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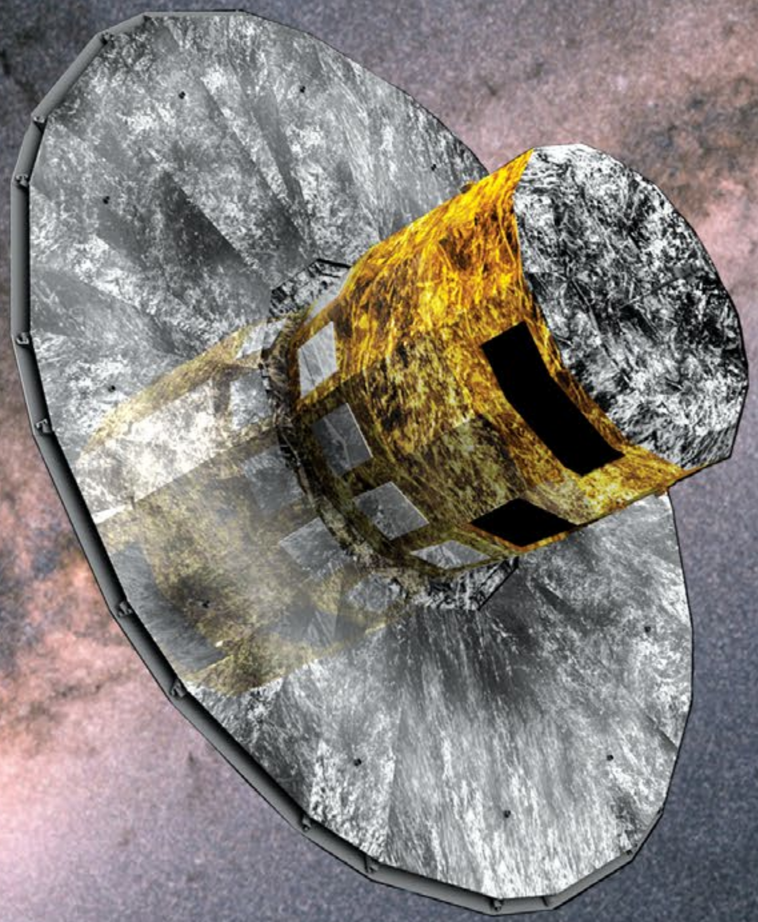
SCIENTIFIC AMERICAN Space & Physics

The Hidden History of the Milky Way

A NEW FLOOD OF STAR DATA REVEALS A GALACTIC COLLISION SOME EIGHT TO 11 BILLION YEARS AGO



Plus:

A DEBATE STEWS OVER THE RATE OF UNIVERSE EXPANSION

THE MAGICAL BEHAVIOR OF GRAPHENE

OPINION: WHEN E.T. COMES KNOCKING, BE KIND

WITH COVERAGE FROM
nature

FROM THE EDITOR

LIZ TORMES

Universe Cryptography

The story of how the universe came to be is constantly evolving. Indeed, a trove of fresh data rolling in from the Gaia spacecraft is refining our view of the early years of our galaxy. A violent collision with a second galaxy about eight to 11 billion years ago left a cohort of stars strewn askew from the plane of the Milky Way—the fingerprint of early galactic growing pains (see “Hidden History of the Milky Way Revealed by Extensive Star Maps”).

At the larger scale, the long-standing estimates of the rate of universe expansion are under scrutiny, as new measurements don’t seem to align with the old. Some novel fundamental physics may be at work (see “Have We Mismeasured the Universe?”). Rather than an ever evolving story of the universe, perhaps it has always been the same but written in a code we can’t understand or break. With each telescope, each spacecraft we send into space, each new technological advancement we achieve to collect data on Earth, we are learning how to read the code and deciphering its entirety piece by piece.

On a much smaller scale, a team at the Massachusetts Institute of Technology has turned two layers of graphene—a single-atom-thick layer of carbon—into a superconductor. The discovery has the potential to revolutionize several modern technologies, including transportation and computing (see “How ‘Magic Angle’ Graphene Is Stirring Up Physics”). Large or small, the physics code breakers are revealing quite a tale. Enjoy!

Andrea Gawrylewski
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Your Opinion Matters!

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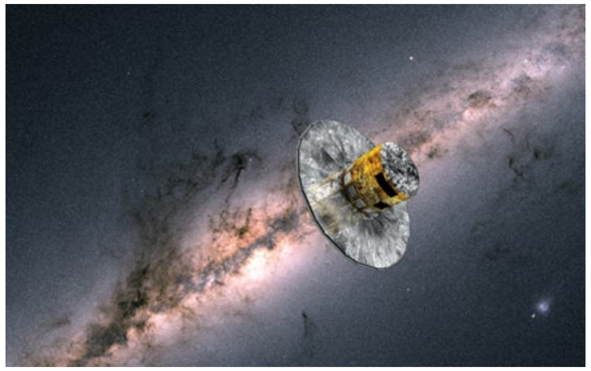


On the Cover

An artist's rendition of the Gaia spacecraft

COVER: ESA, GAIA AND DPAC (CC BY-SA 3.0 IGO); ESA (AN ARTIST'S RENDITION OF THE GAIA SPACECRAFT)

WHAT'S INSIDE

April-May, 2019
Volume 2 • No. 2

P. CARRIL AND ESA

NEWS

4.
Wayward Satellites Test Einstein's Theory of General Relativity
The botched launch of two Galileo navigation probes made for an unexpected experiment

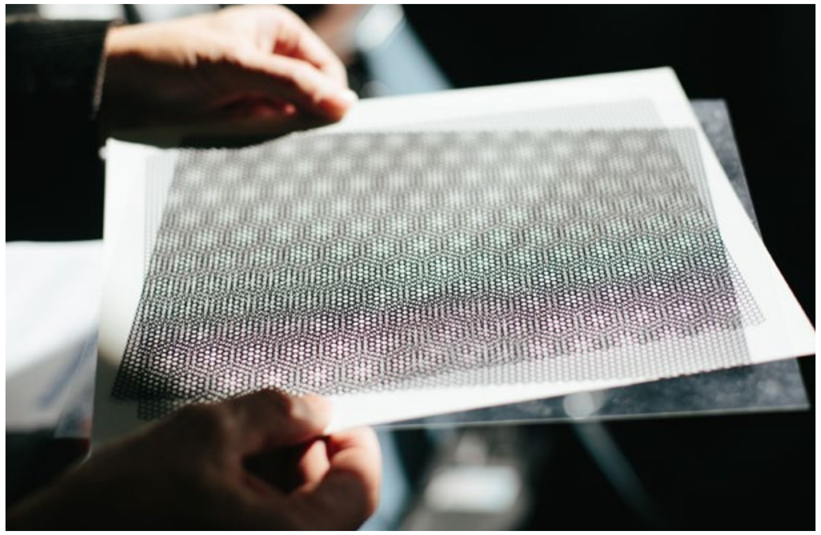
5.
The Universe's Fate Rests on the Hubble Constant–Which Has So Far Eluded Astronomers
Scientists keep getting conflicting calculations of the expansion rate of the universe, but a new technique could help

7.
Monster Magnetar Pinpointed as Trigger of Ultrabright Stellar Detonation
New observations of a superluminous supernova could finally solve the mystery behind these and other bewildering cosmic events

NASA FLICKR (CC BY 2.0)

9.
Ghostly Galaxies Hint at Dark Matter Breakthrough
Two newfound galaxies appear to be devoid of the mysterious substance, paradoxically providing more proof dark matter exists

12.
Physicists Lay Out Plans for a New Supercollider
The proposed facility would become the most powerful—and most expensive—collider ever built



JULIETTE HALSEY *NATURE*

FEATURES

15.
Hidden History of the Milky Way Revealed by Extensive Star Maps
Data from the Gaia spacecraft are radically transforming how we see the evolution of our galaxy

19.
How "Magic Angle" Graphene Is Stirring Up Physics
Misaligned stacks of the wonder material exhibit superconductivity and other curious properties

26.
Have We Mismeasured the Universe?
New studies of the oldest light and sound in the cosmos suggest novel physics—rather than systematic errors—could explain an unsolved scientific mystery

OPINION

30.
Be Kind to Extraterrestrials
We need to tread lightly if we encounter alien ecosystems

32.
The Moment We First Saw Ultima Thule Up Close
What it was like to be with the science team as the New Horizons probe reported back from the most distant object ever visited by a spacecraft

36.
Microbes Might Be Key to a Mars Mission
Engineered yeast could turn waste into food, plastics and other essentials

38.
Celestial Movement
The sky is always changing. To appreciate this ever-changing view, grab these sky maps, go outside at night and look up!
Sky maps: April, p. 41; and May, p. 42.

Galileo satellite

Wayward Satellites Test Einstein's Theory of General Relativity

The botched launch of two Galileo navigation probes made for an unexpected experiment

IN AUGUST 2014 a rocket launched the fifth and sixth satellites of the Galileo global navigation system, the European Union's $11-billion answer to the U.S.'s GPS. But celebration turned to disappointment when it became clear that the satellites had been dropped off at the wrong cosmic "bus stops." Instead of being placed in circular orbits at stable altitudes, they were stranded in elliptical orbits useless for navigation.

The mishap, however, offered a rare opportunity for a fundamental physics experiment. Two independent research teams—one led by Pacôme Delva of the Paris Observatory in France, the other by Sven Herrmann of the University of Bremen in Germany—monitored the wayward satellites to look for holes in Einstein's general theory of relativity.

"General relativity continues to be the most accurate description of gravity, and so far it has withstood a huge number of experimental and observational tests," says Eric Poisson, a physicist at the University of Guelph in Ontario, who was not involved in the new research. Nevertheless, physicists have not been able to merge general relativity with the laws of quantum mechanics, which explain the behavior of energy and matter at a very small scale. "That's one reason to suspect that gravity is not what Einstein gave us," Poisson says. "It's probably a good approximation, but there's more to the story."

Einstein's theory predicts time will pass more slowly close to a massive

P. CARRIL AND ESA

object, which means that a clock on Earth's surface should tick at a more sluggish rate relative to one on a satellite in orbit. This time dilation is known as gravitational redshift. Any subtle deviation from this pattern might give physicists clues for a new theory that unifies gravity and quantum physics.

Even after the Galileo satellites were nudged closer to circular orbits, they were still climbing and falling about 8,500 kilometers twice a day. Over the course of three years Delva's and Herrmann's teams watched how the resulting shifts in gravity altered the frequency of the satellites' superaccurate atomic clocks. In a previous gravitational redshift test, conducted in 1976, when the Gravity Probe-A suborbital rocket was launched into space with an atomic clock onboard, researchers observed that general relativity predicted the clock's frequency shift with an uncertainty of 1.4×10^{-4}.

The new studies, published last December in *Physical Review Letters*, again verified Einstein's prediction—and increased that precision by a factor of 5.6. So, for now, the century-old theory still reigns.

—Megan Gannon

The Universe's Fate Rests on the Hubble Constant—Which Has So Far Eluded Astronomers

Scientists keep getting conflicting calculations of the expansion rate of the universe, but a new technique could help

NASA FLICKR (CC BY 2.0)

A PRECISE MEASUREMENT OF the Hubble constant, the value that describes how fast the universe is expanding, has eluded scientists for decades. Pinning this number down would put a long-simmering debate among astronomers to rest and bring us one step closer to understanding the evolution and fate of the universe. Now researchers have used recent detections of gravitational waves to present a proof of concept for an entirely new method of determining the constant.

Until now astronomers have taken two approaches to reckoning the constant's value. One method uses objects of known brightness, called standard candles, such as Cepheid variable stars. A Cepheid star's light fluctuates at regular intervals, and the interval is related to how much luminosity it puts out. Deriving the star's actual brightness from its rate of fluctuation and comparing that with how bright it appears to Earth observers is how astronomers determine its distance. The scientists then measure the redshift of the same objects—that is, how much their light has been shifted toward the red end of the electromagnetic spectrum. Redshift occurs when a light source moves away from an observer; light waves emitted from it will be stretched. This is similar to how the sound of a car horn drops in pitch as the vehicle drives away. By measuring a distant star's redshift, astronomers can calculate how fast it is receding from Earth. When they combine that information with its distance, they obtain a value for the Hubble constant.

The second technique for figuring out the expansion rate of space relies on the cosmic microwave background (CMB), the ghostly radiation left over from the big bang that permeates deep space. Precise measurements of temperature variations in the CMB from the Planck Space Telescope, when plugged into the Standard Model of the big bang's cosmology, allow astronomers to derive the constant.

The problem is, the values obtained from these methods do not agree—a discrepancy cosmologists call "tension." Calculations from redshift place the figure at about 73 (in units of kilometers per second per megaparsec); the CMB estimates are closer to 68. Most researchers first thought this divergence could be due to errors in measurements (known among astrophysicists as "systematics"). But despite years of investigation, scientists can find no source of error large enough to explain the gap.

A more exciting possibility is the tension reflects a real difference between the Hubble constant at the distance Planck is looking at, the faraway early universe, and that of the standard candle method, the nearby, recent universe. Of course, scientists already know the universe's expansion is accelerating—although they do not know exactly why, and name the mysterious cause "dark energy."

By measuring a distant star's redshift, astronomers can calculate how fast it is receding from Earth. When they combine that information with its distance, they obtain a value for the Hubble constant.

But even accounting for the known acceleration, the tension suggests something strange may be happening to dark energy to cause the Hubble constant to diverge this much. It indicates the rate of expansion during the cosmic epoch that followed the big bang, which the CMB would reflect, was radically different from what cosmologists currently believe it to be. If a dark energy anomaly is not to blame, it is possible some unknown particle such as an undiscovered flavor of neutrino, the nearly massless particles that pervade the cosmos, may be affecting the calculations. "This tension can hide the solution to the description that we have of the universe—its evolution, the sources of energy which are in it," says Valeria Pettorino, an astrophysicist and research engineer at CEA Saclay in France who was not involved in the study. "And in practice, this decides the past, the present and the future of our universe, whether or not it's going to be expanding forever, whether or not it's going to re-collapse and rebound."

WAVES IN SPACETIME

Now, using gravitational-wave signals from the merger of two black holes and redshift data from one of the most ambitious sky surveys ever conducted, researchers have developed an entirely new way to calculate the Hubble constant. They described the method in a study they submitted to *The Astrophysical Journal Letters* and posted on the preprint site arXiv on January 6. In it they report a value of 75.2 for the constant, albeit with a large margin of error (+39.5, −32.4, meaning the actual number could range up to 114.7 or go as low as 42.8). This large uncertainty reflects the fact the calculation comes from a single measurement, and thus does not yet help clear up the tension between the original two calculation methods. But as a proof of concept, the technique is groundbreaking. Only one other measurement, from October 2017, has attempted to calculate the Hubble constant using gravitational waves. Scientists hope future gravitational-wave detections will help them improve the precision of their calculation.

Gravitational waves are ripples in the fabric of spacetime. Einstein's general theory of relativity predicted their existence in 1915, and astronomers had been looking for ways to detect them since. Not surprisingly, collisions of massive objects create a significant splash of gravitational waves. In 1986 physicist Bernard Schutz first proposed these so-called binary systems could be used to determine the Hubble constant. He argued observatories would very likely detect them in the near future; in fact it took nearly 30 years before observatories saw the signals.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) in Louisiana and Washington State made the world's first gravitational wave detection in September 2015, and has seen fewer than a dozen more events since then, along with its European counterpart, Virgo. The experiments look for minuscule alterations in spacetime caused by passing gravitational waves.

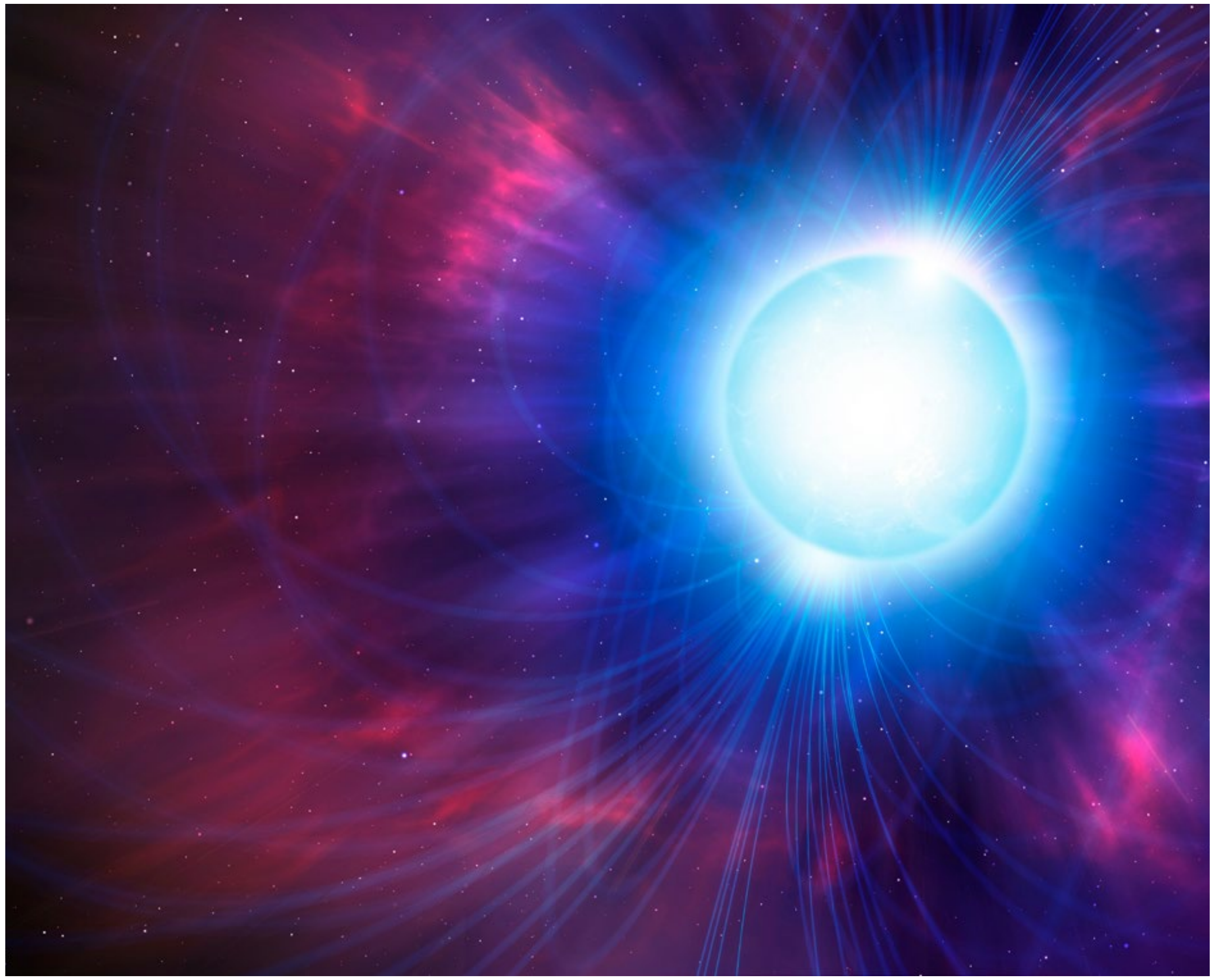
STANDARD SIRENS

A burst of gravitational waves from the merger of two black holes is one piece of the new method for calculating the Hubble constant. Not unlike standard candles, binary black hole systems oscillate. As they spiral into each other, the frequency of the gravitational waves they spew out changes at a rate correlated to the system's size. From this, astronomers derive the waves' intrinsic amplitude. And by comparing that with their apparent amplitude (similar to a comparison of the actual brightness of a Cepheid with its apparent brightness), they compute how far away the system is. Astronomers call these "standard sirens." They measured the distance to this particular collision as some 540 megaparsecs, or about 1.8 billion light-years, from Earth.

An associated redshift, such as that of the sirens' host galaxy, provides the second piece of the new method. The researchers used redshift data from the Dark Energy Survey, which just finished mapping a portion of the southern sky more broadly and deeply than any previous survey. The redshift data combined with the distance measurement provided researchers with their new figure for the constant.

Antonella Palmese, a research associate at Fermilab and co-author of the study, says the method holds promise in part because black hole mergers are relatively plentiful. Although it is still a proof of concept, she says that as more gravitational events from LIGO/VIRGO become available, the statistics will improve. University of Oxford astronomer Elisa Chisari, who was not involved in the study, agrees. "The level of constraints that they obtained on the Hubble rate is not competitive at the moment compared to other measurements," she says. "But as LIGO builds up its catalogue of gravitational wave events in the coming years, then by combining multiple events, this will really become a competitive method."

—Jim Daley



MARK GARLICK *GETTY IMAGES*

Monster Magnetar Pinpointed as Trigger of Ultrabright Stellar Detonation

New observations of a superluminous supernova could finally solve the mystery behind these and other bewildering cosmic events

IT WAS A DAZZLING death. Roughly 1.3 billion years ago a star exploded with such force that it was 50 times brighter than the 100 billion stars in its host galaxy combined. It was so bright that if it took place in the Andromeda Galaxy, it would be visible to the naked eye. The outburst, officially known as PTF10hgi, belongs to a rare class of explosions called "superluminous" supernovae, which can shine a 100 times brighter than typical ones. But astronomers cannot say why.

One hypothesis suggests they are powered by magnetars—ultradense, rapidly spinning and highly magnetized cinders of stellar cores that can form in the aftermath of supernova explosions. If those magnetars are spinning fast enough, say 1,000 times a second, they can slow down rapidly by releasing a magnetized wind. That wind, created the moment the magnetar forms, then shocks the ejecta, adding a steadily increasing amount of heat and light to the explosion over the course of several weeks, making it much more luminous than it would be otherwise. But this scenario is only a hypothesis. “The holy grail—the thing that we’re missing—is this direct observational confirmation that there is a magnetar, this beast, in the center of the explosion,” says Brian Metzger, an astronomer at Columbia University. Now a study posted to the preprint server arXiv in January just might provide that holy grail.

Tarraneh Eftekhari, a graduate student at Harvard-Smithsonian Center for Astrophysics, her adviser Edo Berger, Metzger and their colleagues have detected radio light at the precise location where PTF10hgi once erupted. It is the first time astronomers have spotted radio emission in the aftermath of one of these superluminous supernovae. Because radio light is produced when electrons are accelerated within a magnetic field, the finding suggests a magnetar sits squarely in the spot where the supernova burst—potentially solving a near-decade-old mystery. “It’s the first time that we’re peering through the explosion and seeing the engine—seeing the wizard behind the curtain,” Berger says. “That just by itself is quite remarkable.”

Metzger is a little more conservative in his enthusiasm. “This is an exciting hint that we may have the first direct evidence that superluminous supernovae are powered by central magnetars, but we need more observations,” he says. Already, the team has submitted several proposals to make follow-up studies of the object so they can say with certainty a magnetar, and not another culprit, produces the radio emission. And Deanne Coppejans, an astronomer at Northwestern University who was not involved in the study, agrees the future data are crucial. “At the moment it’s looking very promising, but the observations they’ve proposed should solve the mystery,” she says.

TWO SIDES OF THE SAME COIN

The study might also solve a second mystery—that of fast radio bursts, or FRBs. These brief, bright flashes of radio waves appear to originate in distant galaxies and yet their precise sources remain unknown, making them one of the most intriguing puzzles in astrophysics. Although they might seem unrelated to superluminous supernovae, when Eftekhari and her colleagues picked up the radio emission coincident with PTF10hgi, it was reminiscent of radio light associated with one such FRB. And it was not a surprise to the team—that was precisely the signature Eftekhari and her colleagues had hoped to find.

In 2016 astronomers announced a major clue in the FRB riddle: One of the bursts, known as FRB 121102, flared up more than once, making it the first burst to repeat. The finding allowed scientists to place it on the cosmic map—pinning it to a galaxy roughly 2.5 billion light-years away. Surprisingly, that galaxy was not run-of-the-mill, but rather a dwarf galaxy with few heavy elements—an oddity that looked remarkably similar to the galaxies where superluminous supernovae originate. This caused astronomers to wonder whether the two might somehow be related. In addition, when researchers localized the repeating FRB, they found a persistent source of weaker emission that emanated from the exact spot where the bursts had occurred. That radio emission suggested the burst originated within an intense magnetic field, which could have been produced by a magnetar.

Those two hints led Metzger and Berger to postulate superluminous supernovae and FRBs are two different signatures of the same object. In 2017 they published a study with a number of theoretical calculations that suggested a magnetar would first produce a superluminous supernova—and then, years if not decades later, produce a number of FRBs (although exactly how remains a mystery). And all the while that magnetar would create a nebula that glows in radio light. If the hypothesis is correct, astronomers should be able to look at these superluminous supernovae years after they first erupt and see the nebula's persistent radio light and—if they are really lucky—a fast radio burst or two.

TRACKING MORE CLUES

Recently a number of teams began the hunt for that exact signature. Eftekhari and her colleagues analyzed 25 superluminous supernovae with the Very Large Array (VLA) in New Mexico and the Atacama Large Millimeter/submillimeter Array (ALMA) in the Chilean Andes. When they spotted this radio source it seemed to confirm their highest hopes, offering not only proof (or close to it) that the superluminous supernova was spawned by a magnetar but a hint the same magnetar might also give rise to FRBs. "It was a little too good to be true that in our first search that we've ever done we had such a beautiful result," Berger says.

And others throughout the field are equally excited. "It's a tantalizing discovery that really does hint that some of these mysterious objects that have puzzled us for a long time—superluminous supernovae and fast radio bursts—are all manifestations of the same thing," says Andrew Levan, an astronomer at the University of Warwick in England who did not take part in the study. "It's a great discovery."

But it is still just one clue. To transform that into hard evidence, astronomers would like to see an FRB—and not just radio emission—emanate from a past superluminous supernova. "That would be the real smoking-gun connection," says Casey Law, an astronomer at the University of California, Berkeley, who was not part of the work. And such a find might just be around the corner. A number of scientists are eager to follow up on this object and other superluminous supernovae.

Laura Spitler, an astronomer at Max Planck Institute for Radio Astronomy who discovered the first repeating FRB but was not involved in this research, is planning to observe this object soon. And Law, who has already completed a search for FRBs within superluminous supernovae sites but has yet to analyze the observations, just might have one already hiding within his data.

—Shannon Hall

Ghostly Galaxies Hint at Dark Matter Breakthrough

Two newfound galaxies appear to be devoid of the mysterious substance, paradoxically providing more proof dark matter exists

MUCH AS A RIPPLE in a pond reveals a thrown stone, the existence of the mysterious stuff known as dark matter is inferred via its wider cosmic influence. Astronomers cannot see it directly, but its gravity sculpts the birth, shape and movement of galaxies. This makes a discovery from last year all the more unexpected: a weirdly diffuse galaxy that seemed to harbor no dark matter at all.

Even as some researchers hailed the finding, others aired their doubts, criticizing measurements of the galaxy's distance and motion. The stakes are high: If the galaxy does in fact lack dark matter, that would paradoxically bolster the case for the material's existence. Now the original team is back with additional evidence confirming their initial discovery, plus a newfound second galaxy that appears to show the same thing—or, rather, the lack thereof. Where once there was but one ultradiffuse galaxy seemingly free of dark matter, now, it seems, there are two. "One object, you can always write off as a unicorn, but once you find two unicorns, you start thinking unicorns exist, maybe," says Michael Boylan-Kolchin, an astronomer at the University of Texas at Austin who was not involved in the research. "Then you have to start worrying about how they got there, what are their properties and how common are they?"

FINDING THE UNICORNS

The two galaxies are very faint and far away from Earth: Photons from their smatterings of stars began traveling to Earth in the last days of the dinosaurs' reign, some 65 million years ago. The original galaxy, called NGC 1052-DF2, is the size of the Milky Way but contains just 1 percent of our galaxy's stars. The new one, NGC 1052-DF4, is in the same patch of sky and has roughly the same size and mass. (The name "DF" comes from their discovery using the Dragonfly Telephoto Array, which specializes in detecting faint objects.)

Last March researchers led by

The bizarre galaxy NGC 1052-DF2, a diffuse collection of stars, gas and dust that is apparently devoid of dark matter.

NASA, ESA, AND P. VAN DOKKUM *YALE UNIVERSITY*

Shany Danieli and Pieter van Dokkum of Yale University published a study that sized up NGC 1052-DF2 by observing its starlight as well as the movements of star clusters that surround it. If DF2 contained as much dark matter as astronomers would normally expect for such a galaxy, the dark matter would boost the orbital speeds of those star clusters. But they move sluggishly, which suggests dark matter is absent. Critics countered these star cluster speeds had not been calculated correctly—and, even if the calculations were correct, argued the sample size of just 10 star clusters was too modest for making reliable determinations of DF2's dark matter inventory.

Next, in October, Danieli set out to settle the question using a different technique. She used the Keck Cosmic Web Imager, a new instrument freshly installed behind the giant 10-meter primary mirror of the Keck 2 telescope in Hawaii. The instrument can measure the light from very faint objects at extremely high resolution, making it an ideal instrument for scrutinizing ultradiffuse galaxies such as NGC 1052-DF2. The instrument was so good, in fact, that Danieli no longer needed to study the star cluster motions to infer the galaxy's mass. Instead, she could get at the mass more directly, using the galaxy's starlight.

In terms of information, starlight contains multitudes. By splitting light into its constituent colors, a practice called spectroscopy, scientists can determine a star's makeup, age, direction through the cosmos and speed. Much of that information is conveyed in spectral lines—linear features embedded in a star's spectrum due to the emission or absorption of various chemical elements. The Keck instrument measured the spectra for roughly 10 million stars in the DF2 galaxy. The size of the spread between the fastest and slowest stars in the galaxy gives an idea of how much matter interacts with them. The more matter present—dark or otherwise—the greater the spread in the stellar velocities. "To our own surprise, we measured extremely narrow [spectral] lines, which leaves very little room for more mass other than the mass contributed by the stars in the galaxy," Danieli says. No room for dark matter.

Meanwhile, Eric Emsellem of the European Southern Observatory and colleagues were scrutinizing the galaxy using the Very Large Telescope in Chile's Atacama desert. They also found a low-velocity dispersion, which supports the missing dark matter scenario.

Nicolas Martin, an astronomer at the University of Strasbourg in

France, was among the critics of the original paper. In subsequent work published last year, he argued it is too difficult to estimate the DF2 galaxy's mass based on surrounding star cluster motions. But Martin says he was reassured by the latest results from Danieli and Emsellem. "This is only thanks to brand-new instruments that arrived on the biggest telescopes on the planet that this is feasible. And to be entirely honest, it wasn't clear to me a year ago that it would be feasible," he notes. "A year ago I wasn't ready to say the system was necessarily weird, because I felt the measurement wasn't entirely supported by the data. But now that there are two different teams that have measured the range of velocities of the stars themselves, I think it's clear that this is an oddball."

Danieli presented her new findings at a dark matter conference in January at Princeton University, and has submitted them to *The Astrophysical Journal Letters* for peer-reviewed publication.

In a separate paper she describes the DF4 galaxy, which she and several colleagues observed with the Hubble Space Telescope last year. Examining seven star clusters orbiting DF4, Danieli and her co-workers found they are moving languidly, suggesting there is very little or no dark matter in the galaxy. Taken together, the near back-to-back discovery of DF2 and DF4 lurking in the same patch of sky implies a whole class of such dark matter–poor galaxies exists, she says.

IN SEARCH OF MISSING MATTER

Several astronomers are scratching their heads over how such galaxies could form in the first place, and where the dark matter went. One possibility is the gravitational pull of a much larger galaxy nearby stripped off the dark matter, Boylan-Kolchin says. Or DF2 and DF4 may not be galaxies after all, just modest collections of stars masquerading as such; in that case, these isolated groups of stars may have formed from colliding jets of gas streaming from another location. Or there could be more humdrum scenarios such as the galaxies' orientation with respect to Earth being unfavorable for obtaining accurate spectral measurements of their motions, according to Martin. "I'm a little torn about the system. It's certainly intriguing and it needs to be explained, but it could well be that the explanation is quite mundane, and it's just the wrong angle or something like that," he says.

One thing is clear: If confirmed beyond a reasonable doubt, the galaxies' lack of dark matter would conclusively show the stuff is separable from stars, gas, dust and other regular matter, and would further bolster the case for dark matter's existence.

To date, nobody has definitively detected dark matter despite decades of ardent searching. The absence of evidence has led some astrophysicists to search for alternative ways to sculpt galaxies and dictate their motions by developing classes of hypotheses with names like "emergent gravity" and "modified Newtonian dynamics." Proponents of such ideas argue the sculpting most astronomers attribute to dark matter may actually be a phenomenon that arises from physics we cannot yet comprehend. But if that were the case, those conditions would obtain everywhere. Galaxies like NCG 1052 DF2 and DF4 would be subject to those alternative gravities, too—and those theories would need to somehow explain such galactic oddities (which they currently do not). And so the galaxies' sheer peculiarity suggests these alternatives are wrong, and dark matter must indeed be the cause.

Stacy McGaugh, an astronomer at Case Western Reserve University and a proponent of some dark matter alternatives, notes Emsellem's velocity-dispersion measurement is almost twice as high as Danieli's. "The statement one is obliged to make is that we are still waiting for this to settle out. I would like to see the data be consistent," he says. "But it is consistent with stars only and no dark matter, and that makes it really interesting. The next thing you have to ask is: How did that come to be? Is it an intrinsic property, there are just galaxies like this? My own feeling is no."

More definitive answers could come soon; Danieli says the team is now looking for other dark matter–free dwarf galaxies. "It may be that these objects tell us something about the nature of dark matter, but it's too soon to tell. That's certainly our hope, but we first need to find more objects and study them in greater detail," she says.

—Rebecca Boyle

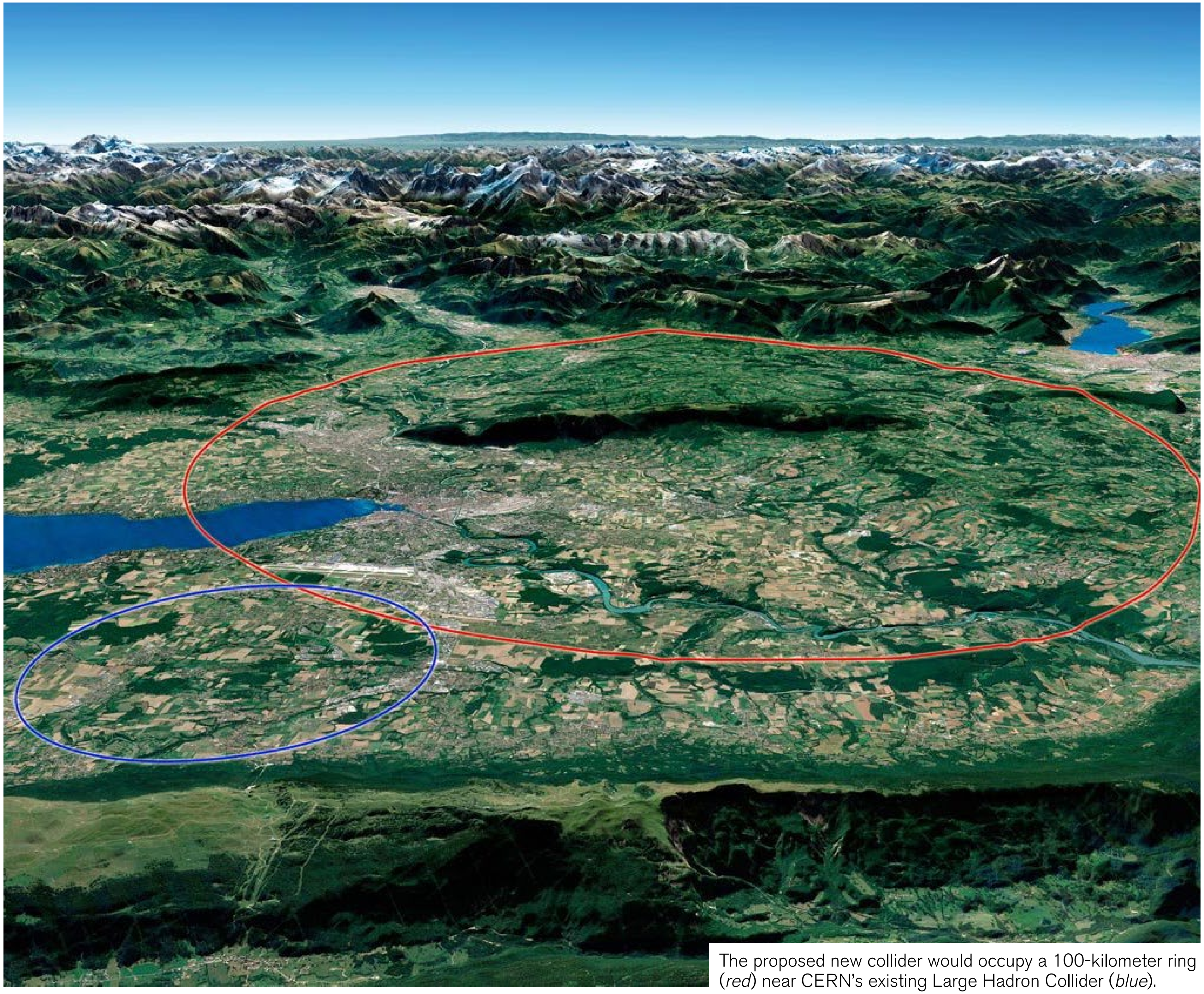
Physicists Lay Out Plans for a New Supercollider

The proposed facility would become the most powerful—and most expensive—collider ever built

CERN HAS UNVEILED ITS bold dream to build a new accelerator nearly four times as long as its 27-kilometer Large Hadron Collider—currently the world's largest—and up to six times more powerful.

The European particle physics laboratory, outside Geneva, Switzerland, outlined the plan in a technical report on January 15.

The document offers several preliminary designs for a Future Circular Collider (FCC)—which would be the most powerful particle-smasher ever built—with different types of colliders ranging in cost from around €9 billion (U.S.$10.2 billion) to €21 billion. It is the lab's opening bid in a priority-setting process over the next two years, called the European Strategy Update for Particle Physics, and it will affect the field's future well into the second half of the century.



The proposed new collider would occupy a 100-kilometer ring (*red*) near CERN's existing Large Hadron Collider (*blue*).

CERN

“It’s a huge leap, like planning a trip not to Mars, but to Uranus,” says Gian Francesco Giudice, who heads CERN’s theory department and represents CERN in the Physics Preparatory Group of the strategy exercise.

After the LHC’s historic discovery of the Higgs boson in 2012, the collider has not discovered any new particles. This points to a need to push energies as high as possible, Giudice says. “Today, exploring the highest possible energies with bold projects is our best hope to crack some of the mysteries of nature at the most fundamental level.”

The potential for a machine such the FCC is “very exciting,” says Halina Abramowicz, a physicist at Tel Aviv University who heads that European strategy process. She adds that the FCC’s potential will be discussed in depth and compared to other proposed projects.

The CERN Council, which includes scientists and government delegates from member countries, will then make the final decision on whether to fund the project.

TOO PRICEY?

Not everyone is convinced the super-collider is a good investment. “There is no reason to think that there should be new physics in the energy regime that such a collider would reach,” says Sabine Hossenfelder, a theoretical physics at Frankfurt Institute for Advanced Studies in Germany. “That’s the nightmare that everyone has on their mind but doesn’t want to speak about.”

> **“There is no reason to think that there should be new physics in the energy regime that such a collider would reach.”**
>
> ***—Sabine Hossenfelder***

Hossenfelder says that the large sums involved might be better spent on other types of huge facilities. For example, she says that placing a major radio telescope on the far side of the moon, or a gravitational-wave detector in orbit, would be safer bets in terms of their return on science.

But Michael Benedikt, a CERN physicist who led the FCC report, says that such a facility would be worth building regardless of the expected scientific outcome. “These kind of largest-scale efforts and projects are huge starters for networking, connecting institutes across borders, countries. All these things together make up a very good argument for pushing such unique science projects.”

Though Hossenfelder says that a similar argument could be made of other big-science projects.

THE OPTIONS

The FCC study started in 2014 and involved more than 1,300 contributors, according to CERN, with a financial contribution from the European Commission’s Horizon 2020 research-funding program. Most of the scenarios it outlines involve a 100-kilometer tunnel to be dug next to the existing Large Hadron Collider’s tunnel. The cost for this and the related infrastructure on the surface would be around €5 billion, says CERN.

A €4-billion machine built in such a tunnel could smash electrons and their antimatter counterparts, positrons, with energies of up to 365 gigaelectronvolts. Such collisions would enable researchers to study known particles such as the Higgs boson with greater precision than is possible at a proton-proton collider such as the LHC. This new research program would start only around 2040, after the LHC—including a planned upgraded version—has run its course.

Physicists have long planned to build an International Linear Collider (ILC) after the LHC, which would also smash electrons and positrons. Japanese scientists pitched to host in 2012. But the LHC’s failure to find any unpredicted phenomena has diminished the case for a linear collider. This is because the ILC would only reach energies sufficient to study the Higgs but not to discover any new particles that may exist at higher energies, as CERN’s planned collider might. The Japanese government has so far delayed their decision whether to host the ILC.

Another option outlined in the report is a €15-billion, 100-kilometer proton-proton collider (also known as a hadron collider) built in the same tunnel that could reach energies of up to 100,000 GeV, much higher than the LHC’s maximum capability of 16,000 GeV. But a more likely scenario would be to build the electron-positron machine first, and move on to the proton-proton collider later on, in the late 2050s. Either way, the higher-energy machine would look for entirely new particles, which could be more massive than the known ones and therefore require more energy to produce.

The hadron collider would be only 15 percent longer than the Superconducting Super Collider, a project in Texas that was abandoned over cost concerns in the 1990s when its tunnels were already in mid-construction. But because of technological improvements, notably in the magnets that bend the protons' path around the ring, it would smash the particles at energies more than twice higher.

Much research and development is still to be done, which is one reason why it might make sense to build the lower-energy machine first. "If we had a 100-kilometer tunnel ready tomorrow, we could start building an electron-positron collider right away because the technology essentially exists already," says Giudice. "But more research and development is needed for the magnets required by a 100-teraelectronvolt collider."

CHINA'S COMPETITOR

Wang Yifang, the director of China's Institute of High Energy Physics (IHEP) in Beijing, says that he does not doubt that the lab could pull off such a project. "CERN has a long history of success. It has the technological capabilities, the management skills and good relationships with governments," he says.

Wang is leading a similar project in China, and he says that reassuringly, both efforts have come to essentially the same conclusion in terms of science goals and technical feasibility. In particular, it is a natural choice to do electron-positron collisions first and then move on to hadrons later, he says.

Much of the added cost for a hadron collider would come from the need for powerful superconducting magnets and the huge helium cryogenic systems to keep them cold. The hadron-colliding FCC would aim at 16-tesla magnets based on the superconducting alloy Nb3Tn, which would be twice as powerful as the LHC while in principle requiring only slightly warmer temperatures. China on the other hand is pushing for more advanced—but less proven—iron-based superconductors that could push temperatures even higher. "If you are able to do it at 20 kelvin, then you get huge savings," Wang says.

Even if particle physicists agree that the world needs a 100-kilometer collider, it is unclear whether it needs two. Whichever side gets such a project going first will probably pre-empt efforts on the other side. Either collider would host experiments open to the broader international community, Wang says, so scientifically it will not make a difference which one ends up being built.

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–Davide Castelvecchi

ESO/B. TAFRESHI (TWANIGHT.ORG)

Hidden History of the Milky Way Revealed by Extensive Star Maps

Data from the Gaia spacecraft are radically transforming how we see the evolution of our galaxy

By Adam Mann

Adam Mann is a freelance journalist
based in Oakland, Calif.

LAST APRIL, AMINA HELMI FELT GOOSE BUMPS WHILE DRIVING to work in the northern Netherlands. It had nothing to do with the weather—it was pure anticipation. Just days earlier, a flood of data had been released from Gaia, a European Space Agency (ESA) mission that has been mapping the Milky Way for five years. The University of Groningen astronomer and her team were racing to comb through the data for insights about the galaxy before others got there first.

Working on fast-forward, unable to sleep from the excitement, Helmi and her colleagues sensed they were on to something. The team had spotted a set of 30,000 renegade stars. Unlike other objects in the main body of the Milky Way, which orbit in a relatively flat disk shape, these nonconformists were moving backwards, in orbits that were carrying them out of the galactic plane.

Within weeks, the team had worked out that the luminous horde pointed to a long-hidden and especially tumultuous chapter in the Milky Way's history: a smashup between the young galaxy and a colossal companion. That beast once circled the Milky Way like a planet around a star, but some eight billion to 11 billion years ago, the two collided, massively altering the galactic disk and scattering stars far and wide. It is the last-known major crash the galaxy experienced before it assumed the familiar spiral shape seen today.

Although the signal of that ancient crash had been hiding in plain sight for billions of years, it was only through Gaia's data set that astronomers were finally able to detect it. "It's just incredible to have been able to find such an important milestone in the history of the Milky Way," says Helmi.

Such monumental discoveries are becoming almost commonplace thanks to Gaia. The mission aims to catalogue more than one billion local stars, charting their brightness, temperatures, ages, locations and velocities. It is those last two properties that are particularly edifying for astronomers: before Gaia, scientists lacked high-precision measurements of the distance to many stars, as well as what's known as proper motion, or a star's movement across the sky. Using this crucial information, researchers can—as Helmi and her colleagues did—hunt for groups of objects traveling together in coordinated trajectories that point to a common history. Stellar velocities can also help astronomers to trace the influence of dark matter—the invisible and still-mysterious substance that constitutes most of the galaxy's mass and bends the paths of stars with its gravity.

Hundreds of papers have been published since Gaia's April 2018 data release. They paint a picture of a Milky Way that is much more dynamic and complex than previously imagined. The galaxy is teeming with surprises, including hints of dark matter clumps that might eventually give scientists a better grasp of the shadowy material's properties. The early, easy-to-spot findings have already been transformational, says astronomer Vasily Belokurov at the University of Cambridge, U.K., and yet they are merely a glimpse of what is to come: "How we see the Milky Way has clearly changed."

A DISRUPTIVE PAST

The solar system sits on the outskirts of the Milky Way, some 8,000 parsecs (26,000 light-years) from the galactic center, on a secondary spiral arm known as Orion. It is from this perch, looking at the enormous starry band stretching across the night sky, that astronomers must map out the galaxy's structure. By the mid-20th century, they had painted a broad-brush picture, determining that the Milky Way's stars are distributed in a central bulge, wrapped by serpentine stellar arms and surrounded by a thin, spherical halo. In the 1970s and 1980s, researchers deduced how this structure had built up over billions of years, beginning with a vast cloud of dark matter, gas and dust. The visible components collapsed into a disk-like structure, which then bulked up by devouring smaller, satellite galaxies. Astronomers later filled in the details by using terrestrial telescopes to repeatedly photograph the entire night sky. Such surveys allowed scientists to peer more closely at large-scale galactic objects such as the stellar halo, where they found remnants of small galaxies that had been stretched out into star-studded debris streams.

But ground-based surveys give astronomers only so much information about the Milky Way's structure, mainly because blurring from Earth's turbulent atmosphere limits how accurately the distances to stars can be determined. And although the speed at which stars move toward or away from Earth can be measured by changes in color, sorting out their proper motion—and so their full 3D velocity—is difficult because most objects move so little across the sky on human timescales. That problem has obscured the relationships between many stars—links that might be revealed by similarities in their movements.

The roughly €740-million (U.S.$844-million) Gaia mission, which was approved in 2000 and launched 13 years later, was designed to fill these gaps. Orbiting the sun slightly farther out than Earth does, the spacecraft snaps the same stars from different positions in its orbit. This allows astronomers to measure distance through a quantity known as stellar parallax—infinitesimal shifts in the apparent position of an object in the sky that accompany a change in perspective. ESA's Hipparcos satellite, which operated between 1989 and 1993, gathered similar parallax data. But Gaia's precision will ultimately be 100 times greater. And thanks to its sensitivity, it can probe deeper into the galaxy: some 99 percent of the more than one billion stars it observes have never had their distances accurately determined.

In a computationally intensive undertaking, Gaia researchers have built up a plot of the location of every star relative to every other star that the telescope sees. This has allowed the team to measure how fast stars seem to travel across the sky—their proper motion. Then, by measuring small shifts in the color of the stars, astronomers can get an indication of how quickly the objects are moving toward or away from the satellite, along its line of sight. The combination of the two measurements, plus the distances calculated from Gaia, provides the stars' full 3D motion. Gaia can measure the line-of-sight motion for the brightest stars it sees, but ground-based telescopes will help to measure the remaining stars. Knowing where each star is and where it's going allows researchers to quickly tease out hidden Milky Way history.

Such was the case for the ancient collision investigated by Helmi and her colleagues. In their work, evidence that the cohort of stars they spotted shared a common origin was bolstered by data from the ground-based Sloan Digital Sky Survey (SDSS) in New Mexico, which showed that the members of the ensemble all had a similar chemical composition. The team chose the name Gaia-Enceladus for the dwarf galaxy that is thought to have been the stars' home. Enceladus was a giant who descended from Gaia in Greek mythology.

As it so happened, Belokurov and his colleagues had also found evidence of the collision, using information from Gaia's preliminary data release in 2016. Those data did not include proper-motion readings, but by comparing stellar positions in that data set with SDSS observations taken about a decade ago, the team could see how stars had moved in the intervening time. They noticed a group of objects traveling together on eccentric orbits that should eventually take them from the center of the galaxy to the outskirts. These seemed to have originated from a single major crash, their shared history apparent because of similarities in metal content. Because the plotted velocities formed a sausage shape, the team dubbed the ancient dwarf galaxy that was once the stars' home the Gaia Sausage.

The double naming has led to some confusion in the community. But whatever the culprit is called, the ancient merger could be a clue to an abiding Milky Way mystery. The galaxy's disk has two components—a thin inner disk containing gas, dust and young stars sits like the filling of an Oreo, inside a thick outer disk consisting almost entirely of older stars. Astronomers have debated whether the thick disk arose first, with gas and dust then condensing down to form a thinner core, or whether the structure began with a thin disk that was then partially puffed up. Because the Gaia-Enceladus-Sausage was a significant fraction of the Milky Way's size during the crash, it would have deposited a great deal of energy into the galactic disk, heating and expanding it. Helmi's group sees this as a mark in favor of the puffing-up scenario, and evidence of a dramatic distortion to the Milky Way.

KNOWLEDGE EXPLOSION

The speed at which such previously difficult insights can be made using Gaia data has astounded researchers. Astronomer Kathryn Johnston at Columbia University recalls the buzz over a paper posted the day after the April data release, showing how the motions of about six million stars near the sun are all aligned in a peculiar spiraling pattern akin to a snail shell.

The pattern seemed to be a fingerprint, Johnston says, stamped by a small satellite galaxy known as Sagittarius. Every time Sagittarius swoops in close, it gravitationally disturbs galactic stars, and this should generate wobbles and ripples in the disk. Researchers had previously conjectured about such imprints, but the signature in the Gaia data seemed to be the first clear and compelling signal of Sagittarius's influence. "For me that was a stunning moment," says Johnston. "The spiral was so clean. It looked like a theoretical prediction from an idealized simulation, not a real data plot."

Thanks to Gaia's eyes, such perturbations are not only standing out, they are also telling a different story about the Milky Way's past. Previously, most astronomers presumed that whereas the outer halo of the galaxy has endured a chaotic collisional history with smaller satellites, the main bulk has lived a fairly quiet life. Features such as the spiral arms and a bar of stars that is thought to cross the central bulge have generally been treated as products of the Milky Way's internal dynamics. But the wobbles that seem to be induced by Sagittarius suggest that external forces have a greater bearing on the Milky Way's shape than was previously recognized.

Gaia is forcing researchers to take a second look at some of the canonical assumptions that are used to simplify models, says astrophysicist Adrian Price-Whelan at Princeton University. "We knew those assumptions were wrong," he adds. "Gaia has now shown us how wrong they were."

PLOTTING THE DARK SIDE

Mapping the Milky Way's luminous objects could also shed light on dark matter, which might constitute as much as 90 percent of the galaxy's mass. Theorists suspect that our galaxy sits inside an enormous, roughly spherical halo of dark matter that, much like ordinary matter, has clumped together into smaller structures thanks to gravity. Cosmological simulations suggest that thousands of large dark matter clumps orbit the galaxy, occasionally getting eaten by a mass of dark matter at the center, in a process akin to the Milky Way's consumption of its small visible satellites.

The vast majority of the dark matter substructures are thought to contain few or no stars, making them difficult to detect. But Gaia might have found a hint of one in GD-1, a long stream of stars discovered in 2006 that stretches across half of the northern sky. This stellar stream is no stranger to scrutiny, but Gaia enabled Price-Whelan and astronomer Ana Bonaca at the Harvard-Smithsonian Center for Astrophysics to more confidently pick out true members of the group. Last November, they and two other colleagues identified structural features, including a distinct gap, that could be the scars of an encounter with a massive object some 500 million years ago. As the putative perturber sped past the stream, it might have separated the train of stars by gravitationally tugging on some, allowing them to pull ahead of their companions.

The most likely culprit seems to be a dense dark matter clump, probably somewhere between one million and 100 million times the mass of the sun, says Bonaca. That estimate could have implications for physical models of dark matter. A dark matter particle's mass helps to dictate how fast it can move and, in turn, the size of clusters it is liable to form. The GD-1 perturber's size is in an interesting range, says Bonaca, that could eliminate hypothesized dark matter candidates that are relatively low in mass.

Bonaca and her team are now interested in using Gaia data to determine the velocities of the disturbed stars in the stream, which might point to the orbit of the putative dark matter clump. If they can ascertain where it could be found today, they might be able to detect its gravitational effects on other material. Or perhaps they could train gamma-ray telescopes on the spot to look for evidence of dark matter particles annihilating one another or decaying, processes that could emit energetic photons. Either technique could offer a more-direct probe of the invisible substance's physical properties.

Yet Price-Whelan says it is hard to infer too much from a single example. He hopes that systematic studies using the Gaia catalogue and future observatories—such as the ground-based Large Synoptic Survey Telescope in Chile, which is expected to begin gathering data in the early 2020s—will reveal fainter stars and other stellar streams. If some of those streams also show effects from encounters with dark matter clumps, they could give astronomers a better idea of the abundance and size of such clusters, which would help to pin down the properties of dark matter.

Astronomers hope that Gaia's data on stellar motions will also help them to map out the general shape of the galaxy's dark side. Depending on the type of particle it is built from, the Milky Way's dark matter halo could have different levels of sphericality or symmetry. Belokurov expects that information from Gaia on local stellar orbits will be sufficient to trace out the overall mass and shape of the dark matter halo in the next two to four years.

Such findings won't be confined to the Milky Way. The conclusions drawn about the galaxy's history and dark matter distribution will feed back into cosmological models that are used to explore how the universe's large structures grew and changed. Gaia has already been granted its first mission extension to the end of 2020, and astronomer Anthony Brown at Leiden University in the Netherlands, who chairs the mission's data-processing and analysis consortium, thinks the satellite can continue to gather data until 2024, for a 10-year mission in total. He says that this extension should provide a factor-of-three improvement in the precision of Gaia's measurement of proper motion for the stars it currently tracks. And it could provide information about ever-more-distant stars.

Gaia's ultimate legacy has yet to be written, but all indications suggest it will be substantial. Data from all-sky surveys such as those conducted by the SDSS continue to provide fruitful discoveries about the universe a decade or more after they were completed. Helmi is looking forward to further rewinding the Milky Way's history as Gaia's catalogue gets bigger and more detailed. "One of the things that I find most exciting," she says, "is that we just started really digging into the past."

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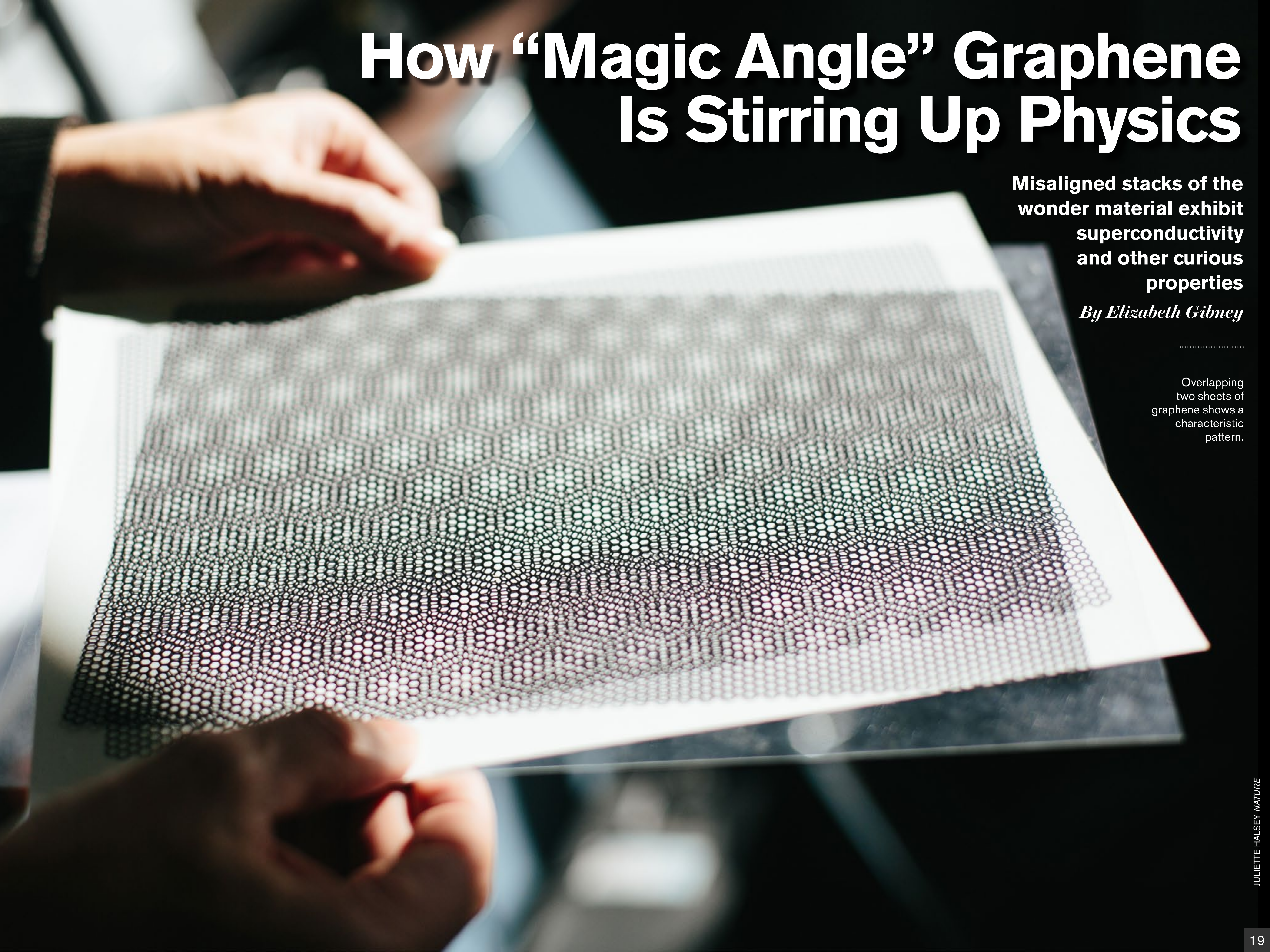
How “Magic Angle” Graphene Is Stirring Up Physics

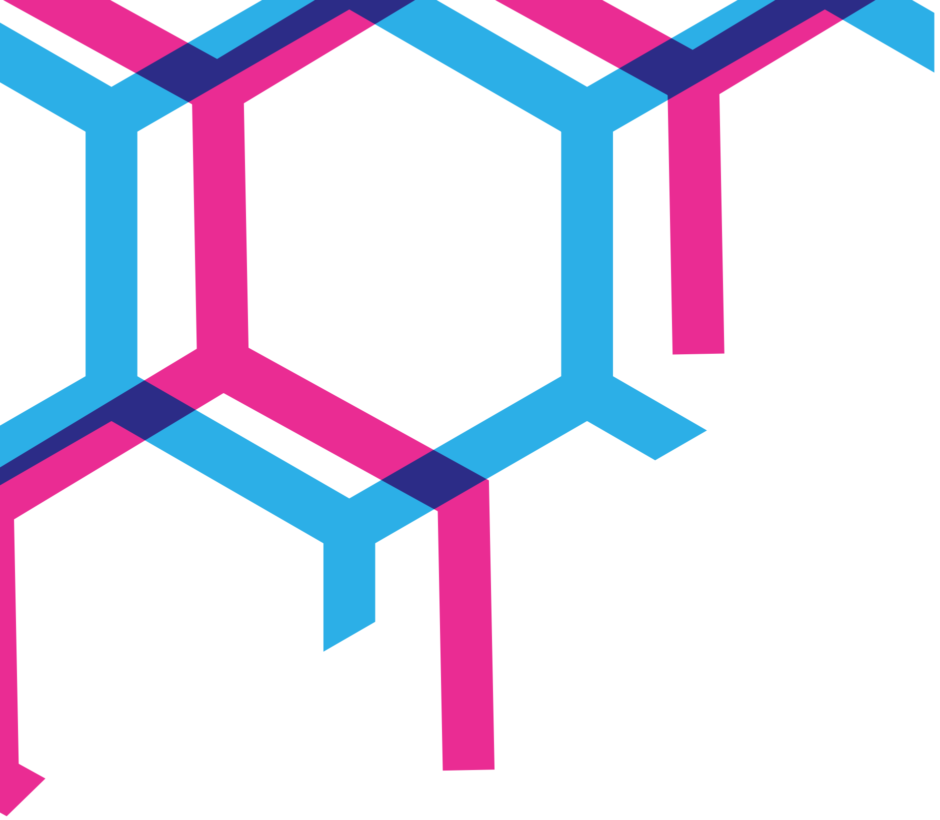
Misaligned stacks of the wonder material exhibit superconductivity and other curious properties

By Elizabeth Gibney



Overlapping two sheets of graphene shows a characteristic pattern.

JULIETTE HALSEY *NATURE*



It was the closest that physicist Pablo Jarillo-Herrero had ever come to being a rock star. When he stood up last March to give a talk in Los Angeles, he saw scientists packed into every nook of the meeting room. The organizers of the American Physical Society conference had to stream the session to a huge adjacent space, where a standing-room-only crowd had gathered. “I knew we had something very important,” he says, “but that was pretty crazy.”

The throngs of physicists had come to hear how Jarillo-Herrero’s team at the Massachusetts Institute of Technology had unearthed exotic behavior in single-atom-thick layers of carbon, known as graphene. Researchers already knew that this wonder material can conduct electricity at ultra-high speed. But the MIT team had taken a giant leap by turning graphene into a superconductor: a material that allows electricity to flow without resistance. They achieved that feat by placing one sheet of graphene over another, rotating the other sheet to a special orientation, or “magic angle,” and cooling the ensemble to a fraction of a degree above absolute zero. That twist radically changed the bilayer’s properties—turning it first into an insulator and then, with the application of a stronger electric field, into a superconductor.

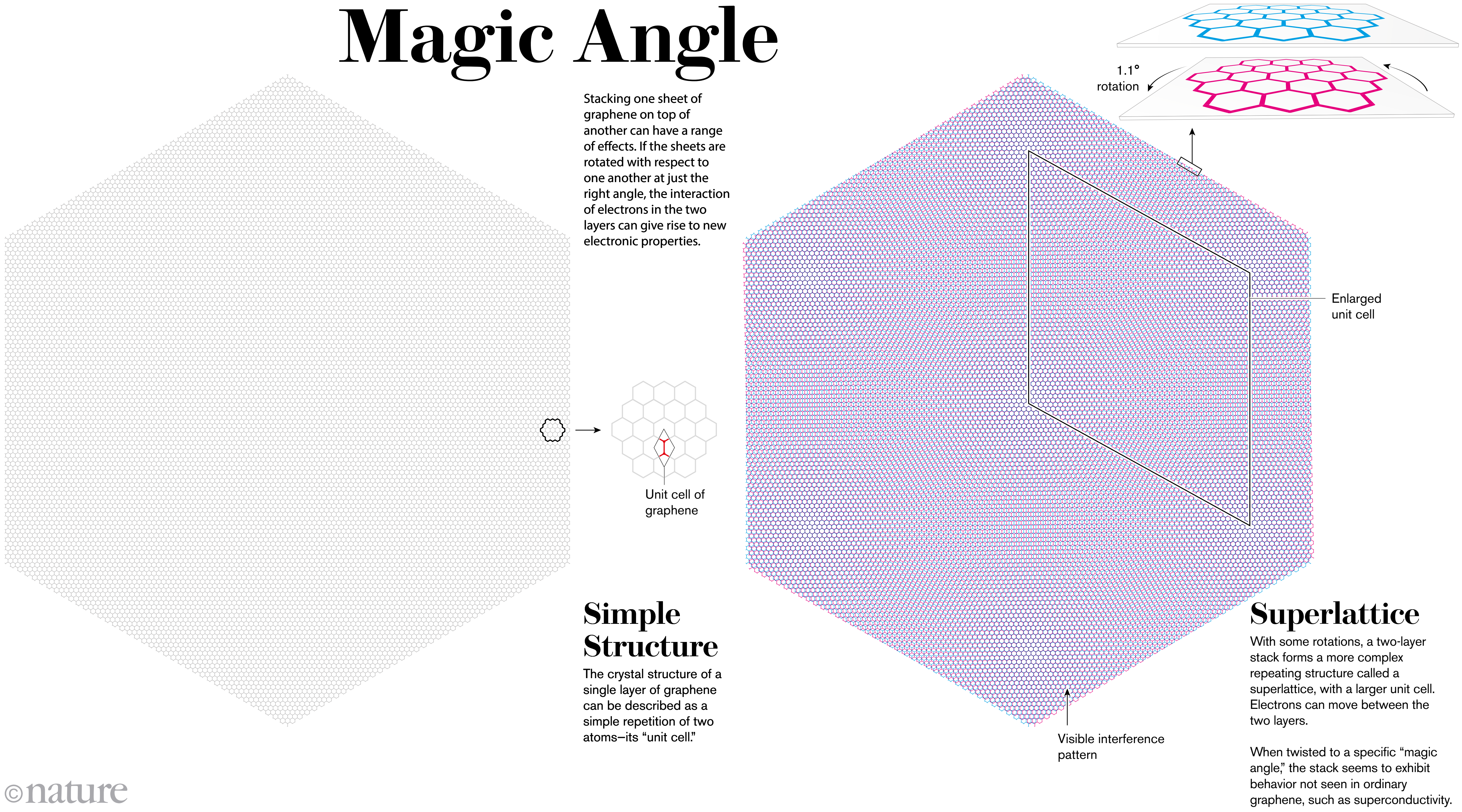
Graphene had previously been cajoled into this behavior by combining it with materials that were already known to be superconductors, or by chemically splicing it with other elements. This newfound ability to induce the same properties at the flick of a switch turned heads. “Now you put two, non-superconducting atomic layers together in a certain way and superconductivity pops up? I think that took everyone by surprise,” says ChunNing Jeanie Lau, a physicist at the Ohio State University.

Physicists at the meeting were even more excited because of the way in which a graphene bilayer seems to become a superconductor. There were hints that its remarkable properties arose from strong interactions or “correlations” between electrons—behavior that is thought to underlie bizarre states of matter in more-complex materials. Some of those materials, namely ones that superconduct at relatively high temperatures (although still well below 0 degrees Celsius), have baffled physicists for more than 30 years. If superconductivity in simple graphene is caused by the same mechanism, the material could be the Rosetta stone for understanding the phenomenon. That, in turn, could help researchers to engineer materials that superconduct close to room temperature, which would revolutionize many areas of modern technology, including transportation and computing.

“Immediately I could see pretty much everyone I know become really excited,” says Lau. But while she listened in amazement to the talk, others couldn’t wait. Andrea Young, a condensed-matter physicist at the University of California, Santa Barbara, had left the meeting to rush back to his laboratory. His team was one of a handful around the world already exploring twisted graphene, looking for hints of recently predicted strange behavior. Young scanned the *Nature* papers from the MIT group, which were published two days ahead of the talk, and found what he needed to know to replicate the experiment. That turned out to be harder than anticipated. But by August, having joined forces with a group at Columbia University led by physicist and friend Cory Dean, he and his team succeeded. “We had reproduced it many times ourselves,” says Jarillo-Herrero. But having the confirmation of a second group, he says, “was tremendously reassuring.”

Elizabeth Gibney works for *Nature* magazine.

Magic Angle



Stacking one sheet of graphene on top of another can have a range of effects. If the sheets are rotated with respect to one another at just the right angle, the interaction of electrons in the two layers can give rise to new electronic properties.

Simple Structure

The crystal structure of a single layer of graphene can be described as a simple repetition of two atoms—its "unit cell."

Superlattice

With some rotations, a two-layer stack forms a more complex repeating structure called a superlattice, with a larger unit cell. Electrons can move between the two layers.

When twisted to a specific "magic angle," the stack seems to exhibit behavior not seen in ordinary graphene, such as superconductivity.

Although the Young and Dean collaboration was the first to publicize its replication results, activity behind the scenes is frenetic, says Lau. "I haven't seen this much excitement in the graphene field since its initial discovery," she says. Three other teams told *Nature* that they have replicated some or all of the MIT findings, although some are keeping their cards close to their chests while they experiment with other 2D materials and tweak layers in new ways, looking for other displays of strong electron interactions. "Everyone is taking their favorite thing and twisting it with their other favorite thing," says Young. Meanwhile, theorists trying to explain the behavior have posted more than 100 papers on the topic to the arXiv preprint server. But sorting out whether the same mechanism that underlies superconductivity in high-temperature superconductors is at play in twisted graphene will take much more information, says Lau. "So far, apart from the fact that this is a really interesting system," she says, "I don't think the theorists agree on anything."

FINDING THE MAGIC

The audience at Jarillo-Herrero's talk in Los Angeles was excited but also skeptical. Conference delegates teased him that the last time someone had presented something so cool, it was Jan Hendrik Schön, whose string of dazzling results on superconductivity and other phenomena turned out to be fraudulent. "They were joking," Jarillo-Herrero says, "but they said they'd need to see this reproduced before they would believe it."

Although twisted graphene's superconducting behavior came as a surprise, the idea that something intriguing could happen was not. Overlaid at angles of more than a few degrees, two graphene sheets usually behave independently. But at smaller angles, the misalignment of the two lattices can create a "superlattice" in which electrons can move between layers. Theorists had predicted that at specific small twists—magic angles—the underlying structure of the superlattice would drastically change the behavior of electrons, slowing them down and enabling them to interact in ways that change the material's electronic properties. In theory, all kinds of layered 2D material, when twisted to the proper angle, can form such superlattices. But no one knew how a material's properties might change, or at what angle such a change might occur.

Back in 2010, Eva Andrei, a physicist at Rutgers University—New Brunswick, and her colleagues saw hints of strange behavior in graphene around the same magic angle later observed by Jarillo-Herrero and his team, but many doubted whether the theory worked at all. "I didn't believe it, says Philip Kim, an experimental physicist at Harvard University. "But I admit I was completely wrong," he says.

When Young arrived back at his lab in March, he thought that reproducing the MIT group's results seemed trivial, he says. Young's team could achieve the very low temperatures needed, and the researchers were already experts in preparing very clean samples. But coaxing graphene sheets to align at just the right angle—a twist of around 1.1 degrees—turned out to be a struggle.

Hitting the angle is difficult, not least because it subtly changes from sample to sample, depending on how each one is made. "You have to do some searching," says Andrei. Moreover, because twisted graphene's structure is so close to that of graphite, in which successive layers are all oriented in the same direction, the slightest heat or strain can cause the layers to fall into alignment. "It doesn't want to stay where you put it," says Young.

Dean's lab, which was also working on the problem, hit on a solution: when the team overshot the twist in a number of devices, at least some samples would settle at the magic angle as they rotated back towards alignment. But getting those samples to superconduct required equipment that could reach a fraction of a

Physicist Pablo Jarillo-Herrero (*far left*) with three graduate students in his lab at the Massachusetts Institute of Technology.

JULIETTE HALSEY FOR *NATURE*

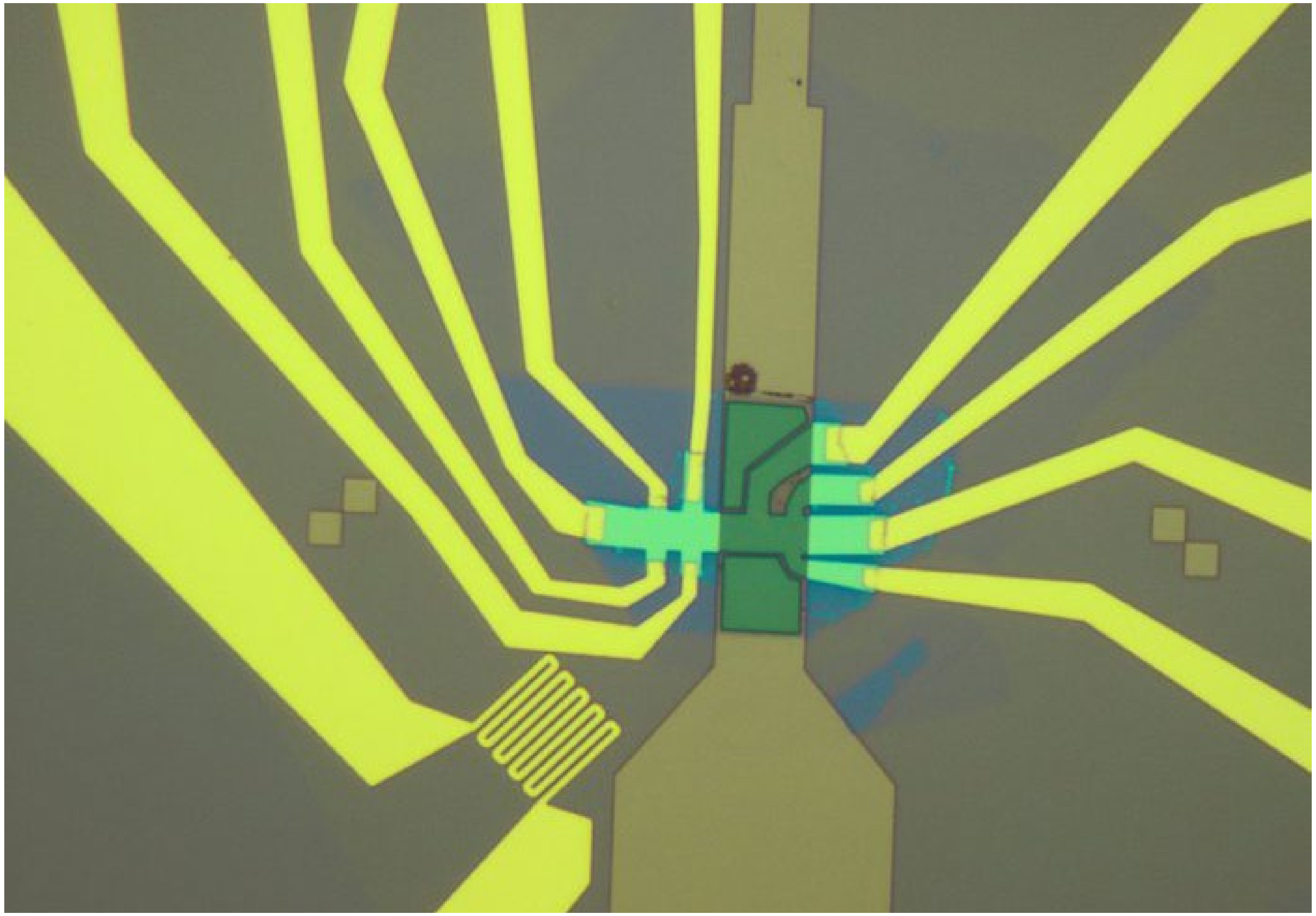
degree above absolute zero, which his lab lacked. Working with Young's team, the researchers soon measured several devices in which resistance shot up—characteristic of an insulator—but dropped to zero, as in superconductors, when they fed in more electrons by applying an electric field.

It is the only other team apart from Jarillo-Herrero's to publish its findings so far, but that will not be the case for long, says Andrei. "Everyone I know is working on this," she says.

SOMETHING UNCONVENTIONAL

One reason for the intense interest in twisted graphene is the stark similarities between its behavior and that of unconventional superconductors. In many of these, electric current runs without resistance at temperatures well above what the conventional theory of superconductivity generally allows. But quite how that happens remains a mystery: one that, when solved, could allow physicists to engineer materials that conduct electricity with zero resistance near room temperature. Achieving that could enable radically more-efficient transmission of electricity, and, by slashing energy costs, allow superconductors to find uses in a host of new technologies.

All forms of superconductivity rely on electrons pairing up in ways that allow them to travel without resistance. In conventional superconductors—the kind that power the magnets in magnetic resonance imaging (MRI) machines—electrons pair up only indirectly, as a by-product of the interplay between the particles and vibrations in their atomic lattice. Electrons ignore their fellows, but end up thrown together in a way that helps them to navigate without resistance at temperatures a few degrees above absolute zero. But in unconventional superconductors—many of which carry current with zero resistance at closer to 140 kelvin—electrons seem to pair up through a direct and much stronger interaction.



A device from Pablo Jarillo-Herrero's lab that was built to test the physics of graphene.

JARILLO-HERRERO LAB

The MIT experiments showed hints of this unconventional superconductivity. Although twisted bilayer graphene became superconducting only at extremely low temperatures, it did so with very few freely moving electrons. That suggests that, unlike in a conventional superconductor, whatever force drew the electrons together must be relatively strong. The proximity of the superconducting state to an insulating one also mirrors what is seen in a group of high-temperature superconductors made from ceramics, called cuprates. In those systems, the zero-resistance state often borders a "Mott" insulator—in which no current flows, despite the presence of free electrons, because mutual repulsion between the particles pins them in place.

If the same mechanisms are at play in twisted bilayer graphene, it could be a boon to theorists. One problem with cuprates, such as yttrium barium copper oxide, is that they are a jumble of elements that proves difficult to model. "The hope is of finding the same phenomenology but in a much simpler system, one which theorists can stick their teeth into and make some progress," says Andrei.

Graphene is also an experimentalist's dream. Studying the switch to superconductivity means measuring what happens as more electrons are added to the material. In cuprates, this is done by inserting atoms of a different element into the material—a process known as doping—which means making an entirely new sample for each point on a chart. In twisted graphene, however, researchers can make the switch simply by turning a knob on a voltage source, says Andrei. "This is a huge benefit."

No one knows yet whether twisted graphene is really acting like an unconventional superconductor, or even whether the behavior arises exactly because of the conditions described by the magic-angle theory. The flood of theory papers posted since last March covers every possibility. Because correlated systems such as those seen in twisted graphene are too complex to calculate in their entirety, theorists use approximations that differ from model to model. That makes theories flexible enough for physicists to sometimes tweak them to fit new data, says Young. Few theories explain the findings in full, and many do not include predictions that would allow experimentalists to tease apart different scenarios, adds Jarillo-Herrero. For "an experimentalist like me they all seem similarly sensible," he says. "I'm a bit disoriented in theory land."

So far, there is evidence for both unconventional and conventional superconductivity in graphene. As-yet-unpublished data from the MIT group suggest that other phenomena seen in unconventional superconductors are also present in the material, says Jarillo-Herrero. For one thing, his team has observed that the strength of the magnetic field necessary to strip superconductivity from a sample, through a process known as the Meissner effect, varies with direction (it should be uniform in conventional superconductors).

> **"You have to be careful about interpreting what you see, because you don't know what's an intrinsic property of the system and what's an effect of the set-up."**
>
> ***—Andrea Young***

CAUTIOUS APPROACH

But results from Young's and Dean's groups suggest more caution is needed. Their samples are more uniform than those of the MIT group, says Young, and show some contrasting results. In particular, superconductivity appears when the number of electrons is turned down but not when it is turned up, an asymmetry that is arguably more consistent with a conventional superconductor. And, in contrast to cuprates, which can be insulating at higher temperatures than those at which they superconduct, in twisted graphene the two states seem to be present in a similar temperature range, he adds. Further tests, such as seeing whether the superconducting state still occurs when experimentalists restrict vibrations in the sample but still allow electron interactions, could help to clarify the situation, says Young. Andrei's group is also working on imaging the material at the atomic level, to reveal effects that could be washed out when studying the sample as a whole. Andrei says her team's preliminary data have revealed new phenomena that could help to make sense of the underlying physics, although she is so far unwilling to give any more away.

Understanding the outcomes of experiments—along with devising set-ups that work well on 2D materials—can be a challenge. In this delicate system, Young says that even the material used to make the electrodes can interfere with results. "You have to be careful about interpreting what you see, because you don't know what's an intrinsic property of the system and what's an effect of the set-up." Young says the mechanism behind the superconductivity could well turn out to be conventional, but that it is exciting even if it doesn't help to explain high-temperature superconductivity. "This is already one of the coolest results to come out of this field in the past 10 years," he says.

Regardless of whether it resembles exotic forms of superconductivity, researchers say the system is fascinating because it is a rare example of dramatic change coming from a small physical tweak. "That fact alone is pretty amazing and remarkable," says Dean. "What is it about this system that gives rise to superconductivity that is absent away from this precise twist angle?"

Whatever is going on in the superconducting state, physicists agree that the accompanying insulating state is almost impossible to explain without some kind of interaction between electrons. Like a metal, graphene is ordinarily conductive, with free electrons that interact only with the atomic lattice and not with one another. Somehow, despite the presence of these free electrons, which are absent in conventional insulators, bilayer graphene can block the flow of electricity, suggesting that interactions are at play.

This is exciting because electron interactions underlie many of the weird and wonderful states of matter that have been uncovered over the past few decades. These include quantum spin liquids—strange disordered states in which electrons' magnetic fields never align—and fractional quantum Hall states, phases of matter defined by topology, a previously unknown kind of unifying property that might be harnessed to build extremely robust quantum computers. "Understanding strongly correlated systems is where a lot of the big questions, and also perhaps big opportunities, are in condensed-matter physics right now," says Young. Many of these states emerge under conditions that, at least to electrons, look similar to those that arise in graphene at the magic angle. This raises the possibility that other intriguing states could emerge from twisted bilayers, says Rebeca Ribeiro-Palau, a physicist at the Center for Nanoscience and Nanotechnology in Palaiseau, France, and formerly a postdoc in Dean's lab. "For me, the presence of a superconducting state is a symptom of something more interesting," she says.

Crucially, graphene and other 2D systems allow for much greater experimental control than do other strongly correlated materials, she says. Researchers can smoothly tune not only the electric field to alter behavior, but also the twist angle—while at Columbia, Ribeiro-Palau and her colleagues used the tip of an atomic force microscope to smoothly spin one layer with respect to the other. As has been demonstrated by the Young and Dean collaboration, experimentalists can also fine-tune the distance between layers by applying pressure. Squeezing the layers closer together increases the strength of the interaction between electrons in the sheets, a boost that means magic-angle conditions can happen at much bigger—and more stable—rotations.

> **"In principle, you can apply the concept to all the 2D materials and twist to see what happens. There is the possibility that you find something completely unexpected."**
>
> ***—Philip Kim***

DOING THE TWIST

Kim and his colleagues have already replicated the graphene finding, he says. Now they are looking to see whether they can also generate superconductivity or perhaps magnetism in twisted layers of more-complex 2D semiconductors, called transition-metal dichalcogenides. Before the MIT result, Kim's was one of a few teams that was already probing the effects of rotating one 2D layer on top of another, a nascent area of research sometimes known as twistronics. With the possibilities demonstrated in graphene, the idea is now taking off. "In principle, you can apply the concept to all the 2D materials and twist to see what happens," says Kim. "There is the possibility that you find something completely unexpected."

Meanwhile, Feng Wang at the University of California, Berkeley, says he and his colleagues have seen signs of superconductivity in triple-stacked layers of graphene even without a twist. Layering three sheets in a particular orientation achieves a superlattice geometry similar to that in magic-angle twisted bilayers, and results in similarly strongly correlated physics, he says.

Physicists are optimistic that the crossover between two previously separate fields—2D materials and strongly correlated systems—will lead to exciting results. "It's giving us an opportunity to talk to a whole community of people we haven't had the chance to talk to in the past," says Dean. And applied physicists are thinking about how the unusual properties of twisted 2D stacks might be harnessed to store and process information in super-efficient ways. Rotating or squeezing materials could also become a new way to switch an electronic device's behavior.

But for now, many researchers are focused on sorting out the fundamentals. In January experimentalists and theorists gathered at the Kavli Institute for Theoretical Physics in Santa Barbara for a workshop to thrash out key questions in the burgeoning field. Jarillo-Herrero hopes the meeting will help bring theorists to alignment. "At the moment, they can't even agree on the basics." More experimentalists might be willing to show their hand and publicly reveal their data, he adds.

Even though physicists don't know how significant the discovery will ultimately be, Young says there's a takeaway message from the dozens of theory papers that have appeared since the MIT publications: "Anything could come out of this, and something certainly will."

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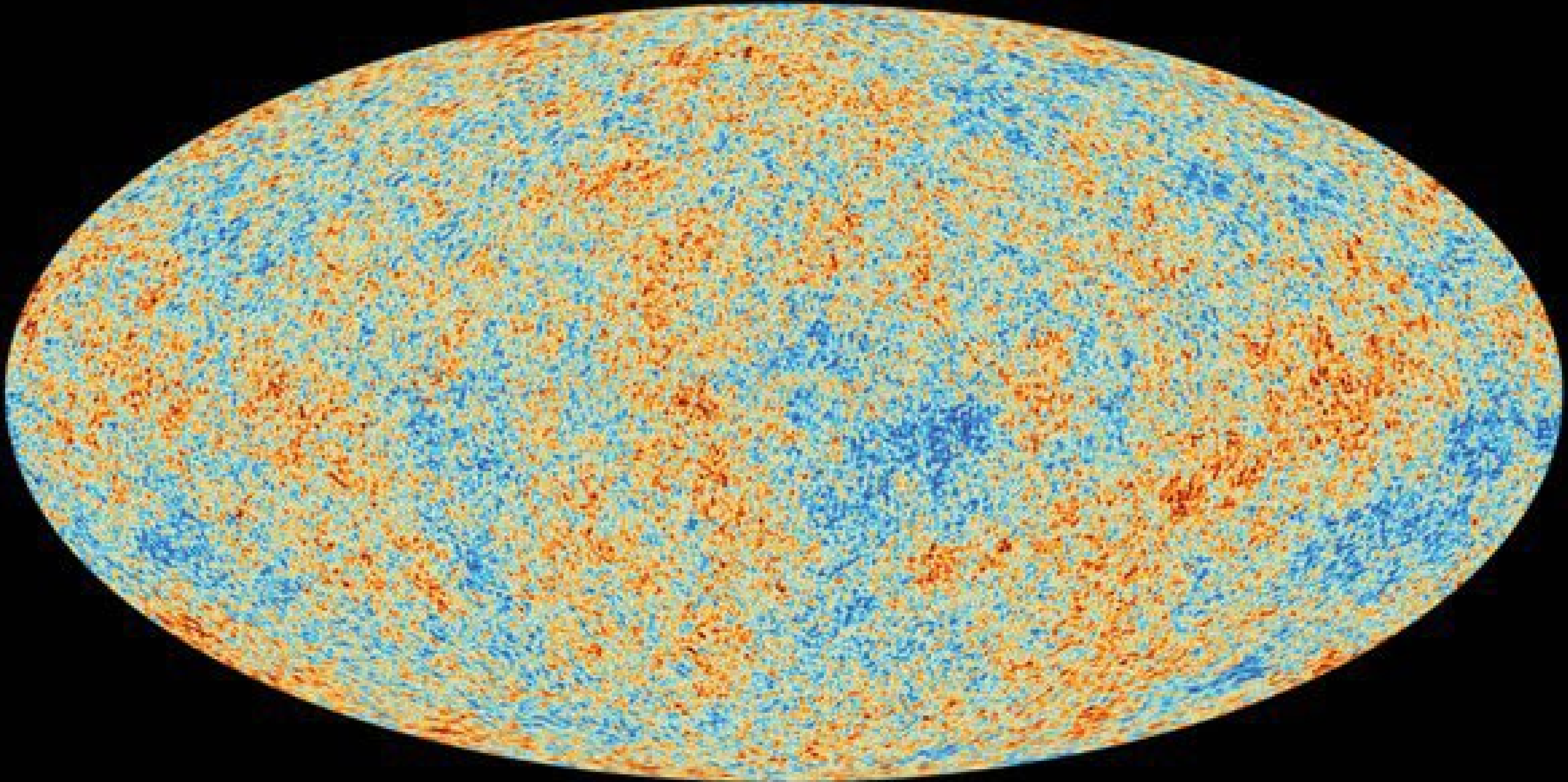


Emitted just 380,000 years after the big bang, the cosmic microwave background is the oldest observable light in the universe. By studying patterns imprinted on this ancient light, scientists can surmise the universe's age, size and large-scale structure.

ESA AND PLANCK COLLABORATION

Have We Mismeasured the Universe?

New studies of the oldest light and sound in the cosmos suggest novel physics—rather than systematic errors—could explain an unsolved scientific mystery

By Corey S. Powell

In the beginning, all of space rang like a bell.

Corey S. Powell is a science writer, blogger and editor living in Brooklyn, N.Y. He is a visiting scholar at New York University's Science, Health and Environmental Reporting Program.

It was the immediate aftermath of the big bang, and the universe was filled with a torrid plasma—an energetic soup of particles and radiation. Although that plasma was remarkably smooth, it wasn't completely smooth. There were slight density and pressure gradients that pushed material around, says Lloyd Knox, a cosmologist at the University of California, Davis, "and when stuff gets pushed around, those are sound waves."

The ringing happened everywhere, so intensely that we can still sense it 13.8 billion years later. It has been detected directly in the cosmic microwave background, the afterglow left over from the big bang's fading fireball, and it has been closely analyzed via the same basic physics used to study the structure of the sun. In fact, the primordial reverberation is so well measured and modeled that it has been used to deduce the precise rate at which the universe is expanding, a number known as the Hubble constant. That constant, in turn, is the cornerstone of our modern understanding of the size, age and structure of the cosmos.

But this seeming triumph has recently led Knox and his colleagues into controversy and confusion. If cosmologists' prevailing theories of the universe are correct, then all the ways of calculating the Hubble constant in the modern era should give the same answer. The value derived by extrapolating from the ancient sound waves should match up exactly with the value derived from independent studies of the light from distant stars and galaxies. In reality, a series of studies show the two approaches yield a vexing disagreement—and the more diligently researchers attack the problem, the more definitive the conflict seems to be.

One possibility is that somebody goofed. As the evidence piles up, however, Knox has come to embrace the other possibility: that the fault lies not with his colleagues but with the universe itself. If so, figuring out why space is not ringing the way they expected could lead cosmologists to previously unknown physics, potentially revealing a whole new aspect of reality. Knox and his co-authors explore that enticing possibility in a new study in *The Astrophysical Journal*. "Over the past two years," he says, "I've evolved from thinking, 'There must be something they did wrong' to thinking, 'Wow, maybe they haven't done anything wrong.' Maybe this is the clue I've been waiting for!"

CHASING THE SOUND HORIZON

In their paper Knox and company fix their attention on the sound horizon, an obscure but crucial aspect of how cosmologists study the early universe. Following the big bang, sound waves produced by the intermingling of light and matter traveled freely through the hot, plasma-filled universe. After some 380,000 years matter cooled enough to form atoms, decoupling from light and dampening the sound waves. Suddenly, the ringing stopped, impressing a final, frozen pattern of waves into the escaping light, which we see today in the cosmic microwave background.

The sound horizon defines the size of those final waves. "How far will the sound disturbances propagate by the time the plasma disappears? That distance is the sound horizon," Knox says.

Just as you can intuit the qualities of a bell from the way it rings (a small glass bell sounding entirely different than a large brass one), researchers can infer the precise properties of the universe from its sounds as recorded in the microwave background. That is how they can confidently declare the cosmos consists of 4.8 percent ordinary matter, 26 percent of the unseen stuff known as dark matter and a full 69 percent dark energy, an enigmatic antigravitational force that stretches empty space apart. More to the point for our story, that is also a way they can derive the expansion rate of the universe to high precision.

In 2015 a huge team led by George Efstathiou of the University of Cambridge crunched microwave measurements from the European Space Agency's Planck spacecraft and revealed the universe's vital stats. Their results indicated the universe is expanding at a rate of 67.8 kilometers per second per megaparsec (a "megaparsec" being a unit of distance equal to 3.26 million light-years). Cosmologists typically drop that mouthful at the end and simply say that the Hubble constant is between 67 and 68.

Meanwhile competing groups of astronomers have been studying the expansion of the universe in a distinctly different way, by seeking out variable stars or supernova explosions of known distance and then directly measuring how quickly they are moving away from us. This "distance ladder" method is trickier than it sounds. Reckoning distances across many millions of light-years is a subtle, time-consuming task plagued with the possibilities for many kinds of systematic errors. Get the location of a star wrong, and the entire calculation goes awry.

"Every time you increase the accuracy, you have to get to a new level with the systematics. That's what keeps me awake at night," says Wendy Freedman of the University of Chicago, who has been laboring away on the Hubble constant problem for more than three decades. By steadily beating down on the uncertainties and drawing on the latest observations of variable stars, her group has come up with its own high-precision answer for the constant: 73.2—and therein lies the controversy. "It's spectacular progress that the two numbers agree to within 10 percent," she says, but rough agreement is no longer good enough. "The error bars are certainly not overlapping, and there's nothing obvious that could be causing the difference." To ferret out any nonobvious problems, she is developing a new type of distance measurement using red giant stars as reference points. At the same time, she is running a double-blind experiment to reanalyze all of her existing data for bias and mistakes.

Cosmologists on both sides are also looking to outside groups for guidance. So far, those referees are only deepening the mystery. A University of California, Los Angeles, study that looks at how light is bent by distant galaxies gives a Hubble constant of 72.5, close to the distance-ladder result. Meanwhile an equally convincing study looking at how primordial sound waves affect the distribution of galaxies in the modern universe gives a constant of—you guessed it—67. Calculations of the Hubble constant anchored to the sound horizon consistently give a lower number than ones based on observations of stars and galaxies—and nobody knows why.

> **"It's been really hard to think of an answer that explains everything perfectly. It will have to be something complicated, because we've tried all the simple things already."**
> **—*Marius Millea***

A COMPLEX DARK COSMOS?

There is one way all of the measurements can be correct, and that is if something is wrong with scientists' interpretations of those measurements. Knox notes everything we know about the origin of the sound horizon depends on a theoretical model of how the universe behaved during its unseen initial 380,000 years. If the models are wrong and the size of the sound horizon is different than what they predict, that adjustment would change all of the numbers derived from it, including the Hubble constant. "If there is a cosmological solution, it has to be one that results in a smaller sound horizon," Knox says. Shrink it by just 7 percent, and all of the studies happily agree with one another. The problem is, it is not at all clear what could account for such shrinking. In almost every other way, the model and the observations fit together tightly.

"It's been really hard to think of an answer that explains everything perfectly. It will have to be something complicated, because we've tried all the simple things already," says Marius Millea, a researcher at the Berkeley Center for Cosmological Physics and one of Knox's co-authors. He notes it is much easier to tick off the things that do not work: Undiscovered kind of neutrino? Nope. New type of interaction between photons? Uh-uh. They all conflict with the data.

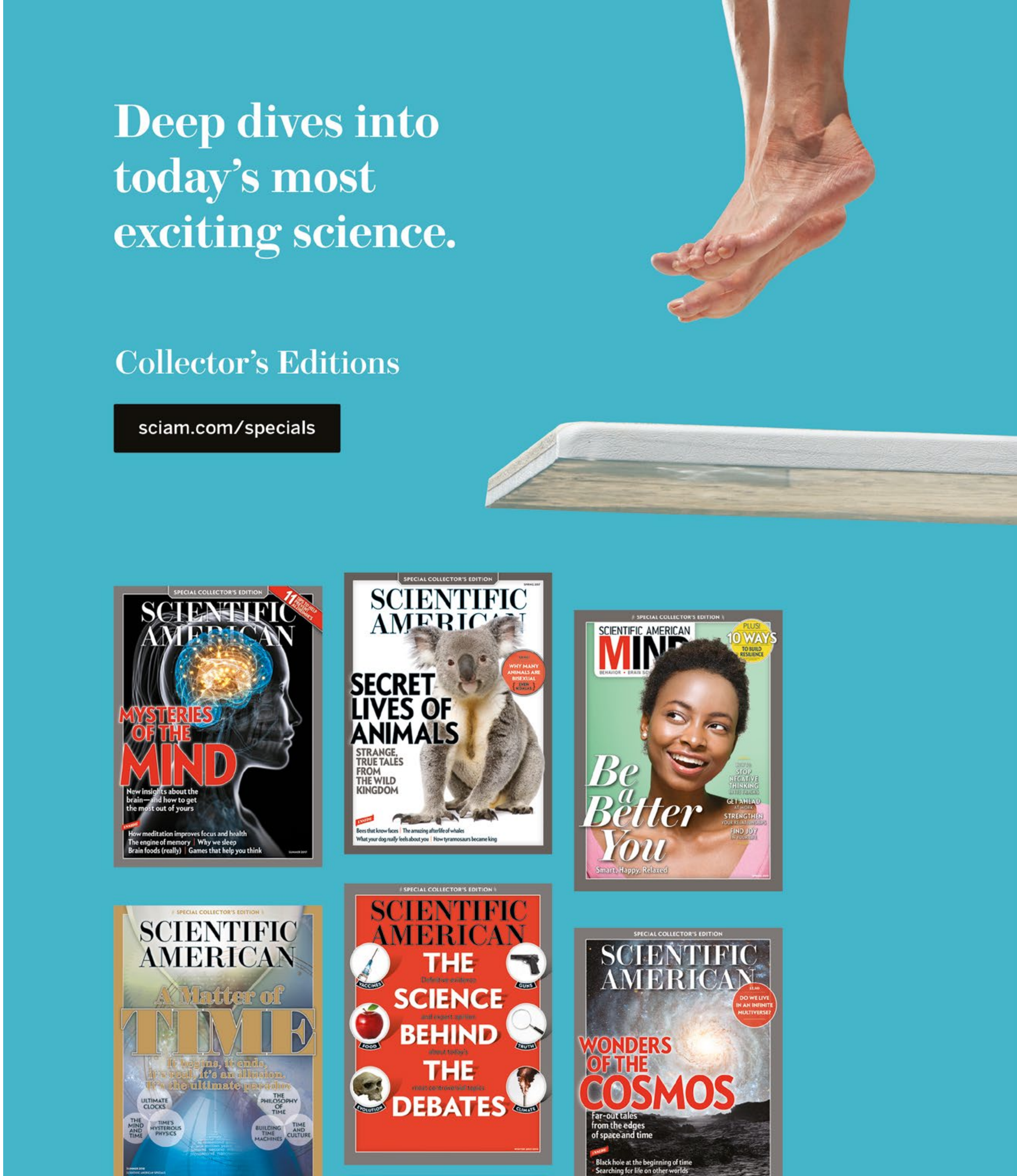
The most convincing explanation, in Knox's view, is that the very early universe was expanding slightly faster than expected. If so, it would have cooled more quickly and frozen the sound horizon in place a little sooner. Then the sound horizon would be smaller than the one theorists have plugged into their models, and—problem solved! Or rather, then the problem is kicked down the road again, because now you need some explanation for what made the early cosmos take off more quickly.

Knox has his suspicion. "Potentially where this is leading us is to a new ingredient in the 'dark sector,'" he says, referring to cosmologists' catch-all term for invisible components of the universe that do not interact with radiation in any way. Researchers already invoke dark matter to explain galactic motion and dark energy to account for the universe's accelerating expansion. The divergent measurements of the Hubble constant may be the first sign of the existence of a third dark component, Knox argues—a "dark turbo," perhaps, that added to the energy of the early universe, hastening its expansion and changing the pitch of its sounds. A related possibility is dark energy has more than one form, or changes over time in complicated ways. A recent study of 1,598 distant quasars using NASA's Chandra X-Ray Observatory offers intriguing, if preliminary, evidence for the latter interpretation.

It may seem like cheating to invoke something new and unseen to explain away a confusing result, but Knox looks at the situation the opposite way: The Hubble constant conflict may be bringing into view an aspect of the universe that had completely eluded detection until now. And he does not see anything strange about there being multiple kinds of dark elements out there. He points out the visible part of the universe contains many different types of particles and forces, and asks: Could not the dark side of the universe be complicated as well?

At any rate, this is not a philosophical debate but a concrete scientific question. New observations of the early universe by the South Pole Telescope in Antarctica and the Atacama Cosmology Telescope in Chile will further probe the sound horizon. Knox is also part of a proposed next-generation ground-based project called CMB-S4 that intends to map the polarization of the microwave sky with great sensitivity. Further, Freedman is nearly finished with her comprehensive data reanalysis. Studies of gravitational waves will provide a completely independent way to assess the true Hubble value as well.

Soon enough, data will settle whether scientists have been chasing errors or advancing on an undiscovered sector of the cosmos. "It's much more interesting if it turns out to be fundamental new physics—but it's not up to us wanting it to be one way or another," Freedman says. "The universe doesn't care what we think!"



Abraham Loeb is chair of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the advisory board for the Breakthrough Starshot project.

OBSERVATIONS

Be Kind to Extraterrestrials

We need to tread lightly if we encounter alien ecosystems

PAUL CAMPBELL *GETTY IMAGES*

In his celebrated book *On Walden Pond*, Henry David Thoreau wrote: "We need the tonic of wildness.... At the same time that we are earnest to explore and learn all things, we require that all things be mysterious and unexplorable, that land and sea be indefinitely wild, unsurveyed and unfathomed by us because unfathomable. We can never have enough of nature."

Thoreau raises a fundamental question in space exploration. Should we allow ourselves to terraform planets in an effort to make them habitable and seed objects in space with life as we know it, or should we leave nature out there to its own devices, intact and pure?

On the one hand, it would be prudent not to keep all our eggs in one basket; we might choose to spread terrestrial life to other worlds in an effort to reduce the risk of it being eliminated by catastrophes on Earth. But at the same time, one might worry that by doing so we could unleash unforeseen forces that would modify natural ecosystems in ways that could get out of hand. Moreover, artificial seeding of Earth life would muddy the waters in extraterrestrial "Walden-like" ponds. It would deprive us from the opportunity to find out if other life-forms may have existed before our arrival.

Such an impact might resemble the effect of the Spanish invasion of South and Central America, which decimated the rich culture of local populations such as the Maya. For this reason, NASA enforces tight regulations on the sterilization of space vehicles in an effort to avoid contamination of space targets with terrestrial microbes.

As we explore nature in extraterrestrial ponds, the key question is whether life there resembles what we see on Earth or takes new forms. Could it follow a different chemical network? Could it flourish in liquids other than water? Could it adjust to conditions more extreme and last longer than on Earth? But most important, how intelligent is it? It would be particularly shocking to find out that our expanded habitat includes creatures that are far smarter than we are.

Our loyalty to Thoreau's legacy would depend on whether we are alone, for if alien civilizations had been already engaged in such activities, then nature had been contaminated by artificial intent and there is no way to find it pure and primitive. Any artifacts could be considered as completing an expanded exhibit of the full scope of nature with no need to separate the biological from the technological. But there is no denying that it would be more poetic to find nature unspoiled.

As Thoreau added: "I went to the woods because I wished to live deliberately, to front only the essential facts of life, and see if I could not learn what it had to teach, and not, when I came to die, discover that I had not lived."

At the same time, it is important to keep in mind that nothing done by humans really matters in the big scheme of the universe. Humans have access to an extremely limited fraction of the cosmic reservoirs of energy and mass, and to potential places for life; there are 10^{20} habitable Earth-like planets in the observable volume of the universe, so the human imprint on the cosmic stage is destined to remain negligible. Perhaps we should limit our cosmic ambitions in light of this perspective.

As Thoreau said: "Let us first be as simple and well as Nature ourselves."

Cosmic modesty would leave us with the sole desire of embedding ourselves in nature, soaking in its beauty as spectators, not reformers, and suppressing ego-motivated plans for space colonization.

As we venture into space we could follow the wisdom of Thoreau: "Every morning was a cheerful invitation to make my life of equal simplicity, and I may say innocence, with Nature herself." Here, "morning" should be interpreted more broadly than its limited meaning on Earth. For example, it could mean "forever" in the permanent dayside of the nearest habitable planet, Proxima Centauri b.

Tod R. Lauer is a research astronomer on the staff of the National Optical Astronomy Observatory in Tucson, Ariz., and is a member of the New Horizons Science Team. Lauer's research has largely been concerned with cosmology, black holes and galaxies, but he works with the New Horizons team to support the processing and analysis of images obtained with the spacecraft.

OBSERVATIONS

The Moment We First Saw Ultima Thule Up Close

What it was like to be with the science team as the New Horizons probe reported back from the most distant object ever visited by a spacecraft

Ultima Thule

NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND SOUTHWEST RESEARCH INSTITUTE

You plan a voyage of exploration for more than three years, and the moment comes when you see a new world for the first time. This is an informal sketch of how I experienced this during the encounter of Ultima Thule by NASA's New Horizons spacecraft. The setting is a simple conference room on New Year's Day 2019 within building 200 on the campus of the Johns Hopkins University's Applied Physics Laboratory, which operates New Horizons. The room supports the analysis activities of the Geophysics and Geology Investigations team of New Horizons, one of three divisions of the overall science team established to investigate Ultima Thule. The other science divisions are hosted in similar rooms elsewhere in building 200. Other buildings at APL host the two navigation teams, the operations team, a diverse set of instrument and spacecraft engineers, and a variety of management and support personnel that make it possible for over 100 people to blend their efforts into common cause. Alan Stern is the principal investigator and responsible for the mission overall.

It took all of us to make the encounter happen. Each of us has a story to tell, a part to play, a unique perspective. The credit for success goes to far, far more people than are shown in the pictures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in this article, let alone the few who I call out in the narrative. In the end, however, the experience of the encounter is always personal—where you where, what you were doing at the time, who you were with and the shared reactions of those on the team with whom you worked most closely. This story is simply what I saw from the vantage point of the small part of the team that I happened to be with at the time.

The arrival of the first high-resolution image of Ultima Thule in physical terms could be more mundane.

In emotional terms, it could not be more electric.

The Deep Space Network has spent an hour capturing the telemetry from the New Horizons spacecraft, all while sending the image line by line to a server and reduction pipeline in Boulder, Colorado. We wait, check, wait some more for a particular file to build up in a particular directory. Who actually sees the image first comes down to who spots the key file update first—or is the fastest typist.

It's Stuart Robbins who finally shouts: "Got it!" and we immediately mob his work area in the rear of our analysis room. That's my back in the lower right of the image above ❶. I can't see a damn thing! I doubt that many of us can. We have a huge display in the front of the room, so then the question is: How fast can Stuart remember how to type the command to link up to it?

We get the image on screen and everyone goes nuts. That's Marc Buie taking a victory lap, above ❷. Marc was the one who discovered Ultima Thule in the first place, and with immense skill, focus, determination, blood, sweat (and tears for that matter), waged a four-year campaign, enlisting fellow team members (and others) to throw everything they had at the object to determine its precise path through space. Thread a needle while flying out to the galaxy at—let's see—only 42 times the speed of sound. There was never a spacecraft that needed such precise navigation until now.

Oh—hey look, that's Brian May standing in the back. He walked in about 30 seconds before the room exploded with three years of pent-up energy. It's showtime, except we're all on stage now. We're all in the zone. All of us have our parts and instruments to play, but always with attention to each other as we listen to where the music is going. See the people with their hands on their keyboards? They're not getting back to work, they're not calming down from the spectacle. They've started the beat, and we will jam into the night. A quick initial read on Ultima Thule is the task in front of us. Everyone contributes. I look around the room at one point and see Brian quietly working with another team member on using stereo imaging to visualize Ultima Thule.

But first John Spencer has a solo. That's John

NASA, JHUAPL, SWRI AND HENRY THROOP

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standing off to the right ❸. (I'm at the far right, almost certainly loading up the image myself.) John has led the team through the definition of the whole observational sequence for Ultima Thule. Three years ago, a few months after we flew past Pluto, we fired the thrusters on New Horizons to set its course to Ultima Thule. John stood up at a team meeting in November of 2015 to pose the question: "Well, OK! So, what are we going to do when we get there?" Uncountable telecons, meetings, PowerPoint presentations, simulations, consultations followed. In the middle of one, I thought "Gawd, John's trying to order Chinese food for 100!" The trick is making sure everyone gets enough to be happy, even if they can't get everything they want. Oh yeah, John was also working side by side with Marc to make sure that we got to Ultima Thule OK in the first place.

So, the solo! While we're all going nuts, John in his unflappable style remembers to ask Stuart the exact position of Ultima Thule in the image and instantly knows that we've dropped it right on the money. The navigation looks perfect—we should get everything we asked for. He sings out over the room. At a concert, the crowd cheers and yells—and so do we.

Marc hugs John, or John hugs Marc. It worked. It all worked ❹.

I'm on the right, grinning, and that's Simon Porter's back to the left. The four of us were the BORG—the Binary Object Reconnaissance Group. As part of a larger hazard reconnaissance team, we had used long-range imaging on the spacecraft to see if the path to Pluto was safe in 2015 and again during the approach to Ultima Thule. The hazard team (led by Mark Showalter, who's in the lower-left corner of the previous picture) declared that the path to Ultima Thule was clear of dust and debris a couple weeks out.

But if the spacecraft was likely safe against physical harm, the project team still worried that as we got closer we might find out that Ultima Thule was really a binary system of two objects, potentially demanding a sharp adjustment to our preprogrammed targeting. We stayed up in the "crow's nest" nearly all the way in, backing the efforts of the two navigation teams. I was more than a little nervous that we could really thread the needle.

So, I have to hug John, too ❺! But there's more. Some two years ago, John tasked me to lead the design of the highest-resolution imaging sequences to be done. Whether or not we could target Ultima Thule with the high-res camera on New Horizons was an open question at first. I was always pestering John about one trick or another we might perform to make it all work. And so it did, so it did.

Here's Ultima Thule! Can you "read" this image ❻? (Full disclosure: here we're looking at an even

NASA, JHUAPL, SWRI AND HENRY THROOP

closer image that came in much later in the evening, not the first one to come down.) I try to learn from my time with the team, but I am not trained as a planetary scientist. As an extragalactic astronomer, I can read galaxies, star clusters, what have you, but this is beyond my experience. But then, it is beyond everyone else's experience as well, and that is the essence of discovery. I do know that Ultima Thule is nothing like anything we've seen before. Is it special, though? We hope not! We've never been out this far before. The whole Kuiper Belt was unknown until the early nineties. We hope that Ultima Thule is not strange but rather is a typical denizen of a strange new place.

Every team member will look at Ultima Thule differently based on their own experience, intuition, knowledge, influences. We will share all these ideas among ourselves, with various bouts of arguing, jaw-boning, calculating, simulating, gesticulating. We will be wrong about some things, right about others. Clever ideas will emerge, often from those not on the team, but waiting patiently (or waiting not so patiently) to see what we've netted from the outer solar system.

But for now, imagine yourself here with us in the darkened room. Stand quietly, look, think, imagine, reflect on how far we've traveled, and what we will learn from the trip. It is your adventure, too.

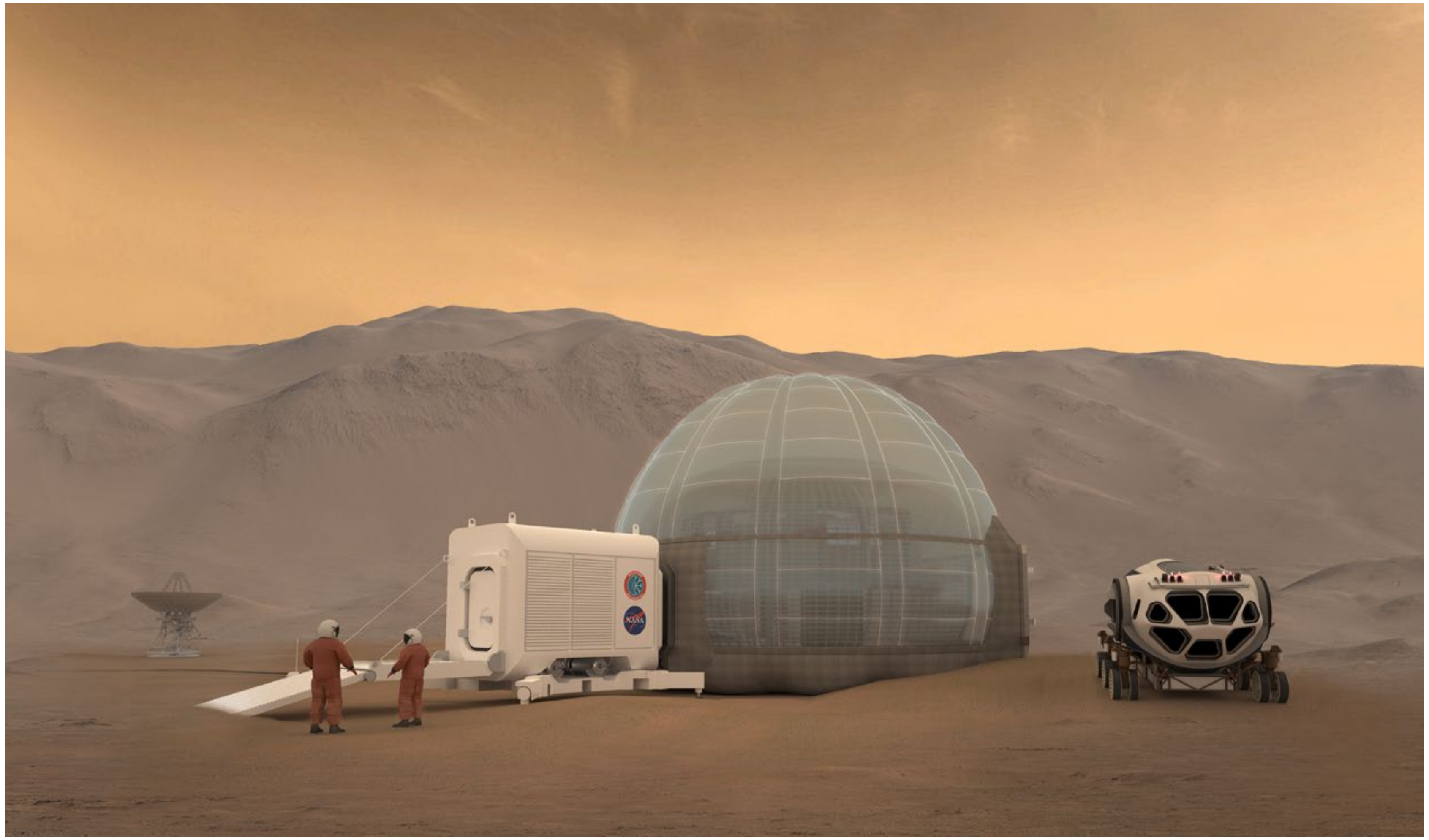
Mark Blenner is the McQueen-Quattlebaum Associate Professor of Chemical and Biomolecular Engineering at Clemson University. His research group engineers yeast and other cells to make value-added products using renewable and waste substrates. His work has been supported with funding from NASA's Space Technology Research Grants program.

OBSERVATIONS

Microbes Might Be Key to a Mars Mission

Engineered yeast could turn waste into food, plastics and other essentials

Picture a group of adventurous companions setting out into the great frontier to explore a barren, wild land. They must bring only the most important things they'll need to survive on their own. Every ounce of weight they decide to take with them means another ounce they must transport. It sounds like an extreme backpacking trip, but I'm actually talking about a future mission to the surface of Mars.



NASA, CLOUDS AO AND SEARCH WIKIMEDIA

We take for granted all the things we have on Earth that support human life—air for breathing, water for drinking and nutrients in the soil that allow us to grow food. On Mars, however, astronauts will need to bring their own life support systems, which can be prohibitively costly to transport. Without a lightweight flexible technology that can manufacture a variety of products using limited resources, the first Mars explorers won't survive their journey.

Typically, microbes are considered a threat to space missions because they could cause illnesses. But nonpathogenic microbes might in fact be part of the solution for getting to Mars. Microbes can convert a wide variety of raw materials into a large number of essential products. Using engineering principles, synthetic biology can be harnessed to turn microbes into tiny programmable factories.

I began to study yeast as way to make chemicals when I joined the chemical and biomolecular engineering department at Clemson University in 2012. My research group works with a type of yeast called *Yarrowia lipolytica*, which efficiently makes fatty acids in the form of trigylcerides from a wide variety of low-value waste streams. Genetic engineering makes it possible to add genes from other organisms to enable production of derivatives of fatty acids, such as biofuels, precursors for adhesives and nutraceuticals.

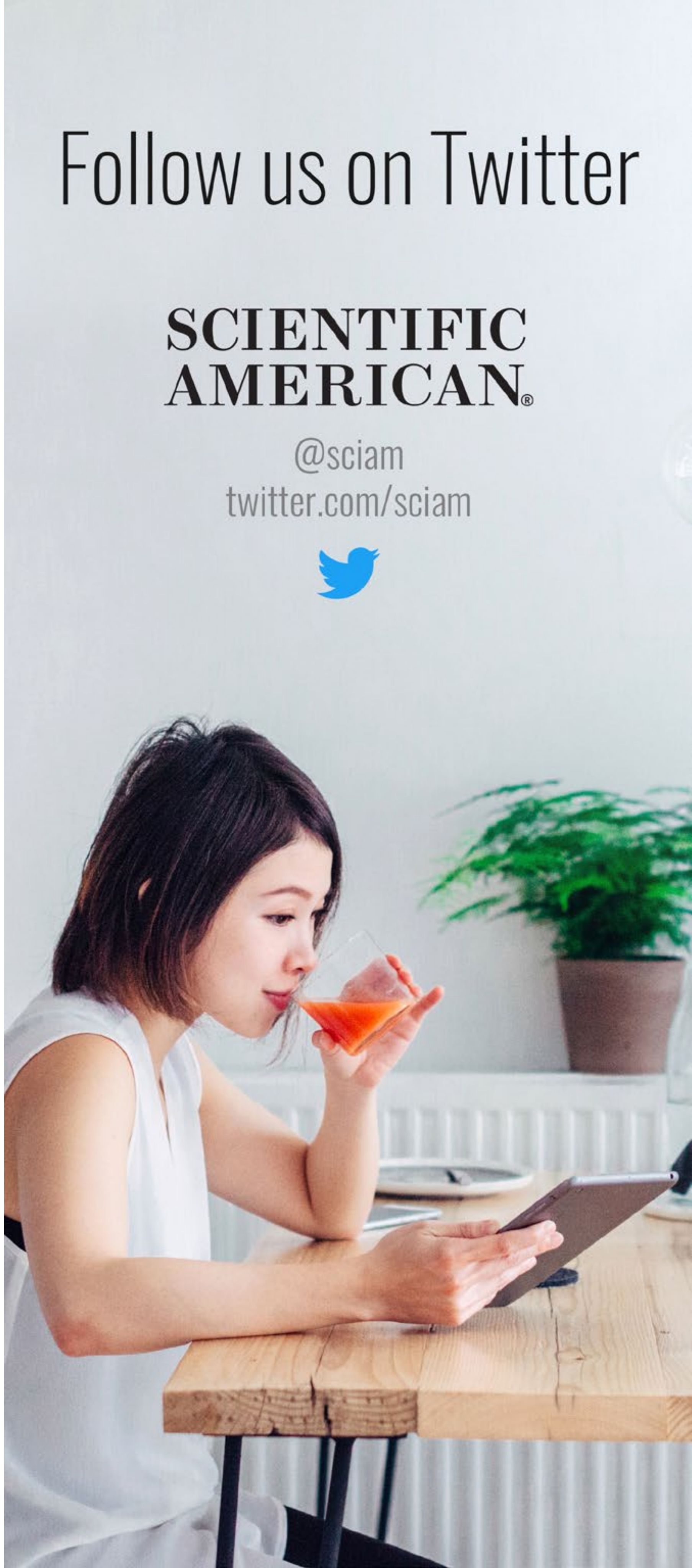
My students and I began to think about where wastes were abundantly available; where their storage posed a significant problem; and where yeast-derived products would be in short supply. It turns out, unsurprisingly, that human waste is both problematic and unavoidable: it generates more than half of the waste on a typical mission. This includes, most obviously, urine and feces. But it also includes carbon dioxide and water from crew respiration, perspiration and hygiene; food waste, packaging waste and even dead skin cells. It sounds pretty gross, but we wondered if we could engineer *Yarrowia lipolytica* to make mission-critical fatty acid–derived products from these materials.

We used synthetic biology to “cut and paste” genes from algae and plants into our yeast. This enabled them to make omega-3 fatty acids like eicosapentaenoic acid (EPA), a bioactive component of fish oil that has been shown to prevent bone density loss in astronauts. In a separate strain, we inserted a gene from bacteria that convert fatty acids into polyesters called polyhydroxyalkonates (PHAs). By engineering the fatty acid metabolism pathway, we can tune the properties of the individual PHA units so we can make plastics with properties matched to their application. This may be important for a Mars mission as a way to make the polymers needed for 3-D printing parts or tools that break or are lost.

Microbes need to eat, and our next challenge was how to feed them. As a source of carbon, we chose carbon dioxide, produced by crew members at a rate of over one kilogram per day. Carbon dioxide is also abundantly available on Mars, making up more than 97 percent of the atmosphere. Since our yeast does not directly consume carbon dioxide, we use a fast-growing cyanobacteria that converts the carbon dioxide into sugars and cell biomass for our yeast.

The other major element needed for growing yeast is nitrogen, which is available in the form of urea in human urine. In a recent publication in *Applied Microbiology and Biotechnology* we reported the efficient use of the urea by *Yarrowia lipolytica*. That’s no surprise: this yeast has genes that are similar to those in microbes that colonize the human urinary tract and eat urea.

While microbes are not the only solution, they should continue to be developed for a future Mars mission. As we get better at designing microbes to make specific products, meeting the needs of Mars-bound pioneers may become as easy as backpacking here on Earth, but we still have many miles to go.



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Celestial Movement

The sky is always changing. The planets move overhead as they trace their paths around the sun, and the moon rotates through the heavens as it circles our own world. Though the stars that provide their backdrop stay fixed in relation to one another, they too spin above as Earth makes its daily revolution and its yearly passage around the sun. To appreciate this ever-changing view, grab these sky maps, go outside at night and look up!

Astronomical Events
April 2019

Day	Event
1	**Dawn: waning crescent moon 8° right of Venus**
	Moon at apogee (405,577 km), apparent diameter 29’ 28”
3	**Evening sky: Mars between Pleiades and Hyades open star clusters**
5	**Moon: new moon**
8	**Evening sky: waxing crescent moon below Pleiades, Mars and Aldebaran**
10	**Jupiter stationary**
11	**Mercury greatest elongation west (28°)**
12	**Moon reaches northernmost declination (+21.3°)**
	Moon: first quarter
14	**Evening sky: moon near Regulus**
16	**Moon at perigee (364,205 km), apparent diameter 32’ 48”**
19	**Moon: full moon**
22	**Uranus in conjunction with Sun**
23	**Morning sky: moon close to Jupiter**
24	**Moon reaches southernmost declination (–23.0°)**
25	**Morning sky: moon near Saturn**
	Pluto stationary
26	**Moon: last quarter**
28	**Moon at apogee (404,582 km), apparent diameter 29’ 32”**
30	**Saturn stationary**

Sky calendar data courtesy of Uwe Reichert

April/May 2019: Visibility of planets

During these two months, Mars is the only planet in the evening sky visible with the unaided eye. The Red Planet is easy to spot in April, but its brightness diminishes during May. Jupiter and Saturn shine brightly in the morning sky, whereas Venus appears as a brilliant morning star at dawn.

Mercury is a no-show all of April and May. Although the innermost planet rises about an hour before the sun on April 11, when it reaches a greatest western elongation of 28°, it is lost in the bright morning twilight. Mercury is in superior conjunction (i.e. behind the sun) on May 21. The next chance to see this planet will come in June.

Mars becomes visible at dusk quite high above the western horizon. The Red Planet moves eastward through the constellation Taurus the Bull in April and is a special sight during the first week of the month, when it marches between the Pleiades and Hyades star clusters. The view becomes even more beautiful when the waxing crescent moon joins the scene on the evenings of April 8 and 9. One lunation later, on May 8, when the waxing crescent passes south of Mars again, both celestial objects are just about to enter the constellation Gemini the Twins.

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Astronomical Events
May 2019

Day	• Event
1	Dawn: waning crescent moon 12° right of Venus
4	Moon: new moon
6	Dusk: waxing crescent moon above Aldebaran
7	Evening sky: moon near Mars
9	Moon reaches northernmost declination (+21.7°)
11	Evening sky: moon right of Regulus
12	Moon: first quarter
	Evening sky: moon upper left of Regulus
13	Moon at perigee (369,009 km), apparent diameter 32’ 22”
18	Moon: full moon
20	Morning sky: moon upper right of Jupiter
21	Morning sky: moon left of Jupiter
	Mercury in superior conjunction
22	Morning sky: moon right of Saturn
	Moon reaches southernmost declination (–23.2°)
23	Morning sky: moon lower left of Saturn
26	Moon at apogee (404,138 km), apparent diameter 29’ 34”
	Moon: last quarter

April/May 2019: Visibility of planets

During these two months, Mars is the only planet in the evening sky visible with the unaided eye. The Red Planet is easy to spot in April, but its brightness diminishes during May. Jupiter and Saturn shine brightly in the morning sky, whereas Venus appears as a brilliant morning star at dawn.

Venus rises some 15 minutes before Mercury in the morning twilight in the east, and thanks to its much greater brightness, it stands out in the brightening sky throughout April. Venus slowly moves closer to the sun but remains visible during May. On the morning of April 1, the waning crescent moon is about 8° right of Venus and about 4° below the planet on the next morning (and therefore hard to spot).

Saturn enters the constellation Sagittarius about two hours behind Jupiter. When twilight starts, the ringed planet has not yet reached is maximum height in the south. The moon passes Saturn on April 25 and May 22.

Jupiter can be seen in the second half of the night. The giant planet is in southern Ophiuchus (the Serpent-bearer) and rises in the southeast well ahead of Saturn. Jupiter reverses its motion relative to the stars from eastward to westward on April 10, and with the naked eye it is barely possible to spot any movement during April. On the morning of April 23, Jupiter forms a close pair with the waning gibbous moon. The next conjunction of the two brightest objects in the night sky on May 20 is much less impressive.

Sky calendar data courtesy of Uwe Reichert

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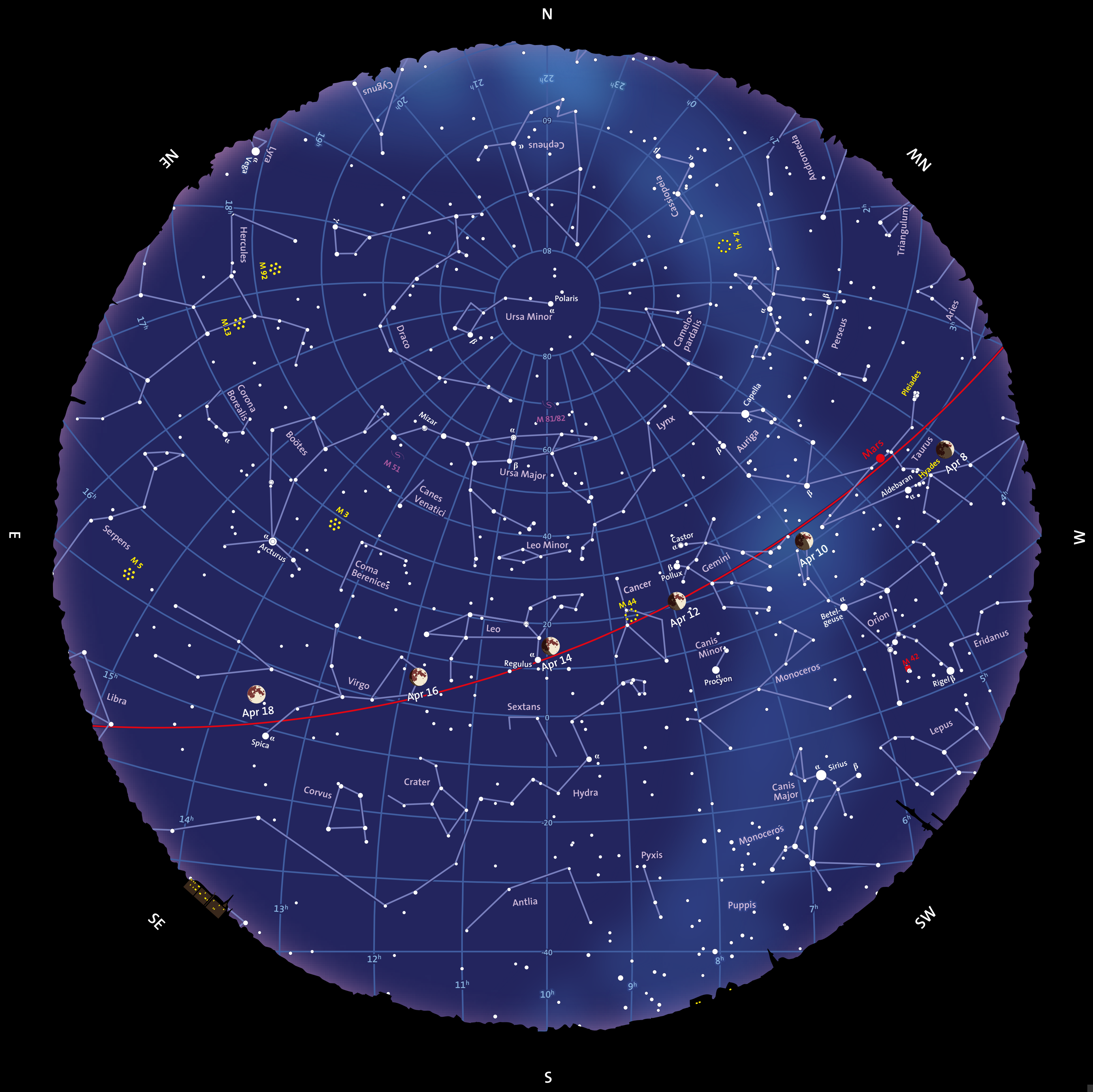
SKY REPORT

April

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.

The reference point is 100° W and 40° N and the exact time is 10 p.m. EST or 9 p.m. CST.



● ● ● ● ● ● ·
−1 0 1 2 3 4 5
Apparent magnitudes

⁛ Open cluster
⁙ Globular cluster
Galaxy
🟥 Nebula

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May

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.

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Open cluster
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Galaxy
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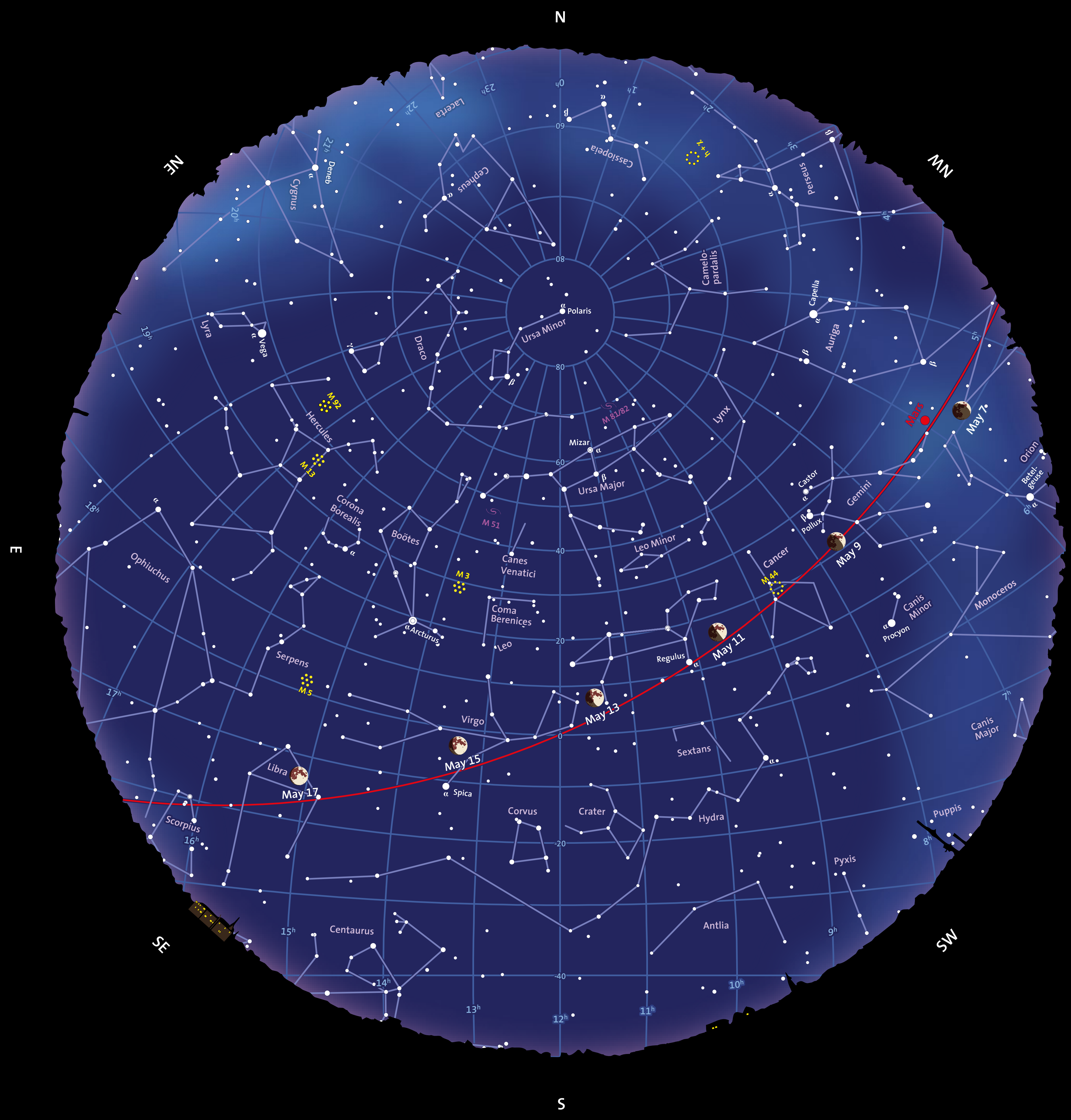

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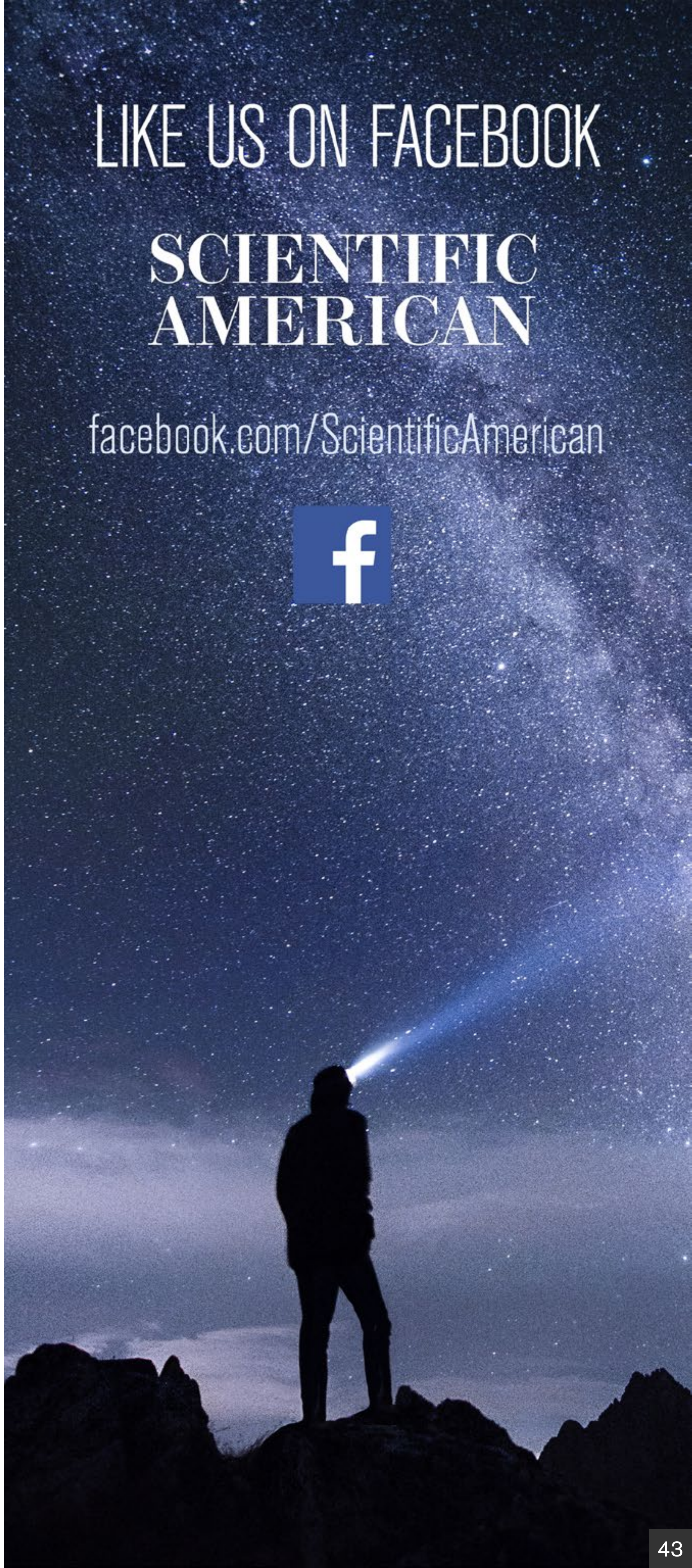


SCIENTIFIC AMERICAN Space & Physics
ISSUE No.2 June–July 2018
Here Come the Waves
GRAVITATIONAL-WAVE ASTRONOMY HAS MADE SOME STAGGERING DISCOVERIES—BUT EVEN MORE ARE ON THE WAY
A GALA WITHO DARK MATT
SAYING GOODBYE STEPHEN HAWKI
WITH COVERAGE FROM nature
SCIENTIFIC AMERICAN Space & Physics
ISSUE No.3 August–September 2018
A Cosmic Crisis
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Plus:
A NEW KIND OF NEUTRINO
Q&A WITH HAWKING'S FINAL CO-AUTHOR
GLITERING DIAMOND DUST IN SPACE
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