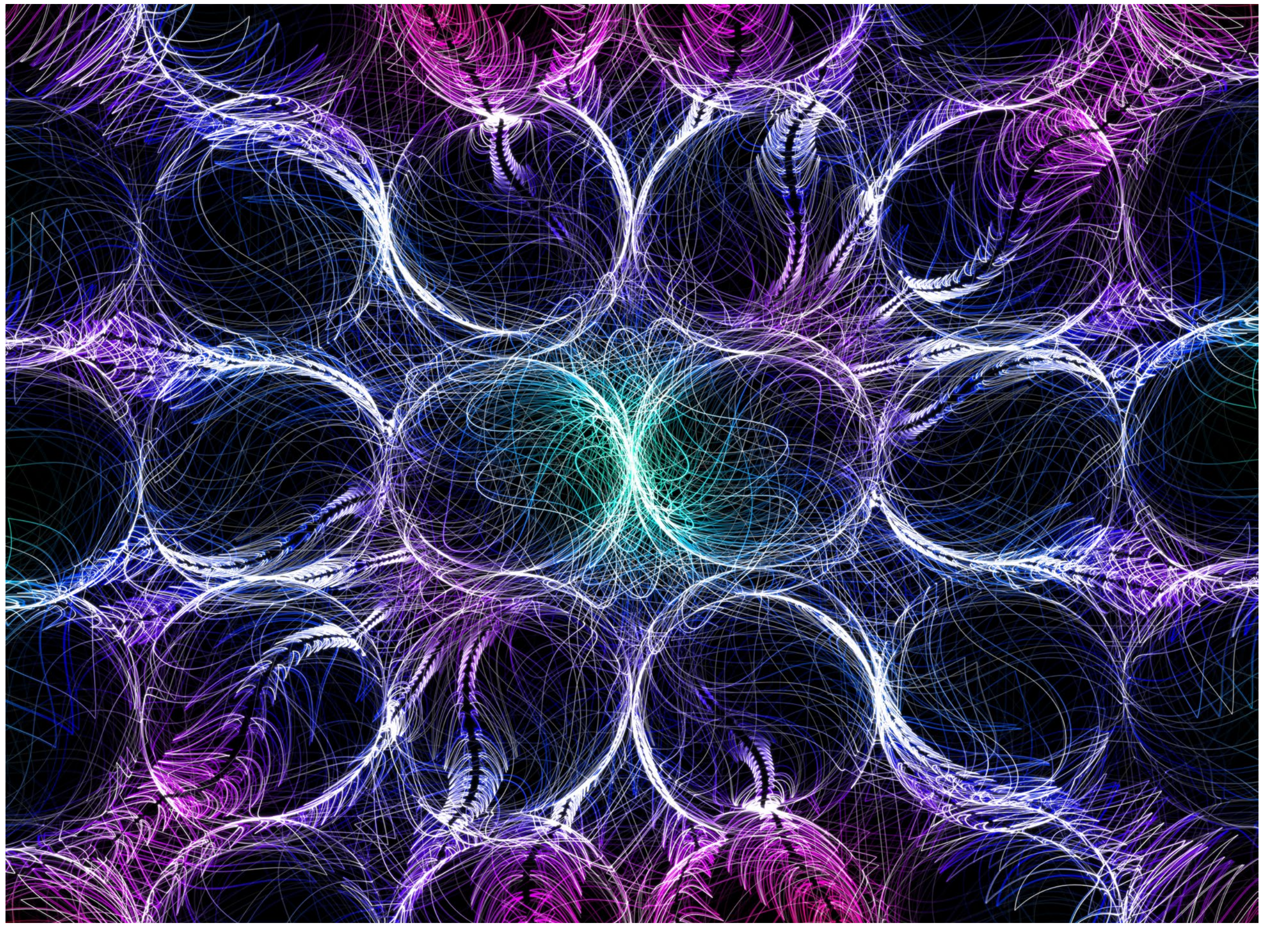
Kareem El-Badry of the University of California, Berkeley, who was also not a part of the study, finds that its claim of discovering the closest black hole ever observed is “definitely plausible.” He notes, however, that this conclusion relies on a few assumptions, notably that the system’s innermost star orbiting the black hole would be about five solar masses. “I think this is less secure,” he says. If that inner star were not as massive as Rivinius and his team assumed, the unseen object would be less massive, too—and potentially not a black hole at all. “I don’t think it’s an imprudent thing to say it’s probably a black hole. But there is some uncertainty there,” El-Badry says.

It is also not currently possible to tell whether the supposed black hole is a single object of 4.2 solar masses or two stars of 2.1 solar masses closely orbiting each other, says Edward van den Heuvel of the University of Amsterdam, who was not involved in the study. "It would be a quadruple [star system], but there are lots of quadruple systems among the bright stars in the sky," he says. "If the thing would start emitting x-rays at some point, we would be sure it was a black hole. But if it never does that, then we stay with the problem: Is it a black hole, or could it be a closed binary of two stars?"

Rivinius, however, says that evidence of such a quadruple system—effectively two binaries co-orbiting each other—would be notable in the emitted light from HR 6819. Ultimately, further studies of the system requiring longer stares with more telescopes will be needed to answer some of these questions. "As soon as our observatories start operating again, we shall try that," Rivinius says, noting the shuttering of telescopes across the globe in response to the ongoing coronavirus pandemic. For the time being, at least, our solar system seems to have a new dark companion lurking in its galactic backyard. —*Jonathan O'Callaghan*

Direct Proof of Dark Matter May Lurk at Low-Energy Frontiers

Mysterious effects in a new generation of dark matter detectors could herald a revolutionary discovery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Even after decades of searching, scientists have never seen a particle of dark matter. Evidence for the substance's existence is close to incontrovertible, but no one yet knows what it is made of. For decades physicists have hoped dark matter would prove to be heavy, consisting of so-called weakly interacting massive particles (WIMPs) that could be straightforwardly detected in the lab.

With no definitive sign of WIMPs emerging after years of careful searching, however, physicists have been broadening the scope of their quest. As new, more precise experiments allow them to ramp up data collection, researchers are reassessing theories about how dark matter particles lighter than a proton might appear in their detectors. Two papers posted on the preprint server arXiv.org earlier this year are emblematic of these shifting sensibilities. They are the first to propose that a detector could find plasmons—aggregates of electrons moving together in a material—produced by dark matter.

The first study was conducted by a group of dark matter researchers at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill., the University of Illinois at Urbana-Champaign and the University of Chicago. They propose that low-mass dark matter could produce plasmons—which they claim some detectors might already be seeing. Inspired by that first paper, physicists Tongyan Lin and Jonathan Kozaczuk, both at the University of California, San Diego, calculated how likely low-mass dark matter is to generate plasmons in a detector.

“We are screaming, ‘Plasmon, plasmon, plasmon!’ because that’s a compelling, existing phenomenon that we think might be relevant for interpreting dark matter experiments,” says Gordan Krnjaic, a dark matter theorist at Fermilab and at the Kavli Institute for Cosmological Physics at the University of Chicago and a co-author of the first study. Particle physicists and astrophysicists have been speculating about how to detect low-mass dark matter for nearly a decade. But they had not previously considered seeking plasmons—which are more familiar to chemists and material scientists—as its signature.

“I think it’s great,” says Yonit Hochberg, a theoretical physicist at the Hebrew University of Jerusalem, who provided feedback to Krnjaic’s team but was not directly involved in either study. “The fact that there are [plasmons] that could be having an impact that haven’t been taken into account is, I think, an extremely important point that really warrants further investigation.”

Other researchers are more dubious about the first paper. That study is “not at all convincing to me,” says Kathryn Zurek, a dark matter theorist at the California Institute of Technology, who was not involved with either study. “I just don’t see how this works.”

Noah Kurinsky, a co-author of the first paper and a dark matter experimentalist at Fermilab and at the Kavli Institute for Cosmological Physics, takes criticism from physicists in stride. “We’ve challenged them to prove us wrong, which I think is superhealthy for this field. And that's exactly what they should be trying to do,” he says.

COME TOGETHER

The hunt for an invisible, nearly traceless substance usually goes something like this: To detect dark matter particles, physicists get a material, put it somewhere deep underground, hook it up to instruments and hope to see a signal. Specifically, they hope dark matter will strike the detector, producing electrons, photons or even heat that their instruments can observe.

The theory behind dark matter detection dates back to a 1985 paper that considered how a neutrino detector could be repurposed to look for particles of the substance. The study proposed that an incoming dark matter particle could hit an atomic nucleus in the detector and give it a kick—similar to one billiard ball crashing into another. This collision would transfer momentum from the dark matter, walloping the nucleus hard enough to make it spit out an electron or a photon.

At high energies, this picture is essentially fine. Atoms in the detector can be thought of as free particles, discrete and unconnected to one another. At lower energies, however, the picture changes.

“Your detectors are not made of free particles,” says Yonatan (Yoni) Kahn, a dark matter theorist at the University of Illinois at Urbana-Champaign and a co-author of the first paper. “They’re just made of stuff. And you have to understand the stuff if you want to understand how your detector actually works.”

Within a detector, a particle of low-mass dark matter would still transfer momentum. But instead of breaking a rack of billiard balls, it might cause them to wobble. In others words, it would act more like a Ping-Pong ball.

“As we go to lower dark matter masses, there are other, more subtle effects that start to kick in,” Lin says. These subtle effects include what physicists like to call “collective excitations.” When several particles move at once, they can be described as a single entity, just as a sound wave is composed of multitudinous vibrating atoms.

Plasmons occur when a group of electrons experiences such motions. When atomic nuclei in a group vibrate, their collective excitation is instead called a phonon. Such phenomena are typically seen as irrelevant by astrophysicists and high-energy physicists studying dark matter.

But as the late physicist and Nobel laureate Philip Anderson once quipped, “More is different”—a nod to the fact that novel effects emerge at different scales. A droplet of water, for example, obeys different rules than an individual molecule of H_2O. “I have totally drunk that Kool-Aid,” Kahn says.

The two papers take slightly different approaches to plasmon production. They come to the same conclusion, however: we should really be on the lookout for such signals. In particular, Lin and Kozaczuk calculated that low-mass dark matter would create plasmons at about one ten-thousandth the rate of directly producing an electron or photon. This may sound infrequent, but it is more than enough for physicists looking to be precise.

SHOT IN THE DARK

Until recently, the most sensitive dark matter detectors used giant vats of liquid xenon. In the past few years, however, a new generation of smaller solid detectors have debuted. Known by clever acronyms such as EDELWEISS III, SENSEI and CRESST-III, they are made of materials such as germanium, silicon and scheelite and are sensitive to dark matter collisions that would create just a single electron.

But all detectors, no matter how well shielded, experience noise from sources such as background radiation. So over the past year or so, when scientists operating several dark matter detectors began seeing more signals at low energies than expected, they stayed rather quiet about it.

The paper by Kurinsky and his colleagues was the first to point out the remarkable similarity between the low-energy "excesses" seen across disparate dark matter experiments. Several excesses seem to cluster around a value of 10 hertz per kilogram of detector mass. Because the detectors are made of different materials, are located in different places and operate under different conditions, it is difficult to come up with a universal reason for this uncanny harmony—except, that is, for the subtle influence of dark matter. This discussion caught the attention of other physicists, such as Lin, who quickly jumped to work on plasmon calculations. But even she has doubts that what the experiments are currently seeing are the results of dark matter creating plasmons. "I'm not saying it couldn't be dark matter," Lin says. "But it doesn't seem convincing to me so far."

As more data come in from the latest generation of dark matter detectors, the hypothesis will be put to the test. But whether or not the detectors are currently seeing the mysterious substance may be beside the point. Researchers in the field are now thinking and talking about plasmons and other ways in which low-mass dark matter could behave. An exploration of the precision frontier is underway.

"There are many ways in which we can be wrong," Krnjaic says. "And they're all exciting."

—Daniel Garisto

Astronomers Get Earliest Ever Glimpse of Ancient Giant Galaxy

The disk of gas and stars resembles our own Milky Way but somehow formed when the universe was only about 10 percent of its current age

A massive galaxy similar to our Milky Way created shockingly early in the universe's history is challenging astrophysicists' understanding of galaxy formation. With observations placing it just 1.5 billion years after the big bang, when the universe was some 10 percent of its current age, the spinning disk of gas and stars is the earliest of its type ever identified. And it provides strong evidence that some of the first galaxies got off to a cold start.

In standard formation models, galaxies coalesce as gas collects in and around diffuse "halos" of dark matter. All that gas becomes extremely hot as it funnels down into the heart of the newborn galaxy, and it must take time to cool down before it can begin forming stars. In contrast, more recent simulations suggest that gas flowing into young galaxies along long filaments of dark matter can remain relatively cool, allowing star formation to begin sooner. These "cold start" galaxies should form spiral-like disks that resemble the Milky Way.

So far most of the early galaxies observers have managed to identify have been irregular blobs without disks, their shapes distorted and their gas heated by repeated collisions with protogalaxies. Astronomers have indeed found a handful of disk galaxies from the first few billion years of the universe's history. But some researchers argue that these objects are old enough for their gas to have already cooled down, making their origins indefinite.

This particular disk galaxy, however, defies such objections. "We found a galaxy that has a lot of cold gas in it," says Marcel Neeleman, an astronomer at the Max Planck Institute for Astronomy in Heidelberg, Germany, and first author of a study reporting the observations, which was published in the May 21 issue of the journal *Nature*. "If it had formed through hot-mode accretion, it wouldn't be there."

Coral Wheeler, an astronomer who studies galaxy evolution at the

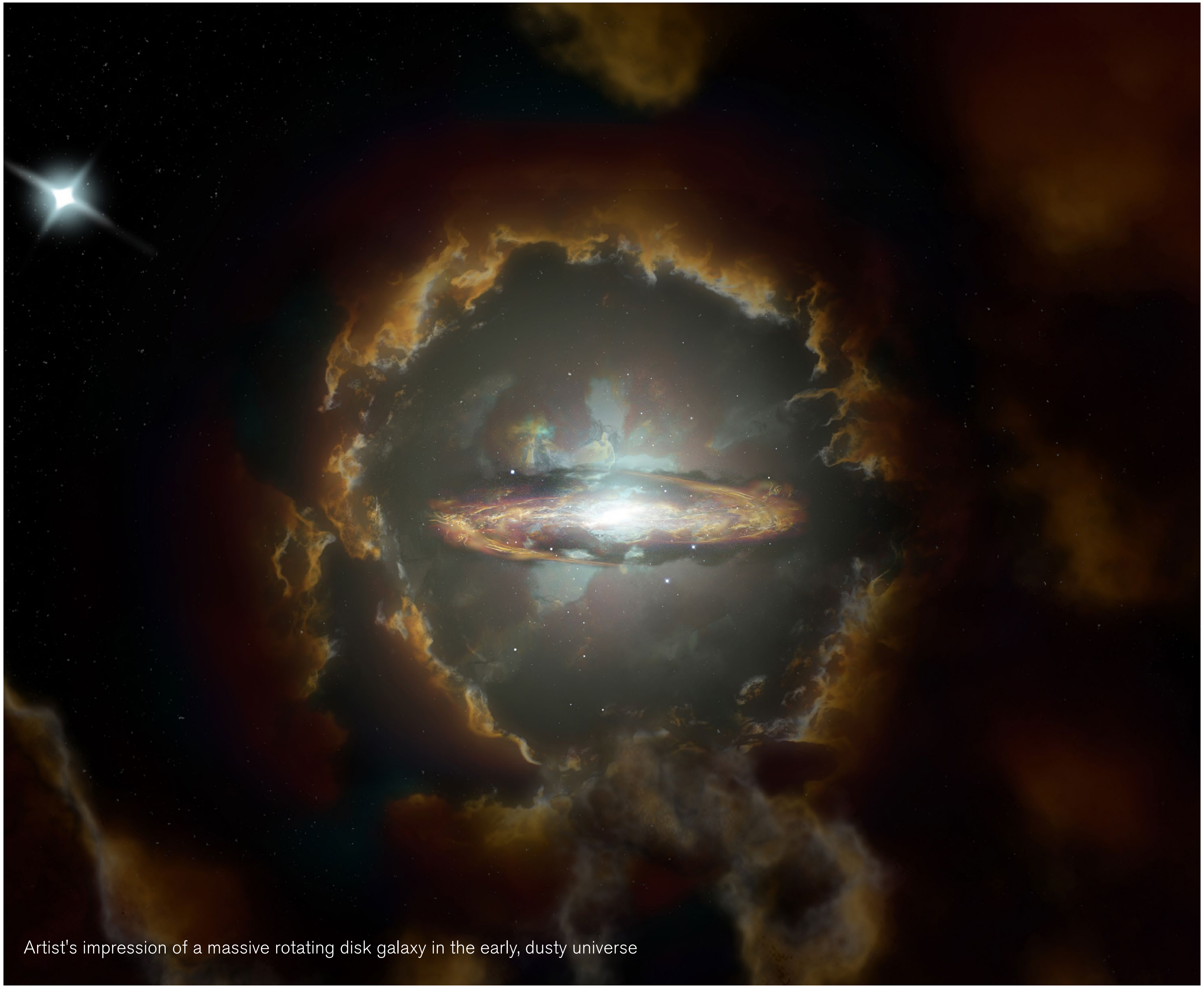
University of California, San Diego, agrees. The galaxy provides "very strong evidence of cold-mode accretion," she says. (Wheeler was not part of the study.)

Neeleman and his colleagues claim that the new finding means that most of the first generation of galaxies formed through either cold-mode accretion or collisions with other young galaxies.

HUNTING SHADOWS

Researchers have long argued over whether gas pouring into the earliest galaxies was hot or cold. Simulations favor cold gas, but skeptics have raised questions about the validity of those virtual conclusions. And they have done so for good reason: by necessity, those models have simplified many of a galaxy's most salient environmental effects, such as feedback processes from supernovae and black holes that could heat otherwise cool gas.

"There's been a controversy about this over the past couple decades now," says Ryan Trainor, an astrophysicist at Franklin & Marshall College, who was not involved in the *Nature* study. One of the challenges of hunting for early galaxies is the need for targets that are big and bright enough to be seen



Artist's impression of a massive rotating disk galaxy in the early, dusty universe

NRAO, AUI AND S. DAGNELLO NSF

across immense cosmic distances. As a result, the most luminous objects are the ones most likely to be observed. To overcome this bias, Neeleman and his colleagues decided to utilize a method pioneered by the late astronomer Arthur Wolfe. Using the Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile, they hunted for galaxies in front of quasars, the brightest known objects in the universe. As light from a quasar passes through a foreground galaxy, the gas from that galaxy absorbs some of the light, creating what Neeleman calls "shadows."

By studying the shadows, or absorption lines, with ALMA, the astronomers could track the rotating motion of the dim gas of the galaxy DLA0817g, which they discovered in 2017. They nicknamed it the Wolfe Disk in honor of the team members' former adviser and colleague. Follow-up observations with the Hubble Space Telescope revealed some of the galaxy's brightest stars, which the scientists used to estimate that the Wolfe Disk is churning out an average of 16 sun-sized stars every year. Hubble's scrutiny also revealed that the gas blocking the quasar came not from the heart of DLA0817g but from the galaxy's outer edges—a region where gas would be expected to thin out rather than thicken. The researchers suspect that what they are seeing is one of the dark matter filaments funneling gas into the Wolfe Disk.

"We can't prove it's a filament, but it's well beyond the star-forming region of the galaxy," says team member and study co-author J. Xavier Prochaska, an astronomer at the University of California, Santa Cruz.

By using quasars, the team hoped to overcome the observing bias faced in previous studies. To some degree, they were successful. "You probably end up with a fairer sampling of the galaxy population this way," says Alfred Tiley, an astronomer at the University of Western Australia. Tiley, who was not involved in the research, authored an accompanying commentary about it in *Nature.*

Not everyone is convinced. Trainor thinks Neeleman and his colleagues' new method avoids the bias of brightness but may come with its own prejudices. "Their technique is biased toward finding stable rotating disks," he says. The extended disks created by cool galaxies are more likely to obscure a quasar than a more compact galaxy might. "It's like throwing darts at a dartboard," Trainor says. "The larger dartboard is more likely going to get hit." That analogy does not diminish the technique, which he calls "a really useful and complementary tool."

Although Prochaska agrees that larger galaxies are more likely to block quasars, he argues that the Wolfe Disk's extended gas in front of the background quasar does not necessarily have a bearing on the galaxy's structure. The large distribution of gas around a quasar-blocking object could come from a spheroidal shell of gas around the galaxy or from extended filaments funneling gas into it.

Trainor questions how common galaxies like the Wolfe Disk might be in the early universe. He is not convinced that a single galaxy is enough to demonstrate that cold accretion dominated early-galaxy formation. But new galaxies may be uncovered soon. Neeleman's team plans to continue using ALMA to study quasar-shadowed galaxies in hopes of finding more.

"It's clear now that you can do this in a subset of cases very early on," Prochaska says of cold-mode accretion. "We're all a bit surprised."

—Nola Taylor Redd

A Hydrogen Iceberg from a Failed Star Might Have Passed through Our Solar System

The interstellar visitor 'Oumuamua, discovered in 2017, may represent an entirely new type of astrophysical object, two astronomers say

Our sun is a ship, our galaxy the sea. Moving in cosmic currents, our star completes a lap of the Milky Way every 230 million years or so with its retinue of planets in tow. For the most part, this journey is solitary save for the occasional close encounter with another star. But a few years ago something remarkable seems to have occurred. While traversing this vast, magnificent ocean, our sun may have come across a cosmic iceberg, a sizable hunk of hydrogen ice adrift in space. As unlikely as this scenario might seem, given that it would involve a new type of astrophysical object that has never been seen before, the evidence is strangely compelling—and the implications are broad.

The idea is the conclusion reached by Darryl Seligman of the University of Chicago and Gregory Laughlin of Yale University in a paper to be published in the *Astrophysical Journal Letters* (a preprint is available at arXiv.org). They examined existing data on an object called ‘Oumuamua, which in October 2017 became the first interstellar object discovered in our solar system. Since then, there has been some debate over whether it was a comet or an asteroid; no one is quite sure. Seligman and Laughlin, however, say the object was neither. “We’re proposing that ‘Oumuamua was composed of molecular hydrogen ice,” Seligman says. “Basically, it was a hydrogen iceberg.”

Astronomers first spotted ‘Oumuamua after it had already made its closest approach to our sun, when it was on its way out of our solar system. That situation made observations somewhat difficult, but researchers were able to discern a few of the object’s features. It measured about 400 meters long, was shaped like a cigar and was spinning rapidly at roughly one revolution every eight hours. Astronomers deduced that it had been born elsewhere because its ex-

Composite image of a giant molecular cloud. One of these dust- and gas-filled stellar nurseries may have also spawned the strange interstellar object ‘Oumuamua.’

NASA, CXC, PSU AND L. TOWNSLEY ET AL. *(X-RAY)*; NASA AND JPL-CALTECH *(INFRARED)*

tremely high-speed trajectory through our solar system suggested that it was moving too fast to be bound to our sun. But somewhat surprisingly, ‘Oumuamua exhibited a slight but significant acceleration as it moved away—the exact opposite of what would be expected to happen to an outbound object fighting against the sun’s gravitational grip. “It was extremely weird,” Seligman says. “This was a force continuously pushing away from the sun with a magnitude of about one one-thousandth of the solar gravitational acceleration.”

Efforts to explain this anomalous acceleration suggested it may have been linked to vaporous jets of sunlight-warmed water ice blasting into space and pushing the object along. But that event alone could not have produced a force large enough to account for the observed acceleration, Laughlin and Seligman claim. “It would require more than 200 percent of the surface to be covered in water,” Seligman says. Seeking more plausible explanations, the researchers examined other types of ice that might have produced sufficiently potent jets to account for the acceleration. And the thing that worked best was hydrogen. “Because molecular hydrogen ice is held together so loosely, you only need 6 percent of the surface to be covered in [it],” Seligman says.

That scenario in itself would have some pretty fascinating implications for where ‘Oumuamua came from. Hydrogen ice sublimates (changes from solid to gas) at an extremely low temperature of just –267 degrees Celsius—only slightly higher than the ambient temperature of space: –270 degrees C. That fact suggests that a hydrogen-ice-rich ‘Oumuamua must have formed somewhere extremely cold. The best bet for such a chilly birthplace would appear to be within a giant molecular cloud—accumulations of dust and gas tens to hundreds of light-years wide where star formation takes place.

Over many millions of years, about 1 percent of the material in a typical giant molecular cloud will come together under the force of gravity to form stars. Before dissipating, each cloud can create thousands of stars, as well as myriads of protostellar cores—half-baked clumps of gas roughly the size of our solar system that never get compact enough to begin nuclear fusion and “switch on” as full-fledged stars. Within such a core’s lightless, dense depths, conditions can be cold enough for hydrogen ice to form.

“It was extremely weird,” Seligman says. “This was a force continuously pushing away from the sun with a magnitude of about one one-thousandth of the solar gravitational acceleration.”

“If you want to get that amount of hydrogen ice, you want to start with a very, very cold environment,” says Shuo Kong of the University of Arizona, an expert in molecular clouds, who provided feedback for Seligman and Laughlin’s research but was not directly involved in the study. “And the coldest environment that is not very far from us would be these starless cores inside molecular clouds. They have very low temperatures in their central regions. So they could be the promising place for the formation of ‘Oumuamua.”

If the idea is true, the object would offer an unprecedented glimpse into these cauldrons of stellar formation. “The reason why that star-formation process is so inefficient in molecular clouds is not fully understood,” Laughlin says. “If these molecular-hydrogen objects are being formed, what that is telling us is the temperature in some clouds has to get extremely low and the densities have to get relatively high. It’s providing a very interesting calibration point as to what conditions are leading to the formation of stars and planets.”

Bizarre as it might seem, this theory appears to explain a lot of ‘Oumuamua’s oddities. Aside from the unusual acceleration, it would reveal why it entered our solar system at 26 kilometers per second—close to the speed at which the sun travels relative to the average velocity of other nearby stars. The object was not moving toward us. Rather we sailed toward it as it simply sat motionless after its initial protostellar core’s failure to become a star.

'Oumuamua's unusual cigar shape also can be explained by the theory. It may actually have been three times larger and spherical in shape—and composed of 99 percent hydrogen ice—when it first formed, likely less than 100 million years ago. The ice would have been worn away as it approached our sun and was heated for the first time, eventually dwindling into its elongated shape in the same way that a bar of soap wears down into a thin sliver over time.

The fact that 'Oumuamua was discovered so rapidly and easily—as part of a four-year survey—also posed a problem for theorists. If it were an interstellar comet or asteroid—like the undisputed interstellar comet Borisov found in 2019—that conclusion would suggest that such objects are up to 100 times more prevalent than had been thought. In contrast, the "molecular cloud" theory of 'Oumuamua's origins would suggest that there might be billions on billions of these objects in the galaxy, in accordance with its quick discovery. "Even though it's only one object that we observed, the number density that is implied is too high," says Amaya Moro-Martín of the Space Telescope Science Institute, who proposed a different theory for 'Oumuamua's origin last year. "This proposal might solve that problem."

Testing the theory on 'Oumuamua any further is now impossible: the object is long gone from our sights. But with a bit of luck, astronomers could sooner or later evaluate the predictions. If they spot a similar interstellar interloper entering our solar system, they might observe a telltale change in the object's mass as its hydrogen ice sublimates away. Upcoming telescopes such as the Vera C. Rubin Observatory in Chile, set to begin a 10-year survey of the solar system in 2022, could look for more.

With proposals to visit some of these objects via missions such as Europe's Comet Interceptor, along with continued remote observations, the scientific possibilities for new investigations of the theory are tantalizing. Floating on our cosmic sea, these hydrogen icebergs that formed inside failed stars may lie in wait for us, secrets and all. "And there's so many of them that we can actually study them up close," Seligman says.

—Jonathan O'Callaghan

The First Footprints on Mars Could Belong to This Geologist

NASA astronaut Jessica Watkins is at the forefront of a new crop of space explorers destined for the moon and maybe one day Mars

Jessica Watkins spent her Ph.D. years studying landslides on Mars. Now she is among the few humans with a shot at being the first to walk on the Red Planet.

In January, Watkins graduated as a member of NASA's newest astronaut class. As a planetary geologist, she is a leading candidate to participate in the agency's Artemis program, which aims to send people back to the moon by the end of 2024. Further down the line—Watkins is only 32 years old—there might even be a trip to Mars.

More immediately, Watkins helped two of her fellow astronauts to prepare for a milestone launch on May 30, which was the first time a commercial company flew astronauts into low-Earth orbit.

Nature spoke to Watkins about her career and about the role of human endeavor in the age of a global pandemic.

Why did you decide to join the astronaut corps?

I have wanted to be an astronaut since I was pretty little. There was something that always pulled me toward space—the idea of exploration, of wanting to push boundaries and capabilities both technically and physically, but also mentally and spiritually. I kind of stumbled into geology and fell in love with that. And then the stars aligned for me to end up here.

What's your favorite planet?

Mars is definitely my first love. I remember writing a book about a Martian in fifth grade. What intrigued me the most about Mars is how Earth-like it is and how we're able to use the Earth as an analogue to understand more about Mars and Mars's history.

Now, given the direction that NASA is going in—we're talking about going back to the moon in 2024 through Artemis—the moon has become a significant interest as well.

I'm definitely brushing up on lunar geology and what it's going to be like on the surface.

What kind of training did your astronaut class get in field geology?
That was one of the most fun parts for me. We went to New Mexico, Utah, Arizona and a lot of the locations where the *Apollo* guys trained. We were literally following in their footsteps. We went to lots of lava flows just really trying to get a good understanding of what types of rocks we may encounter and how to observe and document them—learning just enough skills to enable scientists here on the ground to do their own investigations with the data the crew are obtaining.

What would it be like for you, as a geologist, to step onto the lunar surface?
The first [Artemis] mission or two may look more like test missions where the science might be more limited in order to prove technological capabilities. Thinking a little bit further down the line, when science is really a main goal, the landing site will drive a lot of the interesting scientific questions. Where we're thinking about going—the lunar south pole—one of the big things that we are looking for are potential ice deposits, volatile-rich regions in permanently shadowed regions.

Do you know what your first spaceflight assignment will be?
It is a superexciting time for human spaceflight. We have the International Space Station, which is our main destination right now, and soon we will start up the Artemis program. We are living in this awesome time where there are lots of possibilities. It all depends on how some of those moving pieces shake out. [My first flight] could be soon, or it could be a little bit longer.

How can space exploration inspire us when the world is facing a public health crisis?
This pandemic is asking us to band together as humans, to do the right thing to help save each other. There's something really analogous to human spaceflight in that. Human spaceflight is about humans pursuing hard things, doing it together and doing it in spite of differences that we may have created.

NASA astronaut Jessica Watkins

BILL STAFFORD NASA

Coming up [in May] we're going to be launching a new vehicle, a SpaceX launch in the commercial crew program, the first one from American soil since the space shuttle. That will be a shining moment for us, not just for America but for all humans, to be able to see beyond. Having that perspective allows you to see the Earth for what it is. It's one body. We're all in this together.

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Neutrinos Reveal Final Secret of Sun’s Nuclear Fusion

The detection of particles produced in the sun’s core supports long-held theory about how our star is powered

By Davide Castelvecchi

Our sun, as seen by NASA’s Solar and Heliospheric Observatory

SOHO (ESA & NASA)

Davide Castelvecchi is a senior reporter at *Nature* in London covering physics, astronomy, mathematics and computer science.

PHYSICISTS HAVE FILLED IN THE LAST missing detail of how nuclear fusion powers the sun, by catching neutrinos emanating from the star's core.

The detection confirms decades-old theoretical predictions that some of the sun's energy is made by a chain of reactions involving carbon and nitrogen nuclei. This process fuses four protons together into a helium nucleus, releasing two neutrinos—the lightest known elementary particles of matter—as well as other subatomic particles and copious amounts of energy. This carbon-nitrogen (CN) reaction is not the sun's only fusion pathway—it produces less than 1 percent of the sun's energy—but it is thought to be the dominant energy source in larger stars.

"It's intellectually beautiful to actually confirm one of the fundamental predictions of stellar structure theory," says Marc Pinsonneault, an astrophysicist at the Ohio State University.

The findings, which have not yet been peer-reviewed, were reported on June 23 by the Borexino underground experiment in central Italy, at the virtual Neutrino 2020 conference.

The facility previously made the first direct detections of neutrinos from three distinct steps of a separate reaction that accounts for most of the sun's fusion. "With this outcome, Borexino has completely unravelled the two processes powering the sun," said Borexino co-spokesperson Gioacchino Ranucci, a physicist at the University of Milan in Italy, who presented the results.

The findings are a final milestone for Borexino, which is still taking data but may now be destined to shut down within a year. "We ended with a bang," says Marco Pallavicini of the University of Genoa in Italy, the experiment's other co-spokesperson.

BALLOON DETECTOR

The Borexino solar-neutrino experiment occupies a hall under more than a kilometer of rock in the Gran Sasso National Laboratories, where it has been in operation since 2007. The detector consists of a giant nylon balloon filled with 278 metric tons of liquid hydrocarbons and immersed in water. The vast majority of neutrinos from the sun zip through Earth—and Borexino—in a straight line, but a tiny number bounce off electrons in the hydrocarbons, producing flashes of light that are picked up by photon sensors lining the water tank.

Neutrinos from the sun's CN reaction chain are relatively rare because it is responsible for only a small fraction of solar fusion. Moreover, the CN neutrinos are easy to confuse with those produced by the radioactive decay of bismuth 210, an isotope that leaks from the balloon's nylon into the hydrocarbon mixture.

Although the contamination exists in extremely low concentrations—at most a few dozen bismuth nuclei decay per day inside Borexino—separating the solar signal from bismuth noise required a painstaking effort that began in 2014. The bismuth 210 could not be prevented from leaking out of the balloon, so the goal was to slow the rate at which the element seeped into the middle of the fluid while ignoring any signals from the outer edge. To do this, the team had to control any temperature imbalances across the tank, which would produce convection and mix its contents faster. "The liquid must be extraordinarily still, moving at most at a few tenths of centimeters per month," Pallavicini says.

To keep the hydrocarbons at a constant, uniform temperature, they wrapped the entire tank in an insulating blanket and installed heat exchangers to automatically balance the temperature throughout. Then they waited. It was only in 2019 that the bismuth noise became quiet enough for the neutrino signal to stand out. By early 2020 the researchers had gathered enough of the particles to claim the discovery of detecting neutrinos from the CN nuclear fusion chain.

“It is the first really direct evidence that hydrogen burning through CN operates in stars,” says Aldo Serenelli, an astrophysicist at the Institute of Space Sciences in Bellaterra, Spain. “So this is really amazing.”

SUN SURFACE SPECULATION

As well as confirming theoretical predictions about what powers the sun, the detection of CN neutrinos could shed light on the structure of the core—specifically the concentrations of elements astrophysicists call metals (anything heavier than hydrogen and helium).

The amounts of neutrinos seen by Borexino seem consistent with the standard models in which the sun’s core has similar “metallicity” to its surface. But more up-to-date studies have begun to question that assumption, Serenelli says.

These studies suggest that the metallicity is lower. And because these elements regulate how fast heat diffuses from the sun’s core, this finding implies that the core is slightly colder than previously estimated. Neutrino production is extremely sensitive to temperature, and taken together, the various amounts of neutrinos seen by Borexino seem to be consistent with the older metallicity values, Serenelli says—not with the new ones.

As a possible explanation, he and other astrophysicists have suggested that the core has higher metallicity than the outer layers. Its composition could reveal more about early stages of the sun’s life, before the formation of the planets removed some of the metals that were accreting onto the young star.

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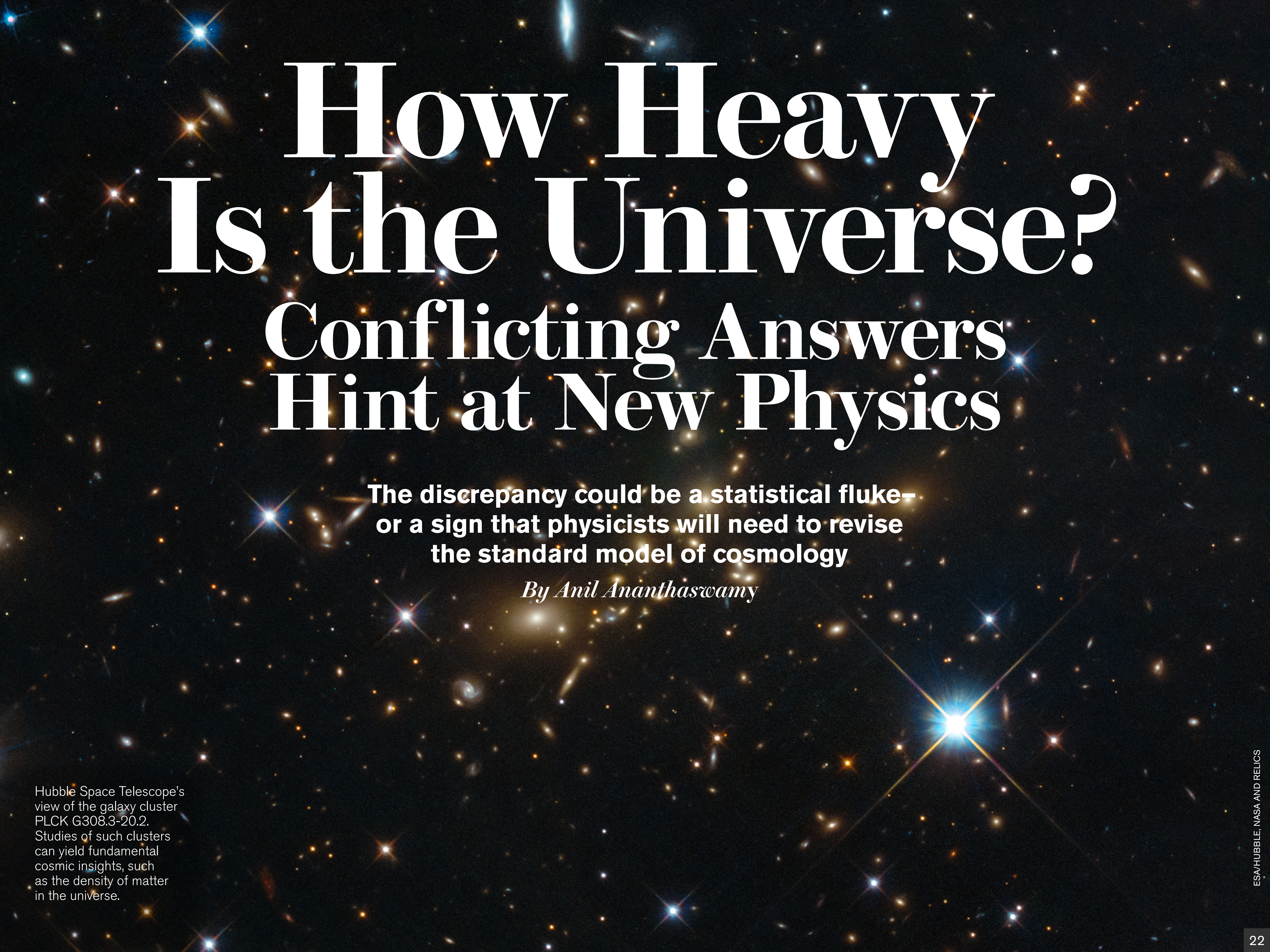


How Heavy Is the Universe?

Conflicting Answers Hint at New Physics

The discrepancy could be a statistical fluke—or a sign that physicists will need to revise the standard model of cosmology

By Anil Ananthaswamy

Hubble Space Telescope's view of the galaxy cluster PLCK G308.3-20.2. Studies of such clusters can yield fundamental cosmic insights, such as the density of matter in the universe.

ESA/HUBBLE, NASA AND RELICS

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.*

TWO ENTIRELY DIFFERENT WAYS OF "weighing" the cosmos are producing disparate results. If more precise measurements fail to resolve the discrepancy, physicists may have to revise the standard model of cosmology, our best description of the universe.

"If this really is a glimpse of the standard model breaking down, that would be potentially revolutionary," says astronomer Hendrik Hildebrandt of Ruhr University Bochum in Germany.

Similar concerns over the correctness of the standard model have been raised over the past few years by two independent calculations of the so-called Hubble constant, or the rate at which the universe is expanding today. Those two measurements also disagreed, creating what has been called the Hubble tension.

The new discrepancy—called the sigma-eight tension—involves measuring the density of matter in the universe and the degree to which it is clumped up, as opposed to being uniformly distributed. The result is encapsulated in a parameter called sigma-eight. To calculate sigma-eight, Hildebrandt and his colleagues turned to an effect called weak gravitational lensing, in which the light from distant galaxies is bent ever so slightly toward our telescopes because of the gravitational pull from matter that lies between the galaxies and Earth.

The resulting distortion is so small that it barely changes the shape of an individual galaxy. But if you take an average of the shapes of tens of thousands of galaxies in a patch of sky, a signal of weak lensing pops out. Presuming that galaxies should be randomly oriented with respect to Earth, their average shape should be nearly circular—without weak lensing, that is. But thanks to the mild distortions from this effect, the average shape instead veers toward the elliptical.

The astronomers used this signal to estimate the amount and distribution of intervening matter (both normal and dark varieties) along the lines of sight to various galaxy-rich regions across a large patch of the sky. In other words, they managed to measure matter's cosmic density.

But doing so precisely requires one more piece of information: the distance to each individual galaxy being studied. Normally, astronomers calculate the distance to another galaxy by finding its spectroscopic redshift—the amount by which the galaxy's light is shifted toward the longer wavelengths of the red side of the spectrum. The greater the redshift, the farther away the object.

Measuring individual spectroscopic redshifts, however, is extremely inefficient when dealing with millions of galaxies. So Hildebrandt's team turned to something called photometric redshift, which involves taking multiple images of the same patch of sky in different wavelengths spanning the optical and near-infrared ranges. The researchers used those images to estimate the redshift of individual galaxies in each one. "They're not as good as the traditional spectroscopic redshift," Hildebrandt says. "But they're much more efficient in terms of telescope time."

For its entire analysis, the team used high-resolution images of hundreds of square degrees of the sky (the full moon is about half a degree across) in nine wavelength bands—four optical and five near-infrared. These observations of about 15 million galaxies were collected by the European Southern Observatory's Kilo-Degree Survey (KiDS) and VISTA Kilo-Degree Infrared Galaxy Survey (VIKING) using two small telescopes at the organization's Paranal Observatory in Chile.

The VIKING data bolstered the KiDS data set by providing multiple observations of the same region of the sky in near-infrared wavelengths. The greater the distances of a galaxy, the higher the speed at which it is receding from us. This causes more of a galaxy's light to be redshifted into the near-infrared range, so relying solely on optical observations is not enough. Infrared measurements capture a greater amount of the light from such galaxies, leading to better estimates of their photometric redshift.

To ensure that photometric redshifts are as accurate as possible, these observations were calibrated against spectroscopic redshift measurements of a few of the same galaxies made with the more massive eight-meter Very Large Telescope at Paranal and the 10-meter Keck telescopes on Mauna Kea in Hawaii.

Astrophysicist and Nobel laureate Adam Riess of Johns Hopkins University approves of the efforts of the KiDS researchers. "Their latest results use infrared data, which probably does a better job of tracing the mass of the lenses and getting reliable photometric redshifts," he says.

Using the combined data, covering about 350 square degrees of the sky, the astronomers estimated sigma-eight.

The value they found conflicts with a sigma-eight figure calculated using the European Space Agency's Planck satellite's observations of the cosmic microwave background (CMB)—the earliest observable light in the universe, which was emitted about 380,000 years after the big bang. Planck mapped the variations in the temperature and polarization of the CMB from point to point in the sky. Cosmologists can employ the map to calculate the sigma-eight value for the early universe. Using the standard model of cosmology (which says that the cosmos is made of about 5 percent ordinary matter, 27 percent dark matter and 68 percent dark energy), they can then extrapolate across more than 13 billion years of cosmic evolution to estimate the present-day value for sigma-eight.

Herein lies the tension. Hildebrandt's weak-lensing study estimates sigma-eight as about 0.74, whereas the Planck data provide a value of about 0.81. "There is about a 1 percent chance or so that this [tension] is a statistical fluctuation," Hildebrandt says. Statistical fluctuations are random noise in data that can mimic actual signals and can disappear with more data. "This is not something to completely lose sleep over."

Not yet, anyway. It is also possible that a systematic error lurks in the calculations of one or both of the teams. After the researchers identify any such errors, the discrepancy could go away.

Or it may not do so, which has been the case with the Hubble tension. As astronomical measurements have become more precise, the statistical significance of the Hubble tension has only grown, inflicting sleepless nights on more than a few anxious theorists. "Something very similar might happen with our sigma-eight discrepancy," Hildebrandt says. "We don't know."

> **"If there was a compelling model, maybe people would jump on that bandwagon."**
>
> ***—Hendrik Hildebrandt***

Riess, who leads one of the teams estimating the Hubble constant using measurements of supernovae in the nearby universe, likens the sigma-eight tension to a "little brother or sister of the Hubble tension." That discrepancy is now considered statistically significant with less than a one-in-3.5-million chance of being a fluke. The sigma-eight tension, with its one-in-100 chance of being a statistical aberration, is where the Hubble tension was a few years ago. "So [it is] less significant but worth keeping an eye on for a possible connection," Riess says.

If the sigma-eight tension ascends to the same level of statistical relevance as the Hubble tension, the pressure to reevaluate the standard model of cosmology could become too enormous to ignore. At that point cosmologists may be forced to invoke new physics to bring the Planck estimates in line with the direct measurements of the parameters of the present-day universe. "That will be the exciting alternative," Hildebrandt says.

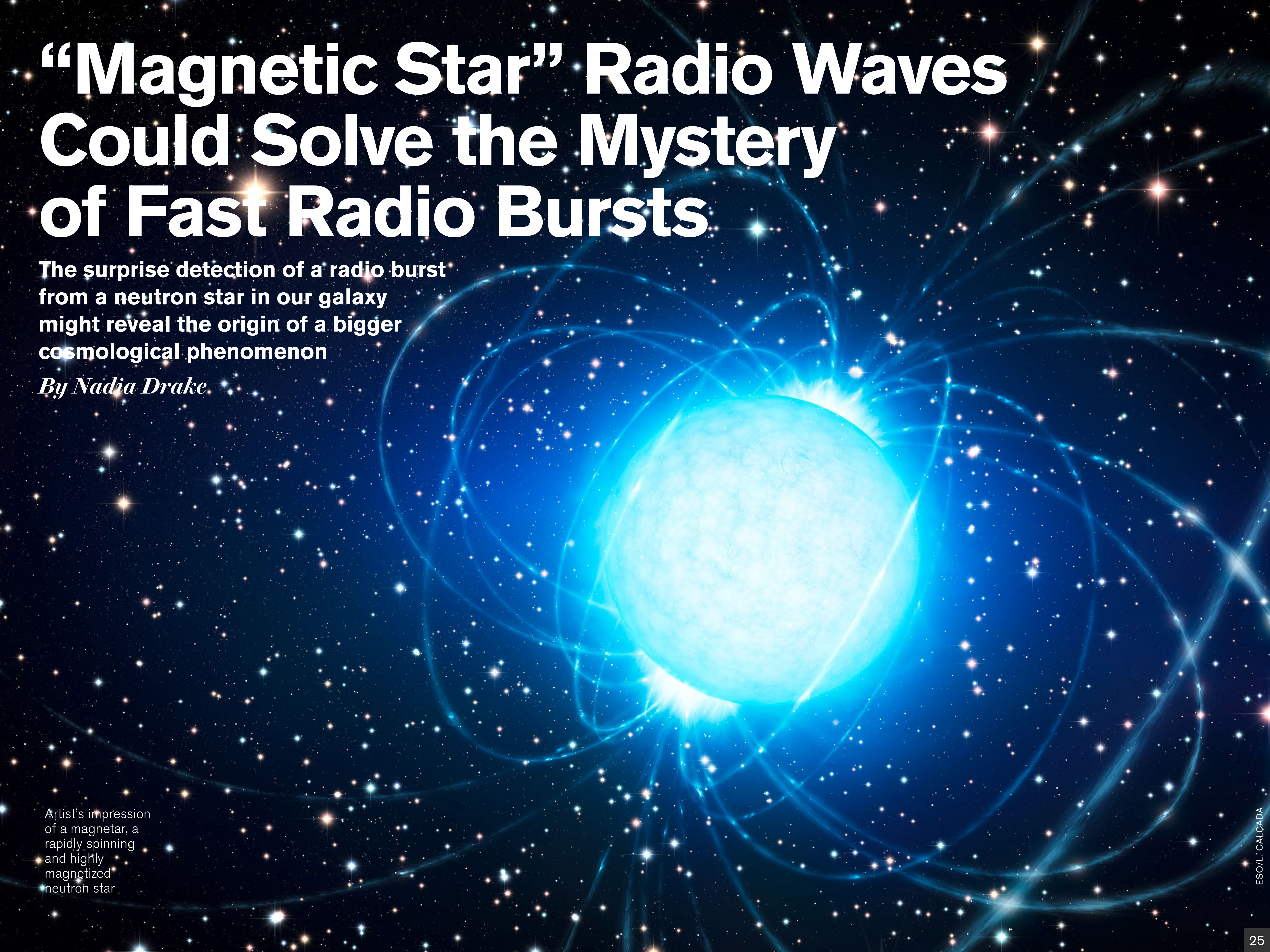
Potential "new physics" fixes to the standard model could involve changing the amount and nature of dark energy or dark matter—or both—as well as tweaks to how they interact with each other and with normal matter, among other, more exotic modifications. "Some theoretical solutions to tinker with the cosmological model to fix the Hubble constant tension make this [sigma-eight tension] worse. Some make it better," Riess says.

Hildebrandt agrees that there is no obvious solution in sight. "If there was a compelling model, maybe people would jump on that bandwagon," he says. "But at the moment, I don't think there is. It's really on us observers to improve the significance [of the sigma-eight tension] or disprove it."

“Magnetic Star” Radio Waves Could Solve the Mystery of Fast Radio Bursts

The surprise detection of a radio burst from a neutron star in our galaxy might reveal the origin of a bigger cosmological phenomenon

By Nadia Drake



Artist’s impression of a magnetar, a rapidly spinning and highly magnetized neutron star

ESO/L. CALÇADA

Nadia Drake is a science journalist whose work has appeared in *National Geographic, Science News, Nature, New Scientist*, the *Proceedings of the National Academy of Sciences USA* and *Wired.*

IN MAY, ASTRONOMERS MONITORED STRANGE, HIGH-ENERGY emissions from the corpse of a long-dead star some 30,000 light-years away. Within the emissions, they found something surprising: a powerful blast of radio waves that lasted mere milliseconds. The blast was in fact the brightest outburst ever seen from this star or any of its kind—immensely magnetic neutron stars known as magnetars.

The eruption of radio waves, though originating in our own galaxy, is remarkably similar to fast radio bursts (FRBs)—fleeting, intensely bright radio flashes launched by as yet unidentified objects that until now had been observed coming only from other galaxies. Although it may raise just as many questions as it answers, this latest observation could solve at least one riddle surrounding the cosmic origin of FRBs.

"Without overusing the word 'breakthrough,' this is really a breakthrough," says Jason Hessels of the Netherlands Institute for Radio Astronomy and the University of Amsterdam. "It doesn't quite get you all the way there, but it gets you such a huge step of the way" toward cracking the case of FRBs.

At least two radio observatories spotted the recent radio burst in late April. Teams traced the radio waves back to a highly magnetic neutron star—the remnant of a star that was maybe 40 or 50 times as massive as the sun—called SGR 1935+2154. Located deep in the disk of the Milky Way, the dense, dead celestial body had been slinging high-energy radiation into the cosmos for a week or so, as a rare class of objects called soft gamma-ray repeaters are known to do.

It is the first time anyone has seen a blaze of radio waves alongside such a barrage of gamma rays. And because of the radio burst's tremendous brightness and short duration, some astronomers now think it is a great local model for FRBs that come from billions of light-years away.

Even so, making that tenuous link more definitive requires a sober assessment of how this source is different from previously observed FRBs, says Emily Petroff of the University of Amsterdam. "As always with FRBs, you have to make sure that you don't miss the forest for the trees. We can get really hung up on one source being typical. But we've already seen so many times—again and again over the past five years—that's not always true."

IN SEARCH OF EXPLANATIONS

FRBs have been among the universe's most stubborn mysteries for more than a decade. Traveling at the speed of light, these radio blasts typically wash over Earth after traversing the cosmos for billions of years, suggesting that whatever celestial engine is heaving them into space must be extremely powerful. All the bursts observed so far have come from distant galaxies. Over the years astronomers have amassed dozens of hypothetical origins for the phenomenon. Among them are evaporating black holes, explosively dying stars, massive colliding objects and—perhaps less seriously—the technobabble transmissions of smart, talkative aliens.

As the observations have piled up, the hypotheses have improved. Astronomers saw some bursts that repeated, proving that whatever their source was, producing a single FRB would not cause its self-destruction. Teams started catching bursts in real time, pointing multiple telescopes toward spots in the sky where one originated. It was not long before several of them had been traced back to their host galaxy. But even though astronomers had gathered data on hundreds of bursts by early 2020, their origins remained fundamentally clouded.

"Every time we find a new one, it's different," Petroff says. "I wish every time we found a new one, it confirmed everything we learned from all the other ones, but it's never like that! There's so much variety; it keeps us on our toes."

SURPRISE LOCAL DETECTION

Astronomers first spotted the new burst using the FRB-hunting CHIME (Canadian Hydrogen Intensity Mapping Experiment) radio telescope, an instrument in southwestern Canada that resembles four skateboarding half-pipes strung together. Since fully opening its eyes in late 2018, CHIME has spotted hundreds of FRBs. This one appeared at the periphery of the telescope's vision in the sky but was so powerful that it was still easily seen.

"It's an extremely bright radio emission coming from a magnetar," says the University of Toronto's Paul Scholz, who reported the burst for the CHIME team on the real-time astronomical observations site The Astronomer's Telegram. "Is this the link between magnetars and FRBs? It might be."

After seeing that notification, astronomers based at the California Institute of Technology performed an early scan of their own data from the time period when the burst went off. Gathered by three radio antennas in California and Utah as part of the STARE2 (Survey for Transient Astronomical Radio Emission 2) project, the Caltech team's observations are specifically designed to detect FRBs coming from within the Milky Way.

Unlike CHIME, STARE2 caught the event head-on, allowing the researchers to quickly calculate the burst's brightness. According to their estimates, if it had occurred at the distance of the nearest known extragalactic FRB—roughly 500 million light-years away—it would still have been easily detectable from Earth. (For comparison, the galaxy nearest to our own, Andromeda, is just 2.5 million light-years away. And the Virgo group of galaxies, the cluster nearest to our own, is about 53 million light-years away.) To Caltech's Shrinivas Kulkarni, the burst's brightness and milliseconds-long duration make it a conclusive link with FRBs.

Based on these observations, "a plausible origin for fast radio bursts is active magnetars in other galaxies," says Kulkarni, who is principal investigator of the STARE2 project. "If we wait long enough, maybe this [magnetar] will have [an even brighter] burst."

A third observation, made by a team using the European Space Agency's orbiting INTEGRAL (International Gamma-Ray Astrophysics Laboratory) observatory, pinned the radio burst on the magnetar by linking it with a simultaneous blast of x-rays from the same object. And China's Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) has since detected another radio burst from SGR 1935+2154 that also points to the magnetar as the source of these outbursts. "I would bet a year's salary on that localization," Kulkarni says.

MAGNETAR OUTBURSTS

Over several years multiple lines of evidence have coalesced to flag magnetars as FRB culprits. These neutron stars spin extremely rapidly and possess immense magnetic fields—a combination that can create enormous eruptions of radiation. And scientists have observed some FRBs that have strong and "twisted" polarization; this arrangement suggests they originated in the vicinity of, or passed through, an intensely magnetic environment, such as those that surround these stellar corpses.

But the full picture had yet to reveal itself. "The counterargument for a long time was: 'Yeah, but we've never seen magnetars in our own galaxy do anything even as close as bright,'" Hessels says. "'So how logical is it that magnetars in other galaxies do this?'"

Now, with this new finding in hand, astronomers are taking a closer look at the connection between FRBs and magnetars. "I wouldn't say that this seals the deal and is the missing link or something like that. It gets us one step closer to finding a link between things in our own galaxy and what's causing FRBs," Petroff says.

Astronomers note that although this burst is brighter than anything yet seen coming from a magnetar, it is still less powerful than most observed FRBs by several orders of magnitude. It is not surprising that researchers might have caught a fainter burst first. Such bursts are likely to be more numerous than exceedingly bright ones, just as weaker earthquakes occur more frequently than bigger ones. Stronger stellar flares might produce stronger radio bursts as well. Some magnetars produce flares so gargantuan that they alter Earth's ionosphere across vast interstellar distances, although such superpowered flares are incredibly infrequent. "I would love to know," Hessels says, "if we were to catch one of those giant flares, would we see an even brighter burst that's easily comparable to an FRB?"

Another lingering question is whether FRBs can come from different sources. Most of those observed to date have been single events, but more than a dozen of them are now known to come repeatedly from their mysterious sources. The nearest repeating FRB, located roughly half a billion light-years away and known as R3, erupts every 16 days. Scientists suspect that R3's periodic activity is linked to some other object locked in its gravitational embrace. But the magnetar SGR 1935+2154 does not appear to have any such orbital companions.

"I hope there isn't just one type of FRB," Hessels says. "I hope that by scratching deeper, we discover multiple things at the same time."

Physicists Criticize Stephen Wolfram's "Theory of Everything"

The iconoclastic researcher and entrepreneur wants more attention for his big ideas. But so far researchers are less than receptive

By Adam Becker

STEPHEN WOLFRAM AND STEPHEN FAUST WIKIPEDIA (CC BY-SA 3.0)

Adam Becker is author of *What Is Real? The Unfinished Quest for the Meaning of Quantum Physics.*

Stephen Wolfram blames himself for not changing the face of physics sooner.

“I do fault myself for not having done this 20 years ago,” the physicist turned software entrepreneur says. “To be fair, I also fault some people in the physics community for trying to prevent it happening 20 years ago. They were successful.” Back in 2002, after years of labor, Wolfram self-published *A New Kind of Science,* a 1,200-page magnum opus detailing the general idea that nature runs on ultrasimple computational rules. The book was an instant best seller and received glowing reviews: the *New York Times* called it “a first-class intellectual thrill.” But Wolfram’s arguments found few converts among scientists. Their work carried on, and he went back to running his software company Wolfram Research. And that is where things remained—until April, when, accompanied by breathless press coverage (and a 448-page preprint paper), Wolfram announced a possible “path to the fundamental theory of physics” based on his unconventional ideas. Once again, physicists are unconvinced—in no small part, they say, because existing theories do a better job than his model.

At its heart, Wolfram’s new approach is a computational picture of the cosmos—one where the fundamental rules that the universe obeys resemble lines of computer code. This code acts on a graph, a network of points with connections between them, that grows and changes as the digital logic of the code clicks forward one step at a time. According to Wolfram, this graph is the fundamental stuff of the universe. From the humble beginning of a small graph and a short set of rules, fabulously complex structures can rapidly appear. “Even when the underlying rules for a system are extremely simple, the behavior of the system as a whole can be essentially arbitrarily rich and complex,” he wrote in a blog post summarizing the idea. “And this got me thinking: Could the universe work this way?” Wolfram and his collaborator Jonathan Gorard, a physics Ph.D. candidate at the University of Cambridge and a consultant at Wolfram Research, found that this kind of model could reproduce some of the aspects of quantum theory and Einstein’s general theory of relativity, the two fundamental pillars of modern physics.

But Wolfram’s model’s ability to incorporate currently accepted physics is not necessarily that impressive. “It’s this sort of infinitely flexible philosophy where regardless of what anyone said was true about physics, they could then assert, ‘Oh, yeah, you could graft something like that onto our model,’ ” says Scott Aaronson, a quantum computer scientist at the University of Texas at Austin.

When asked about such criticisms, Gorard agrees—to a point. “We’re just kind of fitting things,” he says. “But we’re only doing that so we can actually go and do a systematized search” for specific rules that fit those of our universe.

Wolfram and Gorard have not yet found any computational rules meeting those requirements, however. And without those rules, they cannot make any definite, concrete new predictions that could be experimentally tested. Indeed, according to critics, Wolfram’s model has yet to even reproduce the most basic quantitative predictions of conventional physics. “The experimental predictions of [quantum physics and general relativity] have been confirmed to many decimal places—in some cases, to a precision of one part in [10 billion],” says Daniel Harlow, a physicist at the Massachusetts Institute of Technology. “So far I see no indication that this could be done using the simple kinds of [computational rules] advocated by Wolfram. The successes he claims are, at best, qualitative.” Further, even that qualitative success is limited: There are crucial features of modern physics missing from the model. And the parts of physics that it can qualitatively reproduce are mostly there because Wolfram and his colleagues put them in to begin with. This arrangement is akin to announcing, “‘If we suppose that a rabbit was coming out of the hat, then remarkably, this rabbit would be coming out of the hat,’” Aaronson says. “And then [going] on and on about how remarkable it is.”

> **“I think the popular notion that physicists are all in search of the eureka moment in which they will discover the theory of everything is an unfortunate one.”**
>
> ***—Katie Mack***

Unsurprisingly, Wolfram disagrees. He claims that his model has replicated most of fundamental physics already. “From an extremely simple model, we’re able to reproduce special relativity, general relativity and the core results of quantum mechanics,” he says, “which, of course, are what have led to so many precise quantitative predictions of physics over the past century.”

Even Wolfram’s critics acknowledge that he is right about at least one thing: it is genuinely interesting that simple computational rules can lead to such complex phenomena. But, they hasten to add, that is hardly an original discovery. The idea “goes back long before Wolfram,” Harlow says. He cites the work of computing pioneers Alan Turing in the 1930s and John von Neumann in the 1950s, as well as that of mathematician John Horton Conway in the early 1970s. (Conway, a professor at Princeton University, died of COVID-19 in April.) To the contrary, Wolfram insists that he was the first to discover that virtually boundless complexity could arise from simple rules in the 1980s. “John von Neumann, he absolutely didn’t see this,” Wolfram says. “John Conway, same thing.”

FROM PRODIGY TO PRODIGAL SCIENTIST

Born in London in 1959, Wolfram was a child prodigy who studied at Eton College and the University of Oxford before earning a Ph.D. in theoretical physics at the California Institute of Technology in 1979—at the age of 20. After his Ph.D., Caltech promptly hired Wolfram to work alongside his mentors, including physicist Richard Feynman. “I don’t know of any others in this field that have the wide range of understanding of Dr. Wolfram,” Feynman wrote in a letter recommending him for the first-ever round of MacArthur “genius grants” in 1981. “He seems to have worked on everything and has some original or careful judgment on any topic.” Wolfram won the grant—at age 21, making him among the youngest people ever to receive the award—and became a faculty member at Caltech and then a long-term member at the Institute for Advanced Study in Princeton, N.J. While at the latter, he became interested in simple computational systems. He then moved to the University of Illinois in 1986 to start a research center to study the emergence of complex phenomena. In 1987 he founded Wolfram Research, and shortly thereafter he left academia altogether. The software company’s flagship product, Mathematica, is a powerful and impressive piece of mathematics software that has sold millions of copies and is today nearly ubiquitous in physics and mathematics departments worldwide.

Then, in the 1990s, Wolfram decided to go back to scientific research—but without the support and input provided by a traditional research environment. By his own account, he sequestered himself for about a decade, putting together what would eventually become *A New Kind of Science* with the assistance of a small army of his employees.

Upon the release of the book, the media was ensorcelled by the romantic image of the heroic outsider returning from the wilderness to single-handedly change all of science. *Wired* dubbed Wolfram “the man who cracked the code to everything” on its cover. “Wolfram has earned some bragging rights,” the *New York Times* proclaimed. “No one has contributed more seminally to this new way of thinking about the world.” Yet then, as now, researchers largely ignored or derided his work. “There’s a tradition of scientists approaching senility to come up with grand, improbable theories,” the late physicist Freeman Dyson told *Newsweek* back in 2002. “Wolfram is unusual in that he’s doing this in his 40s.”

Wolfram’s story is exactly the kind that many people want to hear because it matches the familiar beats of dramatic tales from science history that they already know: the lone genius (usually white and male), after laboring in obscurity and being rejected by the establishment, emerges from isolation triumphantly grasping a piece of the Truth. But that is rarely—if ever—how scientific discovery actually unfolds. There are examples from the history of science that superficially fit this image: Think of Albert Einstein toiling away on relativity as an obscure clerk in the Swiss patent office at the turn of the 20th century. Or, for a more recent example, consider mathematician Andrew Wiles working in his attic for years to prove Fermat's last theorem before finally announcing his success in 1995. But portraying those discoveries as the work of solo geniuses, romantic as it is, belies the real working process of science. Science is a group effort. Einstein was in close contact with researchers of his day, and Wiles's work followed a path laid out by other mathematicians just a few years before he got started. Both of them were active, regular participants in the wider scientific community. And even so, they remain exceptions to the rule. Most major scientific breakthroughs are far more collaborative—quantum physics, for example, was developed slowly over a quarter of a century by dozens of physicists around the world.

"I think the popular notion that physicists are all in search of the eureka moment in which they will discover the theory of everything is an unfortunate one," says Katie Mack, a cosmologist at North Carolina State University. "We do want to find better, more complete theories. But the way we go about that is to test and refine our models, look for inconsistencies and incrementally work our way toward better, more complete models."

Most scientists would readily tell you that their discipline is—and always has been—a collaborative, communal process. Nobody can revolutionize a scientific field without first getting the critical appraisal and eventual validation of their peers. Today this requirement is performed through peer review—a process Wolfram's critics say he has circumvented with his announcement. "Certainly there's no reason that Wolfram and his colleagues should be able to bypass formal peer review," Mack says. "And they definitely have a much better chance of getting useful feedback from the physics community if they publish their results in a format we actually have the tools to deal with."

Mack is not alone in her concerns. "It's hard to expect physicists to comb through hundreds of pages of a new theory out of the blue, with no buildup in the form of papers, seminars and conference presentations," says Sean M. Carroll, a physicist at Caltech. "Personally, I feel it would be more effective to write short papers addressing specific problems with this kind of approach rather than proclaiming a breakthrough without much vetting."

So why did Wolfram announce his ideas this way? Why not go the traditional route? "I don't really believe in anonymous peer review," he says. "I think it's corrupt. It's all a giant story of somewhat corrupt gaming, I would say. I think it's sort of inevitable that happens with these very large systems. It's a pity."

So what are Wolfram's goals? He says he wants the attention and feedback of the physics community. But his unconventional approach—soliciting public comments on an exceedingly long paper—almost ensures it shall remain obscure. Wolfram says he wants physicists' respect. The ones consulted for this story said gaining it would require him to recognize and engage with the prior work of others in the scientific community.

And when provided with some of the responses from other physicists regarding his work, Wolfram is singularly unenthused. "I'm disappointed by the naivete of the questions that you're communicating," he grumbles. "I deserve better."

Mario Livio is an astrophysicist and author. His most recent book is *Galileo: And the Science Deniers*.

OBSERVATIONS

Did Galileo Truly Say, “And Yet It Moves”? A Modern Detective Story

An astrophysicist traces genealogy and art history to discover the origin of the famous motto

“And yet it moves.” This may be the most famous line attributed to the renowned scientist Galileo Galilei. The “it” in the quote refers to Earth. “It moves” was a startling denial of the notion, adopted by the Catholic Church at the time, that Earth was at the center of the universe and therefore stood still. Galileo was convinced that model was wrong. Although he could not prove it, his astronomical observations and his experiments in mechanics led him to conclude that Earth and the other planets were revolving around the sun.

That brings us to “and yet.” As much as Galileo may have hoped to convince the church that he was not contradicting scripture by moving Earth from its anointed position, he did not fully appreciate that church officials could not accept what they regarded as his impudent invasion into their exclusive province: theology.

During his trial for suspicion of heresy, Galileo chose his words carefully. It was only after the trial that, angered by his conviction no doubt, he was said to have muttered to the inquisitors, “*Eppur si muove*” (“And yet it moves”), as if to say that they may have won this battle, but in the end truth would win out.

But did Galileo really utter those famous words? There is no doubt

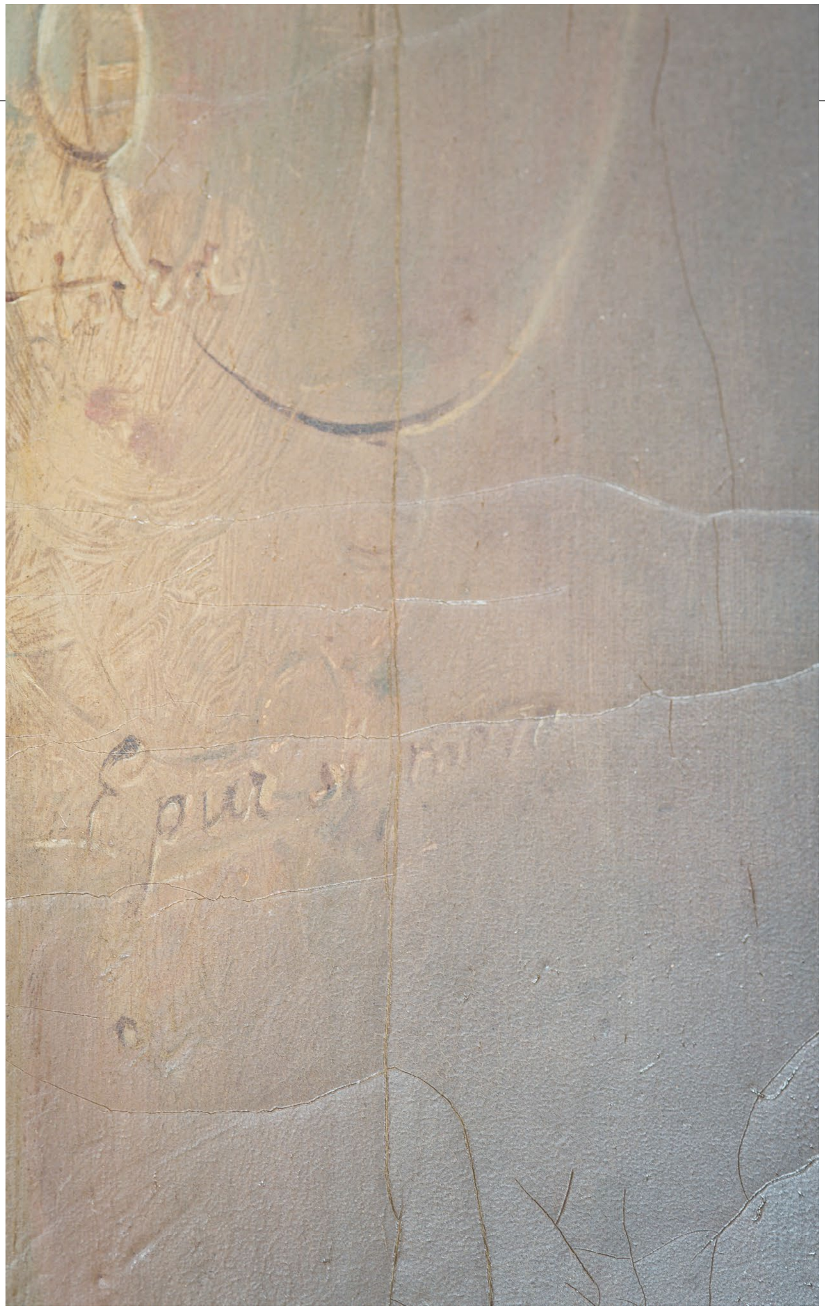
Galileo in Prison, by Romain Eugène Van Maldeghem. This painting is at Stedelijk Museum Sint-Niklaas in Belgium.

GERALD DELVAUX

that he thought along those lines. His bitterness about the trial, the fact that he had been forced to abjure and recant his life's work, the humiliating reality that his book *Dialogue Concerning the Two Chief World Systems* had been put on the church's Index of Prohibited Books, and his deep contempt for the inquisitors who judged him continually occupied his mind for all the years following the trial. We can also be certain that he did not (as legend has it) mutter that phrase in front of the inquisitors. Doing so would have been insanely risky. But did he say it at all? If not, when and how did the myth about this motto start circulating?

Science historian Antonio Favaro dedicated four decades to the study and contextualization of Galileo's life and work, eventually producing the monumental book *Le Opere di Galileo Galilei* (*The Works of Galileo Galilei*). As part of that Herculean effort, in 1911 he also published a few articles describing his extensive research devoted to uncovering the origins of the motto. Favaro determined that the earliest mention of the phrase in print was in a book entitled *The Italian Library,* published in London in 1757 by Italian author Giuseppe Baretti.

Baretti colorfully wrote, "This is the celebrated Galileo, who was in the Inquisition for six years, and put to the torture, for saying, that the Earth moved. The moment he was set at liberty, he looked up to the sky and down to the ground, and, stamping with his foot, in contemplative mood, said, *Eppur si move;* that is, still it moves, meaning the Earth."



Detail of Van Maldeghem's painting *Galileo in Prison* shows the motto written as "*E pur si move*" and Earth orbiting the sun.

GERALD DELVAUX

Even if we were to disregard the unhistorical embellishments in this account, it would be difficult to accept the testimony of a book that appeared more than a century after Galileo's death as evidence of the veracity of the quote. Favaro was equally skeptical initially—until an unexpected event caused him to reconsider the question.

AN INTRIGUING PAINTING

In 1911 Favaro received a letter from a certain Jules Van Belle, who lived in Roeselare, Belgium. Van Belle claimed to own a painting that had been painted in 1643 or 1645 and that contained the famous motto. If true, this assertion would have meant that the phrase was already known very shortly after Galileo's death in 1642.

The painting, of which Favaro saw only a photograph, showed Galileo in prison. He held a nail in his right hand, with which he had apparently traced Earth moving around the sun on the wall with the words "*E pur si move*" written underneath.

Based on an unclear signature, Van Belle attributed the painting to the 17th-century Spanish painter Bartolomé Esteban Murillo. And he speculated that it had originally belonged to the Spanish army commander Ottavio Piccolomini, brother of the Archbishop of Siena, in whose home Galileo served the first six months of his house arrest.

Favaro publicized this story of the presumed discovery of a portrait of Galileo dating to the 17th century and containing the celebrated motto, and the tale made it to the pages of several newspapers. Belgian physicist Eugene Lagrange even went to Roeselare to see the painting with his own eyes, as he reported in the Belgian newspaper *L'Etoile Belge* on January 13, 1912.

The discovery of the painting definitely had an impact. Until then most historians had considered the famous phrase to be a myth, but the new finding caused a number of Galileo scholars to change their minds. Science historian John Joseph

Fahie wrote in 1929, "We must revise our judgments, and conclude that Galileo did utter these words, not, however, in the awful chamber of the Inquisition, as the fable has it, but to some sympathetic friend outside, from one of whom, doubtless, Piccolomini had them." Renowned Galileo scholar Stillman Drake also concluded, "In any case, there is no doubt now that the famous words were attributed to Galileo before his death, not invented a century later merely to fit his character."

Strangely, in spite of its great value for the history of science, Van Belle's painting has never been subjected to any independent examination by experts. When I wanted to initiate such a scrutiny, I was astonished to discover that not only was the current location of the painting unknown, but as far as I could initially determine, no science or art historian had even seen it after 1912. Naturally, I decided to search for it.

THE HUNT

First, I wanted to get an expert opinion on the attribution to Murillo. To this end, I sent a copy of the photograph of the painting to four Murillo specialists (two in Spain, one in the U.K. and one in the U.S.). They all independently responded that although it is difficult to provide conclusive opinions based on a photograph, when considering the style, subject matter and relevant historical facts, they were quite convinced that Murillo did not paint this portrait. One said that the painter was probably not Spanish, and another suggested that the painting was from the 19th century.

Motivated to continue to investigate by these unanimous, unexpected judgments, I discovered that an article about the painting appeared simultaneously in two Belgian newspapers (*De Halle* and *De Poperinghenaar*) on February 23, 1936. The feature reported that an important portrait of Galileo had been exhibited at Museum Vleeshuis in Antwerp, Belgium.

> **"In any case, there is no doubt now that the famous words were attributed to Galileo before his death, not invented a century later merely to fit his character."**
> **—*Stillman Drake***

Inquiry at Vleeshuis revealed that on September 13, 1933, Van Belle had indeed loaned it a painting entitled *Galileo in Prison.* The loan was also reported (with the title "Galileo and His *E pur si muove*") in the *Gazet Van Antwerpen* on September 15, 1933. Further inquiries uncovered the surprising fact that Stedelijk Museum Sint-Niklaas (SteM Sint-Niklaas) in Belgium has in its collection a painting that appears to be identical to the one loaned to Vleeshuis. Moreover, a close inspection of the wall in front of Galileo in this painting revealed a drawing of Earth orbiting the sun, a few other drawings (possibly of Saturn or the phases of Venus) and the famous motto. This portrait was documented as having been painted in 1837 by Flemish painter Romaan Eugeen Van Maldeghem. It was donated to the city of Sint-Niklaas by art collector Lodewijk Verstraeten, and the museum obtained it after his wife's death in 1904 or 1905.

This development created a very interesting situation. There were two virtually identical paintings. One, owned by Van Belle, was claimed to have been painted in 1643 or 1645. The other, by Van Maldeghem, was painted in 1837. The Van Belle painting made its first documented public appearance in 1911. It was loaned to Vleeshuis in 1933 and was exhibited there in 1936. Since then, its whereabouts have been unknown. The second painting has been in the collection of SteM Sint-Niklaas since 1904 or 1905. The extreme similarity of the two paintings left no doubt that either Van Maldeghem copied an earlier painting or someone copied Van Maldeghem's painting in either the 19th or the early 20th century.

To complicate things further, I discovered that in 2000 the Antwerp auction house Bernaerts Auctioneers took bids on a painting entitled *Galileo in Prison*. It was listed as having been painted by Flemish painter Henrij Gregoir in 1837—the same year in which Van Maldeghem painted his portrait of Galileo with the same title. Fortunately, I was able to obtain a photograph of the painting, and although the title is the same, the artwork is very different.

EUREKA!

To make further progress, I tried to uncover more information about Van Maldeghem and his painting. Two Flemish books on the lives and works of Flemish and Dutch artists—one by J. Immerzeel, Jr., from 1842 and another by Christiaan Kramm from 1859—listed *Galileo in Prison* as one of Van Maldeghem's original paintings, without any hint or suggestion that it might have been a copy. Significantly, these two books were published while Van Maldeghem was still alive, when all the information concerning the painting was still readily available. It was difficult, therefore, to avoid the impression that his painting was the original after all. This feeling was further enhanced by the realization that the theme of Galileo's conflict with the Inquisition became quite popular with painters only in the 19th century. And it was also entirely consistent with the opinions previously expressed by the Murillo experts. Recall that one suggested that the painter was not Spanish, and another judged that the painting was from the 19th century.

All of this, however, still did not explain what happened to Van Belle's painting after 1936. I could think of three main possibilities: The painting could have been sold by Jules Van Belle himself. Or it could have been inherited by a relative (and perhaps sold later). Or it might have been destroyed during World War II. Following this line of thought, I decided to attempt some genealogy research.

To make a very long story short, with a serious effort, considerable help and quite a bit of luck, I managed to find a living great-grandson of Van Belle's niece. And through him, I discovered that in 2007 his grandmother sold a collection of paintings via the Campo & Campo auction house and gallery in Antwerp. Lot number 213 on the list was entitled *Galileo in Prison*. The auction house's photograph shows it to be the very painting I was searching for. I rediscovered Van Belle's painting!

Common practice in the art world prevents auction houses from revealing the identity of buyers, but I did find out that the painting was bought by a private collector and not by a dealer. There were two other noteworthy pieces of information that were revealed in the auction. First, Campo & Campo judged the painting to be from the 19th century. Second, a close inspection did not find any date or signature. This observation was confirmed by a representative from the auction house.

So what can we say about the question of whether Galileo said those famous words? The historical evidence points to the story first appearing (or at least being documented) only in the middle of the 18th century—long after Galileo's death. This makes the motto much more likely to be apocryphal. Nevertheless, it would be thrilling if (perhaps as a result of the present article) the current owner of *Galileo in Prison* would allow it to be thoroughly examined to determine its exact age.

Even if Galileo never spoke those words, they have some relevance for our current troubled times, when even provable facts are under attack by science deniers. Galileo's legendary intellectual defiance—"in spite of what you believe, these are the facts"—becomes more important than ever.

Dario Gil is director of IBM Research, one of the world's largest and most influential corporate research laboratories, with more than 3,000 scientists at 19 locations on six continents. He leads innovation efforts at IBM, directing research strategies in AI, cloud, quantum and exploratory science. He is a founder and co-chair of the COVID-19 High Performance Computing Consortium.

COMPUTING

The Quantum App Store Is Coming

Quantum computing is still the province of specialized programmers—but that is likely to change very quickly

GETTY IMAGES

Currently quantum computing researchers and enthusiasts need to know quantum programming; it is simply a must. Soon, though, all they will need is a quantum app store and a line of code. Not an app store as in your smartphone but something similar to a code repository of today such as GitHub—a type of digital library where software developers make the code they have written available to anyone. And in the near future, developers will be able to put in lines of code that will call on quantum computers to deal with specific tasks a regular computer cannot.

I predict that quantum computers will undergo the same stages of development as classical computers have over multiple decades—but much faster and within just this decade.

A decade ago there were just a few dozen research groups who could code in quantum. When IBM launched its online platform Quantum Experience in 2016, giving everyone free access to quantum processors through the cloud, that number grew to a few thousand within just a week. Four years later the number of programmers experimenting with quantum algorithms—what the community calls quantum circuits, the sequences of instructions that define commands for manipulating data and making a quantum computer work—is in the hundreds of thousands. And soon millions of software developers in the IT mainstream will start building on that effort and designing a myriad of quantum circuits for everyone to use.

This evolution will parallel the same stages of development that classical computers have gone through over multiple decades but much faster—within just this decade. Remember Alan Turing? He developed his theory of software in 1936, jump-starting computer science and software engineering. Four decades later it was still the case that only those who knew how to write software were able to use mainframe computers. And in the 1970s, when companies such as IBM and Apple began building and selling the first personal computers, it was often left to software enthusiasts to write applications that would run on them.

But rapidly, software businesses took the lead, and as personal computers became more mainstream, users could assemble their own software stacks without having deep computer knowledge. We saw a repeat of this with mobile devices in the 2000s—very quickly people with no programming experience began creating apps and designing Web sites. Today all they have to do is input a simple line of code into a templated program, and in the background the wheels are turning automatically.

Quantum computers hold the same promise. First enthusiast programmers, then developers, and eventually quantum circuit repositories—or perhaps libraries—with both open-source and copyright-protected circuits, a natural extension of the software ecosystem of today.

This is the inevitable next step from what companies and university labs have been focused on over the past few years: building qubits. These basic units of quantum information are analogous to the much more familiar bits used by classical computers, simple binary digits that can have a value of either 1 or 0, true or false. Qubits, in contrast, can be in a superposition of 0 and 1 states. In our daily life we do not see superposition when it comes to objects—only with waves. But in the realm of the very small, particles can be in multiple states at once. Atomic nuclei with two spin orientations can do it, as can photons with two directions of polarization—and, in the case of IBM quantum computers, qubits made from superconducting electric currents.

Today qubits are not high performing enough for a quantum computer to outmatch a classical machine in a useful task. But quantum computers are getting better faster; we are getting pretty good at making qubits, and the theory behind the next steps is solid. We are executing a road map to make qubits with very low noise, meaning they will be as free from the influence of external disturbances as possible. Any noise disrupts the quantum realm, making the fragile superposition collapse into the qubit's final state, which is always 0 or 1. Once we have enough such low-noise qubits—a few hundred—we will apply special error-correcting codes to fix or mitigate any remaining problems and to be able to run more complex quantum circuits.

Already, when working with just a few dozen qubits limits us to moderate-size circuits, quantum aficionados all over the world are busy creating code to run on our quantum computers using the IBM Quantum Experience. To create their circuits, they code using Qiskit, an open-source software development kit we introduced in 2017. Qiskitters have already designed billions and billions of quantum circuits. In early May, during IBM's Digital Think conference, nearly 2,000 people from 45 countries took part in our Quantum Challenge and—using 18 IBM Quantum systems through the IBM Cloud—ran more than a billion circuits a day on real quantum hardware.

Today these quantum enthusiasts have to know quantum programming, gates and circuits. If they do not, they cannot write code for a quantum computer and cannot create or use a quantum circuit. But that is only temporary, as we are still at the dawn of the age of quantum computers. It is just a matter of time before developers start designing more and more circuits for their specific purposes, from machine learning to optimization to scientific calculations. That will lead to quantum circuit libraries for everyone to benefit from. You will simply have to write a line of code in any programming language you work with, and the system will match it with the circuit in the library and the right quantum computer—the one with the most appropriate configuration of the chip (the way the superconducting wires are put together to join the qubits).

Frictionless quantum computing. Just a line of code: that is all it will take to get a result on your classical machine through the cloud, while behind the scenes, invisible to the user, the quantum mystery will unfold, with superposition, entanglement and interference.

If you ask me, the future is nearly here.

Sabine Hossenfelder is a physicist and research fellow at the Frankfurt Institute for Advanced Studies in Germany. She currently works on dark matter and the foundations of quantum mechanics.

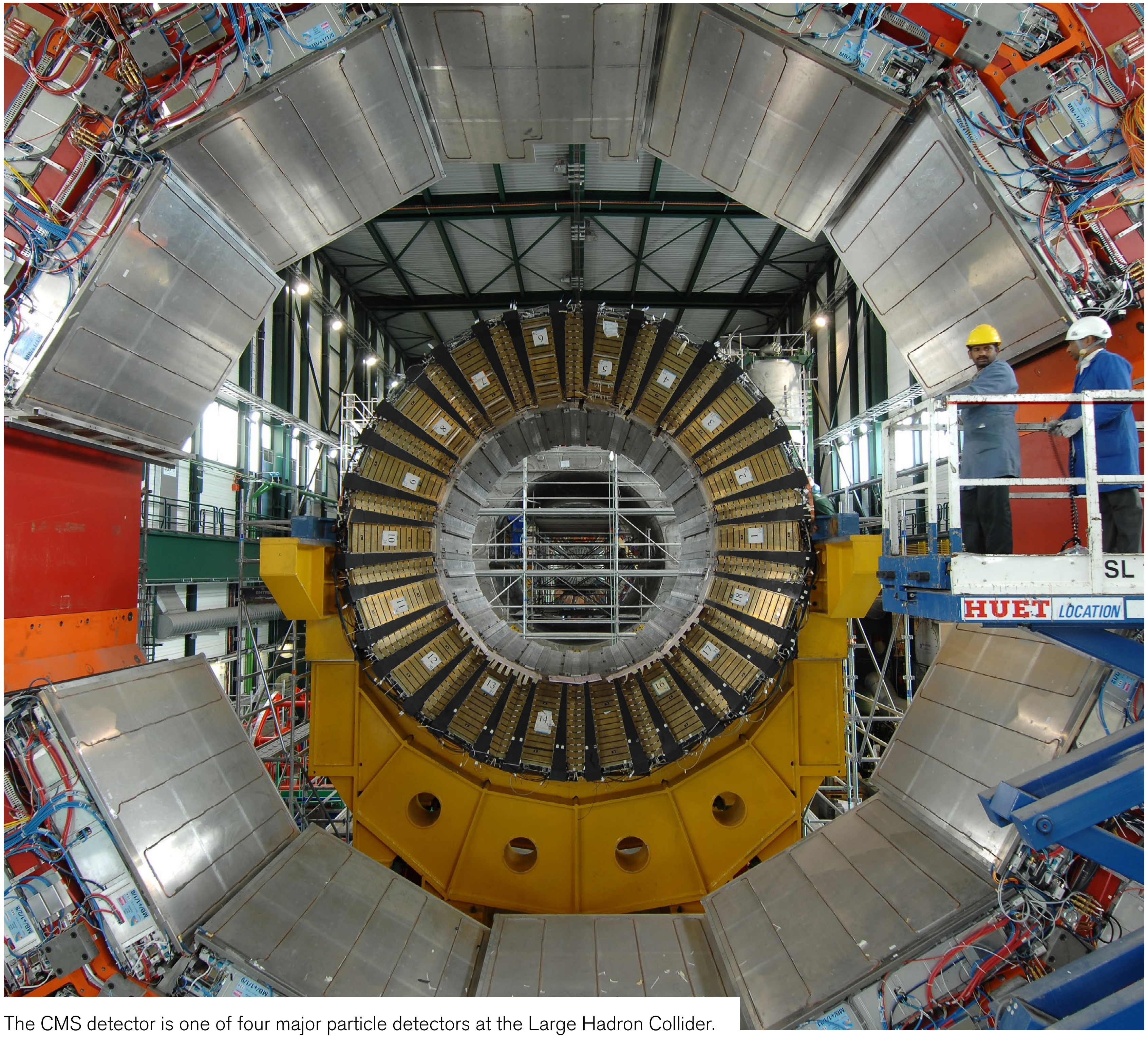
POLICY & ETHICS

The World Doesn't Need a New Gigantic Particle Collider

It would cost many billions of dollars, the potential rewards are unclear—and the money could be better spent researching threats such as climate change and emerging viruses

This is not the right time for a bigger particle accelerator. But CERN, the European physics center based in Geneva, Switzerland, has plans—big plans. The biggest particle physics facility in the world, currently running the biggest particle collider in the world, has announced that it aims to build an even bigger machine, as revealed in a press conference and press release in June.

With that, CERN has decided it wants to go ahead with the first step of a plan for the Future Circular Collider (FCC), hosted in a ring-shaped tunnel 100 kilometers, or a bit more than 60 miles, in circumference. This machine could ultimately reach collision energies of 100 tera-electron-volts, about six times the collision energy of the currently



The CMS detector is one of four major particle detectors at the Large Hadron Collider.

LIONEL FLUSIN *GETTY IMAGES*

operating Large Hadron Collider (LHC). By reaching unprecedentedly high energies, the new collider would allow the deepest look into the structure of matter yet and offer the possibility of finding new particles.

Whether the full vision will come into existence is still unclear. But CERN has announced that it is of "high priority" for the organization to take the first step on the way to the FCC: finding a suitable site for the tunnel and building a machine to collide electrons and positrons at energies similar to that of the LHC (which, however, uses protons on protons). The decision as to whether CERN will then move forward to high-energy collisions between protons will come only after several more years of study and deliberation.

This first step has also been dubbed a "Higgs factory" because it is specially designed to produce large amounts of Higgs bosons. The Higgs boson, discovered at CERN in 2012, was the final missing particle in the Standard Model of particle physics. With the new machine, particle physicists want to measure its properties, as well as the properties of some previously discovered particles, in more detail. (Japan is considering building a linear collider with a similar purpose as CERN's Higgs factory, but the committee working on the idea made no definitive decision in its last annual report. China is considering a circular collider similar in scope and size to CERN's full FCC plan, but a decision is not expected until next year.)

But CERN's plan, if fully executed, would cost tens of billions of dollars. Exact numbers are not available, because budget estimates put forward by CERN usually do not include the cost of operation. Going by the running costs for the LHC, those costs for the new collider would probably amount to at least $1 billion a year. For a facility that might operate for 20 years or more, this is comparable to the construction costs.

These are eye-popping numbers, no doubt. Indeed, particle colliders are currently the most expensive physics experiments in existence. Their price tag is higher than that of even the next most expensive type of experiments, telescopes on satellite missions.

The major reason the cost is so high is that since the 1990s, there have been only incremental improvements in collider technology. As a consequence, the only way to reach higher energies today is to build bigger machines. It is the sheer physical size—the long tunnels, the many magnets needed to fill it, and all the people needed to get that work done—that makes particle colliders so expensive.

But while the cost of these colliders has ballooned, their relevance has declined. When physicists started building colliders in the 1940s, they did not have a complete inventory of elementary particles, and they knew it. New measurements brought up new puzzles, and scientists built bigger colliders until, in 2012, the picture was complete. The Standard Model still has some loose ends, but testing them experimentally would require energies at least 10 billion times higher than what even the FCC could test. The scientific case for a new, larger collider is therefore at present not very strong.

Of course, it is possible that a new, larger collider would lead to a breakthrough discovery. Some physicists hope, for example, that it could offer clues about the nature of dark matter or of dark energy.

Yes, one can hope. But there is no reason that the particles that make up dark matter or dark energy should show up in the new device's energy range. And that is assuming they are particles to begin with, for which there is no evidence. Moreover, even if they are particles, highly energetic collisions may not be the best way to look for them. Weakly interacting particles with tiny masses, for example, are not something one looks for with large colliders.

And there are entirely different types of experiments that could lead to breakthroughs at far lower costs, such as taking high-precision measurements at low energies or increasing the masses of objects in quantum states. Going to higher energies is not the only way to make progress in the foundations of physics; it is just the most expensive one.

In this situation, particle physicists should focus on developing new technologies that could bring colliders back into a reasonable price range and should hold off on digging more tunnels. The most promising technology on the horizon is a new type of "wakefield" acceleration that could dramatically decrease the distance necessary for speeding up particles and hence shrink the size of colliders. Another game-changing technology would be room-temperature superconductors that could make the strong magnets that colliders rely on more efficient and affordable.

Looking into these new technologies is also among CERN's priorities. But as the strategy update reveals, particle physicists have not woken up to their new reality. The construction of larger particle colliders has run its course. Today it offers little scientific return on investment and at the same time has almost no societal relevance. Large scientific projects tend to generally benefit education and infrastructure, but this is not specific to particle colliders. And if those side effects are what we are really interested in, then we should at least put our money into scientific research with societal relevance.

Why, for example, do we still not have an international center for climate predictions, which by current estimates would cost "only" $1 billion spread over 10 years? That is peanuts compared with what particle physics sucks up, yet this kind of project is vastly more important. Or why, you may have wondered recently, do we not have a center for modeling epidemics?

It is because too much science funding is handed out on the basis of inertia. In the past century particle physics has grown into a large, very influential and well-connected community. Its members will keep building bigger particle colliders as long as they can simply because that is what particle physicists do, whether it makes sense or not.

It is about time society takes a more enlightened approach to funding large science projects than continuing to give money to those it has previously given it to. We have bigger problems than measuring the next digit in the mass of the Higgs boson.

Rebecca Oppenheimer is a curator and a professor of astrophysics at the American Museum of Natural History in New York City.

OBSERVATIONS

Missing Memories of the Universe

With observatories shut down because of the pandemic, the photons that reveal the secrets of the cosmos can't be recorded or decoded

Palomar Observatory

REBECCA OPPENHEIMER

I am an astrophysicist. I read the memories of the universe encoded in photons—tiny bits of light that have traveled to Earth over vast distances of space and time. Those photons carry within their electromagnetic oscillations a record of their voyages and what transpired in the past, from hours ago to billions of years ago depending on their origins in, say, the volcanoes on Jupiter's moon Io or the violent cores of distant quasars.

Now, because of an utterly unemotional biological force that does nothing but replicate, most observatories around the world are closed, and vast numbers of these memories are going unnoted. The constant rain of photons normally recorded by advanced, supremely sensitive detectors on telescopes instead slams into shuttered observatory domes after the long journey. There the photons transform into tiny motes of heat only to be whisked away by a gentle breeze in the night, the memories they carried lost forever.

Several times a week I video-chat with my graduate student Rose Gibson, one of the best emerging scientists I have ever worked with. I have not seen her since March 15, the last day we were both in the American Museum of

We are some of the standard-bearers of modern science, an enterprise that has outlasted countries, wars, depressions—and even global pestilences.

Natural History, where she is finishing her dissertation. She lives less than a mile away from me in Manhattan. The video-chat is better than naught, but it is inefficient and nothing like working together in the same room.

We have data to study that we obtained over this past winter. For example, we observed the giant star Betelgeuse, which we see, thanks to the finite speed of light, as it was about 500 years ago. But we have lost two weeks of observing time at the 200-inch Hale Telescope at Palomar Observatory, where we use our radical new instrument designed to find and study the smallest planets around the most common stars in the galaxy. This project requires regular, repeated observations to detect changes in the motions of the stars we are scrutinizing. Once we can resume our work, we will again learn fascinating things about these denizens of the Milky Way—but there is a personal sadness in the loss.

Over the 27 years I have worked at Palomar Observatory, I have created many memories of my own. I remember the peace and beauty of sleeping by day to work on gorgeous moonless nights, the whole sky ablaze with tiny lights that have turned out to be some of the most complicated and fascinating phenomena human beings have ever attempted to understand. I remember the elation of seeing something no one had ever seen before—the first object smaller than a star ever observed outside the solar system, a so-called brown dwarf. I remember the valleys filled with clouds below the mountain as the sun came up, ending a wonderful, efficient night of collecting memories. I remember the technical crew—family, really—the dedicated people who keep that venerable observatory running. I remember the rattlesnakes in the summer, the occasional secretive bobcat peeking out of a shrub, and the beauty of a winter snow in southern California.

Most of all, I miss the moments when we set the telescope to stare at some star for an hour or so while the instrument I built runs smoothly, collecting photons. While they accumulate, I go up to the catwalk, a grated walkway about 50 feet above the ground. It wraps around the telescope dome, and as I walk the full circle, I assess the clarity of the sky, a task in which personal observation cannot be replaced by videos and cameras. I remember feeling supremely calm as I looked at the night sky, knowing that a few of the universe's memories were being recorded.

Many people might think my job is nonessential, and I suppose in some ways it is. I do not create food, shoes or toilet paper. But I do create knowledge and guide people to achieve the most advanced degree in the world: the doctor of philosophy. These people, my former Ph.D. students, have gone on to academic careers and to other types of work such as providing real-time data to people who have heart problems or building some of the most sophisticated satellites ever conceived.

Perhaps more important, though, astrophysics, if not essential to our basic survival, is tied to the core of humanity itself—to understanding where, what and who we are. Understanding what is in this universe and how it works is utterly essential to human curiosity. Because of this, some 15,000 people in the world practice astrophysics. We are some of the standard-bearers of modern science, an enterprise that has outlasted countries, wars, depressions—and even global pestilences. Indeed, I believe that the current pandemic has already unleashed a new, infectious interest in science.

Although many of the universe's memories that have rained down on Earth over the past couple of months are lost forever, human curiosity has not diminished; it will demand that we resume astronomical observations as soon as we can. Even now photons are traversing the Oort cloud of icy cometary debris at the outer reaches of our solar system. Those photons will reach Earth a few months from now. Perhaps by then I will be back on that magnificent catwalk at Palomar, marveling once again at the majesty of the night sky while my instrument, quietly humming inside the dome, collects them.

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