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Mysterious Neutrinos

RESEARCHERS ARE ONE STEP CLOSER TO DETERMINING HOW HEAVY THE UNIVERSE'S LIGHTEST MATTER PARTICLE MIGHT BE

Plus:

HOW MACHINE LEARNING CAN BOOST ASTRONOMY

A NEW LOOK INTO THE EARLY UNIVERSE

FUTURE MISSIONS TO THE OUTER PLANETS

WITH COVERAGE FROM nature

LIZ TORMES

To See or Not to See

As you read this word, and now this one, some billions of subatomic particles called neutrinos are whizzing through your body. The most mind-boggling aspects in physics are often the invisible ones, as well as where the biggest research booty lies. Discovering the nature of that we can't see in the universe promises to answer the most enticing cosmic questions: What spurred the formation of the universe, and what propels it ever outward? So while they can't see neutrinos, physicists still want to learn all they can about them. As Clara Moskowitz reports in "Mysterious Neutrinos Get New Mass Estimate," the mass of neutrinos—yes, they have some—has upper limits. Further, the more we learn about this mysterious particle, the more we question the Standard Model of particle physics.

Back in the visible realm, Shannon Hall describes the renewed push to explore the planets Neptune and Uranus, which have been on the back burner for decades (see "The Solar System's Loneliest Planets, Revisited"). And if it seems like discoveries in physics and astronomy are constantly ramping up, think of the torrents of data rolling in from the telescopes and detectors on Earth. As Anil Ananthaswamy reports, multimessenger astronomers are turning to machine learning to help them process the influx of measurements pouring in from exploding stars, galactic nuclei and colliding neutron stars, to name a few (see "Faced with a Deluge, Astronomers Turn to Automation"). Visible or not, we're diving in.

Andrea Gawrylewski
Senior Editor, Collections
editors@sciam.com

Your Opinion Matters!

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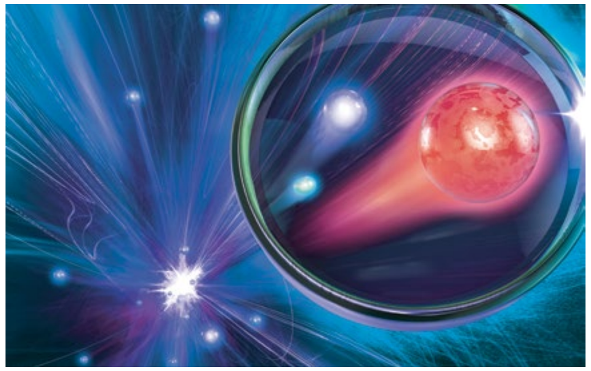

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MARK ROSS STUDIO

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DANA BERRY *NASA*

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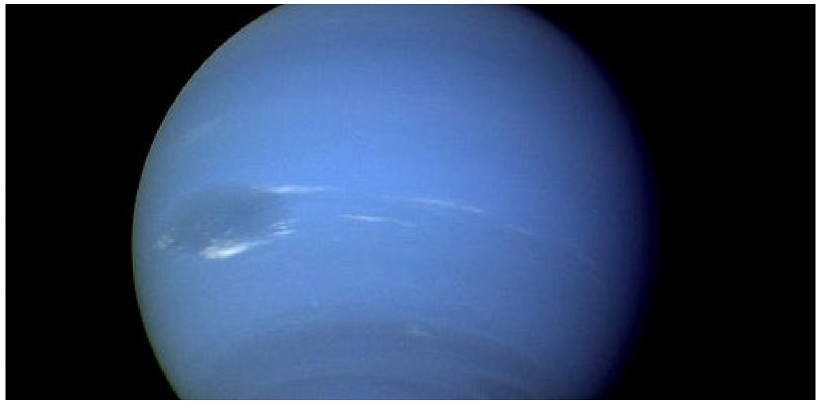

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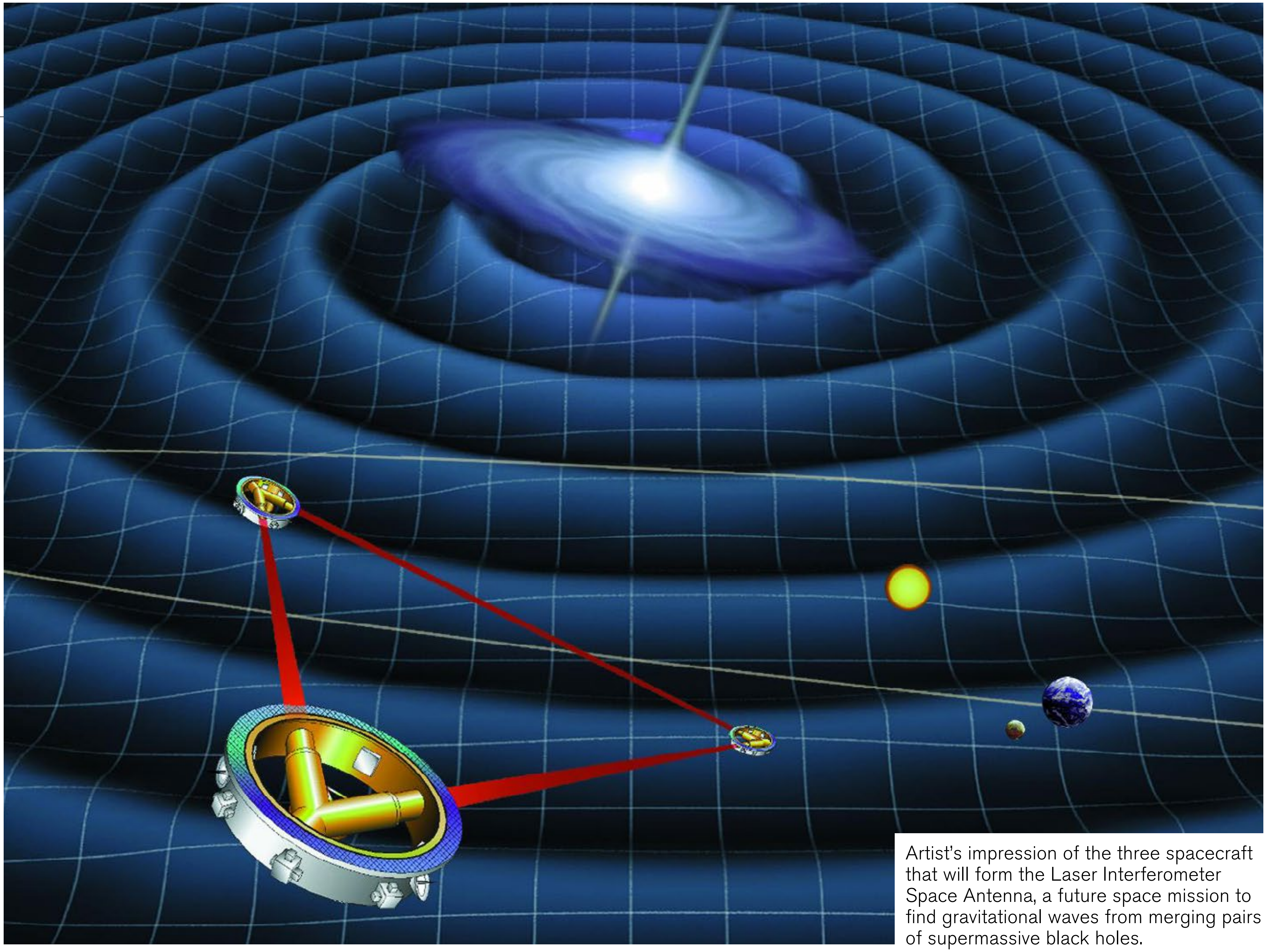
Future Gravitational-Wave Detectors Could Find Exoplanets, Too

Although meant to study merging supermassive black holes, the European Space Agency's LISA mission might also discover hundreds of worlds around white dwarf stars



Artist's impression of the three spacecraft that will form the Laser Interferometer Space Antenna, a future space mission to find gravitational waves from merging pairs of supermassive black holes.

NASA AND JPL *WIKIMEDIA*

MORE THAN 4,000 exoplanets are now known to orbit other stars. Indeed, astronomers suspect that such worlds are ubiquitous, estimating that, on average, every star in the Milky Way must have at least one planetary companion. But therein lies the rub: Although exoplanets seem to pop up everywhere, "everywhere" is far from the truth in describing where astronomers have actually looked. The vast majority of exoplanet surveys have stuck to either stars closely neighboring the sun or those farther off, in the direction of the Milky Way's central galactic bulge. Truth be told, no one yet knows the true abundance of planets throughout the Milky Way or, for that matter, the prevalence of planets in galaxies other than our own.

According to a study published on July 8 in *Nature Astronomy,* a major step toward completing this exoplanet census could begin in 2034, with the launch of the European Space Agency's LISA mission. LISA stands for Laser Interferometer Space Antenna, a name that hints at the mission's primary purpose: to detect ripples in spacetime—gravitational waves—by looking for minuscule changes in the distances among three satellites arranged in a triangular constellation with sides 2.5 million kilometers long. LISA will be custom-built to tune in to gravitational waves from merging supermassive black holes, but it could apparently listen to gravitational waves from some exoplanet systems, too.

Nicola Tamanini, a co-author of the recent study and an astrophysicist at the Max Planck Institute for Gravitational Physics in Potsdam, Germany, explains that LISA could uniquely probe for a wide range of planets in certain types of binary star systems. “Moreover,” he says, “in practice, LISA should allow us to make detections across the entire Milky Way, into the Magellanic Clouds and even in the Andromeda galaxy, if conditions are optimal.”

The detection works like this: When two stars form a binary system, they do not technically orbit each other; instead they orbit a common center of mass. If a planetary body resides in such a system, the planet’s gravitational influence will perturb this center of mass, causing it to cyclically wobble back and forth in sync with the planet’s to-and-fro tugging. The wobble’s strength would provide an estimate of the planet’s mass, and its recurrence over time would reveal the planet’s orbital period. For light-based telescopes, this wobble would almost always be far too small to be seen. But the wobble could be discerned as a subtle periodic modulation of the gravitational waves emanating from the binary system. For one class of binaries—systems composed of two white dwarfs, burned-out remnants of sunlike stars—such modulations should be detectable by LISA.

Astronomers already know that white dwarf binary systems are out there in abundance and expect to see tens of thousands of them in our galaxy alone using LISA, Tamanini says. The gravitational waves such systems generate will, in fact, be used to calibrate the mission’s observations, guaranteeing that LISA will be tuning in. Even if just 1 percent of the Milky Way’s white dwarf binaries harbor planets, he says, LISA should find such worlds by the hundreds.

Kaze Wong, a Ph.D. student in astrophysics at Johns Hopkins University and an affiliate member of the LISA Consortium who was not involved in the recent study, welcomes its findings. “Previous research has looked at the potential for using gravitational waves to detect exoplanets that orbit a single star,” he says, “but work we undertook suggests that the gravitational waves produced by such a combination will be too weak to be detectable.” This method shows more promise, Wong says, because the gravitational wav g[AG: PLSE FIX] planets all across our galaxy and even in other adjacent galaxies, astronomers would still struggle to learn much more about those newfound worlds. Beyond the orbital period and mass estimate provided with the initial gravitational-wave-based detection, follow-up observations with traditional telescopes could perhaps pin down a planet’s precise mass and size and additional orbital parameters. According to study co-author Camilla Danielski, a researcher at the French Alternative Energies and Atomic Energy Commission, even accounting for future technological advances, such telescopic observations of any planets found by LISA would be limited to relatively nearby regions of the Milky Way, within roughly 10,000 to 20,000 light-years of our solar system.

> **“So far nobody has thought about modeling exoplanets around binary systems like these, so we have very little knowledge about their existence.”**
>
> ***—Camilla Danielski***

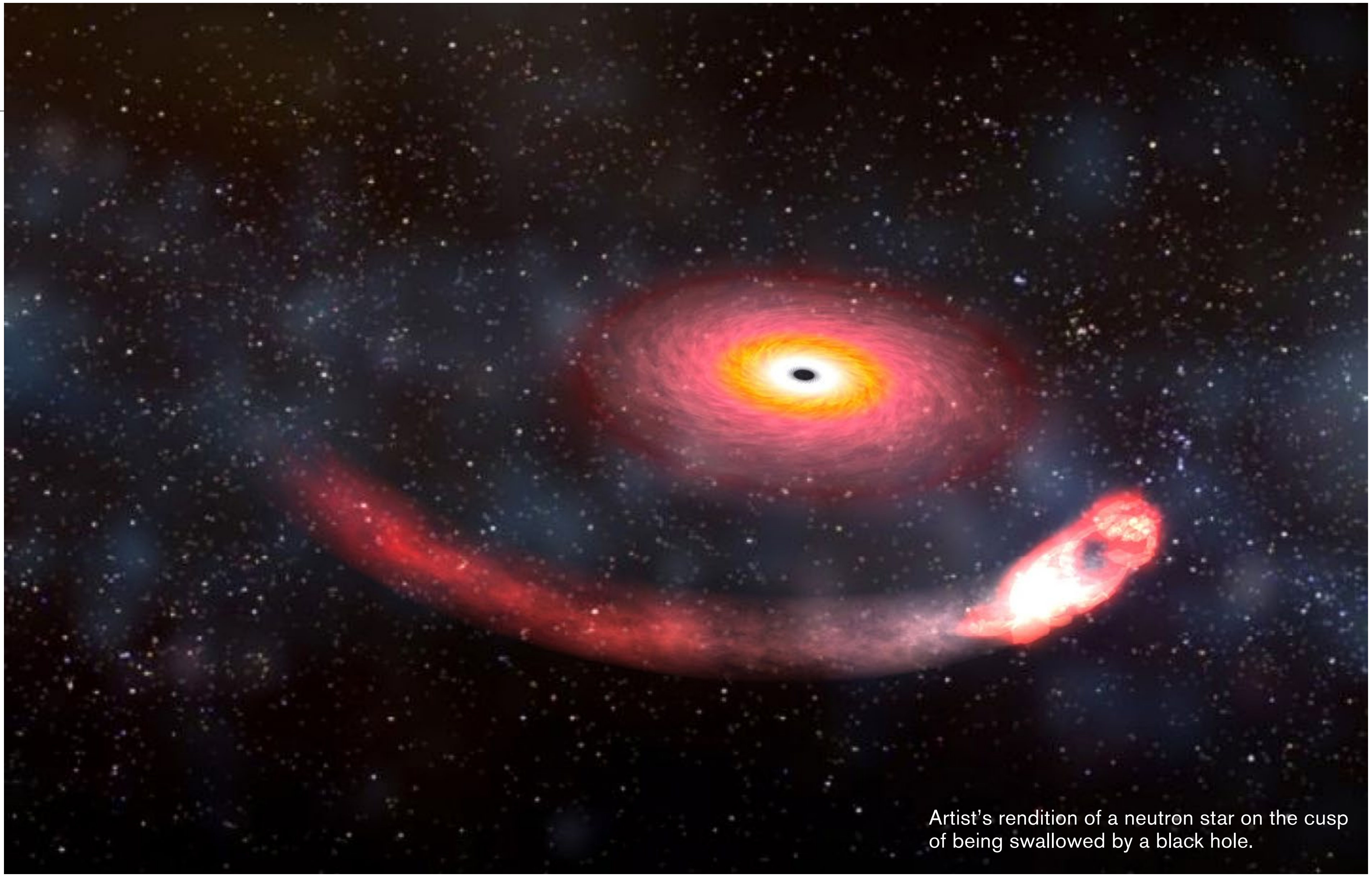
Furthermore, the technique would be unlikely to yield any habitable, Earth-like planets. White dwarfs are essentially stellar corpses, the slowly cooling cores left behind after sunlike stars exhaust their nuclear fuel. But before a star becomes a white dwarf, it first goes through a red giant phase in which it balloons in size, swelling to scorch or even swallow any close-in planets. Consequently, Wong says, any surviving worlds will probably be uninhabitable—and those producing the strongest gravitational-wave signals will be uncomfortably close to their white dwarf hosts.

More fundamentally, there is no guarantee that LISA will find any exoplanets at all—because so little is known about whether and how worlds can arise and persist in such extreme binary systems. But Danielski points out that even if planets are not found around white dwarf binaries, that null result would still provide useful insights about planetary evolution.

"So far nobody has thought about modeling exoplanets around binary systems like these," she says, "so we have very little knowledge about their existence." Finding those planets would show that such worlds can somehow survive—or be resurrected from—the deaths of their stars. Finding none at all would provide a new constraint, all across the galaxy, on where planets simply cannot be. Knowing where *not* to look would be a useful thing in a universe supposedly so chock-full of worlds to explore.

"Ultimately, using LISA in this way," Danielski says, "we will establish something certain about planetary formation throughout the Milky Way."

—*Conor Purcell*


Artist's rendition of a neutron star on the cusp of being swallowed by a black hole.

DANA BERRY *NASA*

Astronomers Spy a Black Hole Devouring a Neutron Star

If confirmed, the detection could be the first of its kind and would open new vistas on Einstein's general theory of relativity and the physics of extreme matter

SOME 870 MILLION years ago two dead stars became one. Their merger shook the fabric of space with a gravitational wave that swept through Earth on August 14, rippling through three pairs of carefully calibrated lasers designed to detect their passage. An automated system sent out a preliminary alert 21 seconds later, vibrating smartphones and pinging laptops around the world.

Three years after the Nobel Prize–winning first gravitational-wave detection, which stemmed from a pair of colliding black holes, such alerts have become commonplace. This time, however, astrophysicists instantly knew that the observed event was special.

"My jaw dropped when I saw the data," says Geoffrey Lovelace of California State University, Fullerton (C.S.U.F.), a member of the Laser

Interferometer Gravitational-Wave Observatory (LIGO) Scientific Collaboration.

The wave was detected by LIGO in the U.S. and the Virgo Observatory in Italy at 21:11:18 UTC on August 14. An automatic first pass pegged it as resulting from an unprecedented merger between a pair of bodies too light to classify, sending astronomers scrambling to look for additional electromagnetic emissions from the event.

Subsequent analysis recategorized the signal as a collision between a black hole and a neutron star, a stellar remnant in which gravity squeezes an entire sun's mass into a ball the size of a city. This would be the first such event detected with confidence and, after black hole–black hole mash-ups and mergers between two neutron stars, the third variety of collision detected by gravitational waves.

If the current analysis stands, this event, dubbed S190814bv, will mark the beginning of a new era of astrophysical studies, with implications for how researchers understand Einstein's general theory of relativity, the deaths of stars and the behavior of extreme matter.

> **"The first thing I knew was that it was extremely significant, kind of off-the-charts loud."**
> *—Chad Hanna*

AN "OFF-THE-CHARTS" SIGNAL

Chad Hanna, a LIGO collaborator and astrophysicist at Pennsylvania State University, was celebrating his wedding anniversary with his wife when his phone went off. His group specializes in rapid classification of LIGO events, so he immediately logged in to check the wave's details. "The first thing I knew was that it was extremely significant," Hanna says, "kind of off-the-charts loud."

The LIGO-Virgo collaboration's algorithmic pipeline spits out a basic classification based on the shape of a wave, its duration and other factors almost instantly—Hanna's team aims for under 20 seconds—so astronomers can immediately slew their telescopes in the celestial direction the wave came from.

On August 14, the automatic system confidently declared that at least one of the objects that produced S190814bv fell into the "mass gap," a wasteland, spanning three to five solar masses, seemingly bereft of black holes and neutron stars. All known black holes weigh more than five suns, while all known neutron stars—born from lighter stars that stopped short of becoming black holes—weigh less than three suns. A mass gap detection would have been a first for LIGO-Virgo—one that would have sharpened the theoretical line separating the heaviest neutron stars from the lightest black holes—but the preliminary label would not last. "There was a handoff around the globe," says Jocelyn Read, an astrophysicist at C.S.U.F. and a LIGO member, beginning with researchers in the U.S. on the afternoon of August 14 and with calculations continuing in Europe well into the following morning.

American scientists woke up on August 14 to a new classification. Human analysis had pegged the event as a neutron star–black hole merger with greater than 99 percent confidence. LIGO-Virgo has heard the collisions of more than a dozen black hole pairs, as well as two pairs of neutron stars, but it has never conclusively heard the rumbles from a black hole swallowing a neutron star.

"I've waited for this for a long time," says James Lattimer, an astronomy professor at Stony Brook University and a pioneering nuclear astrophysicist, who showed that neutron star–black hole mergers can spray heavy elements such as gold and uranium into space in his 1976 thesis.

Researchers detected a similar wave in April, but they were not able to confirm it came from deep space—the signal associated with that potential event, models suggest, had a one-in-seven chance of being a false alarm produced by terrestrial sources, meaning a spurious detection would be expected about once every 20 months. August's signal, however, is so clear that a false alarm would be a once-in-trillions-of-years event. "When it's more than the age of the universe," Lovelace says, "you know it's the real deal."

S190814bv's deafening signal, however, does not guarantee that astrophysicists have definitely bagged their first neutron star–black hole collision. While the current label clearly puts the heavier object in black hole territory (more than five suns), it leaves the lighter partner in the murky zone below three solar masses. If further analysis places that partner between one and two solar masses, it must be a neutron star. But a measurement closer to three suns could break either way—toward the universe's heaviest known neutron star or its lightest known black hole.

Future mass estimates will give a clearer picture, but first LIGO-Virgo will have to check the wave against our best models, which are too complicated to run overnight. Theoretical tools get shaky as the masses skew away from two evenly balanced partners, so researchers caution they must tread lightly in this uncharted territory. "We're still analyzing and checking things," Lovelace says. "But it's the most promising case like this that's come up so far."

"I opened up [the new] sky map, and I was like, 'Oh, they accidentally updated a blank sky map.'"
—Jocelyn Read

LOOKING FOR LIGHT

Virgo's detector in Italy—along with only one of LIGO's two detectors—recognized the wave initially, but the collaboration was able to manually incorporate data from the second LIGO detector overnight. Triangulating from that third detection allowed researchers to pinpoint the source's location in the sky more precisely than any previous wave so soon after detection. "I opened up [the new] sky map, and I was like, 'Oh, they accidentally updated a blank sky map,'" Read recalls thinking before she noticed the tiny dot marking the wave's origin.

The narrowed location, which amounted to 0.06 percent of the sky's total area, came as a boon to astronomical teams hunting for a flash of gamma rays or visible light that could accompany the death of a neutron star. "In principle, it's a manner of minutes to cover that area," says Marcelle Soares-Santos, a cosmologist at Brandeis University, who coordinated follow-up observations using the Dark Energy Camera on a four-meter telescope in Chile.

The black hole may have shredded the neutron star, leaving behind a ring of glittering wreckage that faded as it fell into the hole's waiting maw. Alternatively, the black hole could have swallowed the neutron star in one clean gulp, with little left to see. LIGO-Virgo simulations for S190814bv predict the latter scenario, but no one knows for sure what actually transpired. For a first-time observation, even seeing nothing can be informative. "We're going in with an open mind," Soares-Santos says. "If there's no electromagnetic counterpart, we will be able to establish with enough significance that it will have a big impact on the theories."

PROBING NEUTRONIUM

And neutron star theories abound. Nuclear physicists seek a glimpse inside the objects, where matter exists at densities that challenge the present best models. If the pressure dissolves neutrons into a plasma of fundamental particles, for instance, neutron stars of a certain mass should appear smaller than they otherwise would be. Fine features of the detected gravitational wave produced as the star spiraled into the black hole may reveal the star's size and, accordingly, the consistency of the matter that fills it. Similarly, whether astronomers see a flash or not will also set limits on the star's size. Such precise measurements of a neutron star's dimensions are "sort of the holy grail of nuclear physics," says Ben Margalit, a postdoctoral researcher at the University of California, Berkeley, who is not part of the collaboration that observed the event.

A black hole obliterating a neutron star also represents a new arena for testing general relativity. Applying Einstein's theory of gravity to the smooth fabric of spacetime around black holes is tough enough, Lovelace says. Adding in hot, turbulent magnetized neutron star matter—an exotic substance sometimes called "neutronium"—elevates the challenge to a messy new level.

Even if August's ripple in spacetime doesn't divulge any of nature's secrets, researchers feel confident it is just the first of many to come. "I hope it tells us something about black hole–neutron star [mergers]," Lovelace says. "But if not, it still makes me really optimistic that the gravitational sky is bright." *—Charlie Wood*

“Qutrit” Experiments Are a First in Quantum Teleportation

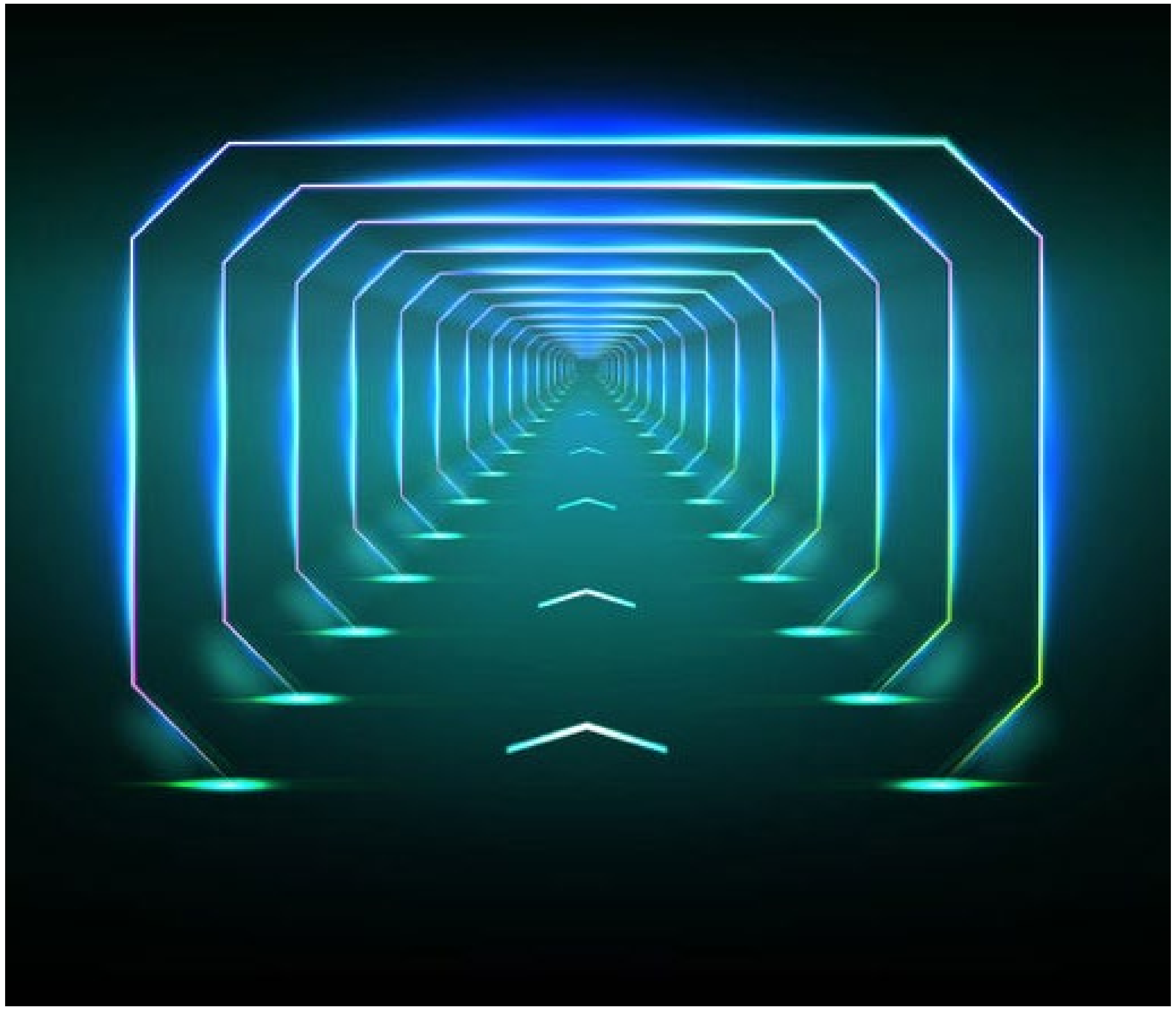
The proof-of-concept demonstrations herald a major step forward in quantum communications

FOR THE FIRST TIME, researchers have teleported a qutrit, a tripartite unit of quantum information. The independent results from two teams are an important advance for the field of quantum teleportation, which has long been limited to qubits—units of quantum information akin to the binary “bits” used in classical computing.

These proof-of-concept experiments demonstrate that qutrits, which can carry more information and have greater resistance to noise than qubits, may be used in future quantum networks.

Chinese physicist Guang-Can Guo and his colleagues at the University of Science and Technology of China (USTC) reported their results in a preprint paper on April 28, although that work remains to be published in a peer-reviewed journal. On June 24 the other team, an international collaboration headed by Anton Zeilinger of the Austrian Academy of Sciences and Jian-Wei Pan of USTC, reported its results in a preprint paper that has been accepted for publication in *Physical Review Letters*. That close timing—as well as the significance of the result—has each team vying for credit and making critiques of the other’s work.

“Each of these [experiments] is an important advance in the technology of teleportation,” says William Wootters, a physicist at Williams College, who was not involved with either study.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BEAM ME UP?

The name “quantum teleportation” brings to mind a technology out of *Star Trek,* where “transporters” can “beam” macroscale objects—even living humans—between far-distant points in space. Reality is less glamorous. In quantum teleportation, the states of two entangled particles are what is transported—for instance, the spin of an electron. Even when far apart, entangled particles share a mysterious connection; in the case of two entangled electrons, whatever happens to one’s spin influences that of the other, instantaneously.

“Teleportation” also conjures visions of faster-than-light communication, but that picture is wrong, too. If Alice wants to send Bob a message via quantum teleportation, she has to accompany it with classical information transported via photons—at the speed of light but no faster. So what good is it?

Oddly enough, quantum teleportation may also have important utility for secure communications in the future, and much of the research is funded with cybersecurity applications in mind. In 2017 Pan, Zeilinger and their colleagues used China's Micius satellite to perform the world's longest communication experiment, across 7,600 kilometers. Two photons—each acting as a qubit—were beamed to Vienna and China. By taking information about the state of the photons, the researchers in each location were able to effectively construct an unhackable password, which they used to conduct a secure video call. The technique acts like a wax seal on a letter: any eavesdropping would interfere and leave a detectable mark.

Researchers have attempted to teleport more complicated states of particles with some success. In a study published in 2015 Pan and his colleagues managed to teleport two states of a photon: its spin and orbital angular momentum. Still, each of these states was binary—the system was still using qubits. Until now, scientists had never teleported any more complicated state.

MAKING THE IMPOSSIBLE

A classical bit can be a 0 or 1. Its quantum counterpart, a qubit, is often said to be 0 *and* 1—the superposition of both states. Consider, for instance, a photon, which can exhibit either horizontal or vertical polarization. Such qubits are breezily easy for researchers to construct.

A classical trit can be a 0, 1 or 2—meaning a qutrit must embody the superposition of all three states. This makes qutrits considerably more difficult to make than qubits.

To create their qutrits, both teams used the triple-branching path of a photon, expressed in carefully orchestrated optical systems of lasers, beam splitters and barium borate crystals. One way to think about this arcane arrangement is the famous double-slit experiment, says physicist Chao-Yang Lu, a co-author of the new paper by Pan and Zeilinger's team. In that classic experiment, a photon goes through two slits at the same time, creating a wavelike interference pattern. Each slit is a state of 0 *and* 1, because a photon goes through both. Add a third slit for a photon to traverse, and the result is a qutrit—a quantum system defined by the superposition of three states in which a photon's path effectively encodes information.

Creating a qutrit from a photon was only the opening skirmish in a greater battle. Both teams also had to entangle two qutrits together—no mean feat, because light rarely interacts with itself.

Crucially, they had to confirm the qutrits' entanglement, also known as the Bell state. Bell states, named after John Stewart Bell, a pioneer of quantum information theory, are the conditions in which particles are maximally entangled. Determining which Bell state qutrits are in is necessary to extract information from them and to prove that they conveyed that information with high fidelity.

What constitutes "fidelity" in this case? Imagine a pair of weighted dice, Wootters says: If Alice has a die that always lands on 3, but after she sends it to Bob, it only lands on 3 half of the time, the fidelity of the system is low—the odds are high it will corrupt the information it transmits. Accurately transmitting a message is important, whether the communication is quantum or not. Here the teams are in dispute about the fidelity. Guo and his colleagues believe that their Bell state measurement, taken over 10 states, is sufficient for a proof-of-concept experiment. But Zeilinger and Pan's group contends that Guo's team failed to measure a sufficient number of Bell states to definitively prove that it has high enough fidelity.

Despite mild sniping, the rivalry between the groups remains relatively friendly, even though provenance for the first quantum teleportation of a qutrit hangs in the balance. Both teams agree that each has teleported a qutrit, and they both have plans to go beyond qutrits: to four level systems—ququarts—or even higher.

Some researchers are less convinced, though. Akira Furusawa, a physicist at the University of Tokyo, says that the method used by the two teams is ill suited for practical applications because it is slow and inefficient. The researchers acknowledge the criticism but defend their results as a work in progress.

"Science is step by step. First, you make the impossible thing possible," Lu says. "Then you work to make it more perfect." *—Daniel Garisto*

Editor's Note (8/6/19): This story was edited after posting to correct the date for the recent preprint study by Anton Zeilinger and Jian-Wei Pan and the description of their 2017 experiment involving China's Micius satellite.

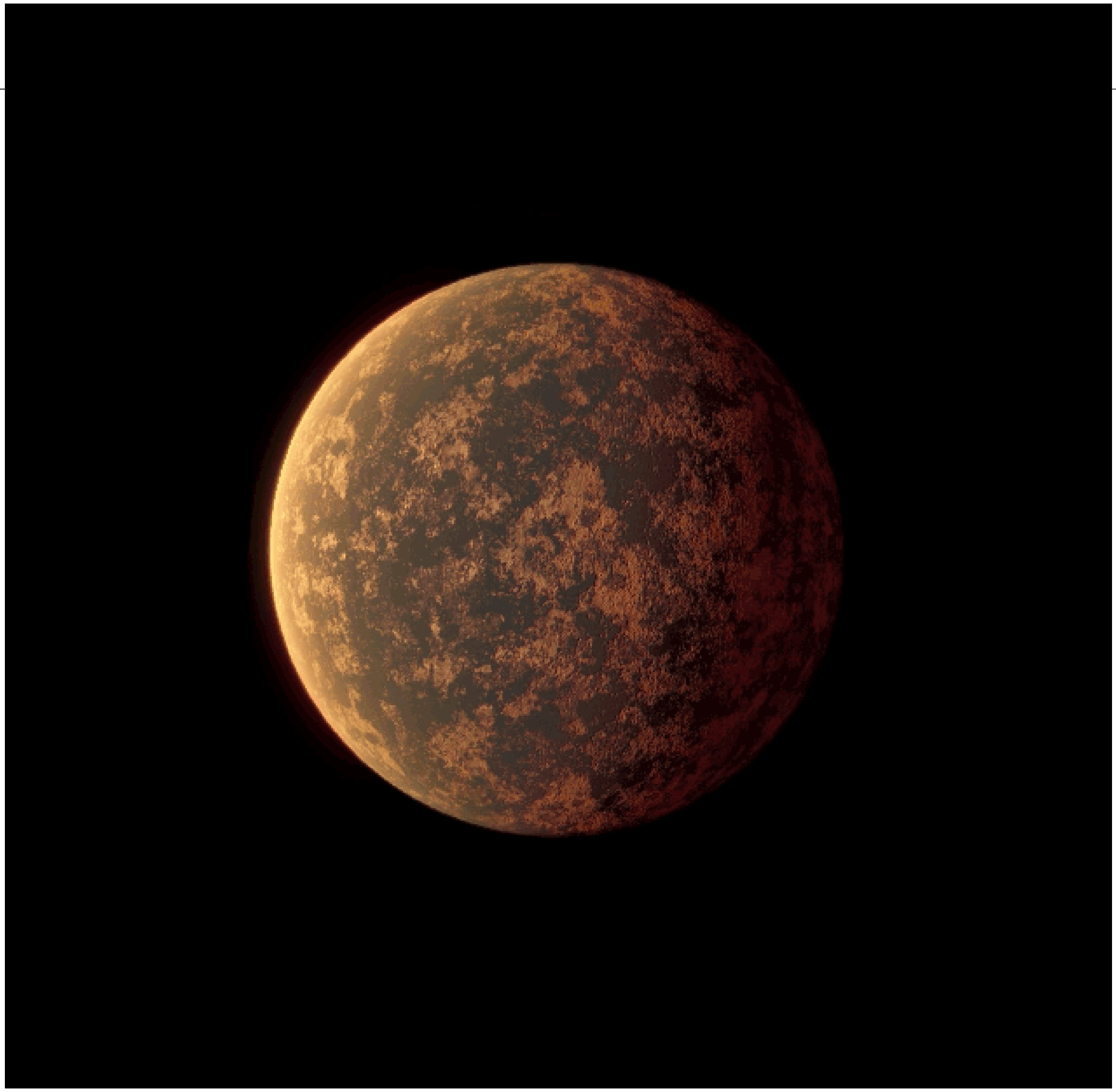
Scientists Mull the Astrobiological Implications of an Airless Alien Planet

A rocky world devoid of atmosphere arouses debate over the habitability of the Milky Way's most common star systems

ASTRONOMER Laura Kreidberg admits she was initially a bit worried about her latest results. Examinations of a planet orbiting the red dwarf star LHS 3844 seemed to indicate that the rocky super-Earth, 30 percent larger than our world, possessed little or no atmosphere.

Kreidberg's concern stemmed from the fact that researchers are in the midst of a heated debate about the habitability of planets around red dwarfs, which make up 70 percent of the stars in our galaxy. A universe teeming with life is more likely if the worlds orbiting these diminutive entities, which are smaller and cooler than our sun, could be a good abode for biology.

But red dwarfs are harsh hosts, emitting frequent flares containing x-rays and ultraviolet radiation that could sterilize a planet, as well as energetic stellar winds that can strip it of its protective atmosphere. Kreidberg and her colleagues' findings, which appeared in August in *Nature*, could be seen as a mark against the idea that planets around small red stars could provide a nurturing environment.



Artist's impression of the exoplanet LHS 3844 b depicts the world as an airless, rocky orb. New measurements now confirm this "super-Earth" lacks a substantial atmosphere.

NASA, MIT AND TESS

In recent years astronomers have announced numerous exciting discoveries regarding red dwarfs, such as Proxima Centauri b, a potentially habitable planet orbiting our sun's nearest star, and the TRAPPIST-1 system, which contains a whopping seven Earth-sized worlds. Red dwarfs are not only abundant but are also the longest-living stars, with a lifetime that can span 10 trillion years—1,000-fold longer than that of our sun. Should a biosphere arise on a red dwarf world, it might stick around for an exceptionally long time.

Astronomers are therefore interested to know whether or not red dwarfs' planets are good places to go looking for living creatures. "To have life as we know it, you need to have liquid water," says Abraham Loeb, a co-author of the *Nature* study and an astrophysicist at the Center for Astrophysics at Harvard University and the Smithsonian Institution (CfA). "In order to have liquid water, you need an atmosphere."

Kreidberg, who is also at the CfA, has been in the daily habit of checking for new results from NASA's Transiting Exoplanet Survey Satellite (TESS), a space-based observatory hunting for nearby planets that "transit" their host stars—flitting across the faces of those stellar hosts and casting shadows toward our solar system. Among TESS's first discoveries was the rocky world LHS 3844 b, located just under 49 light-years away, and Kreidberg quickly recognized that it was in an ideal position to test the atmospheric-retention capabilities of red dwarf exoplanets.

LHS 3844 b orbits incredibly close to its parent star, zipping around in a mere 11 hours. This orbit more or less guarantees that the star's gravitational pull has tidally locked the planet, meaning one side of the world always faces the star. The exoplanet's dayside is scorching, while its space-facing hemisphere sits out in the cold.

But while the exoplanet experiences 70 times more radiation than Earth, Kreidberg says it would not necessarily lose its atmosphere at this distance. For instance, an envelope of thick carbon dioxide could be heavy enough to endure the bombardment from the nearby star. Or the world might have once contained a vast ocean that was boiled off by the intense starlight, which also would have split the water into its constituent molecules. The lighter hydrogen could have drifted away, leaving an atmosphere of pure oxygen.

Although the researchers could not directly see the planet, using NASA's infrared Spitzer Space Telescope, they were able effectively take its temperature, detecting a periodic variation in the thermal emissions from its host star that was caused by the planet's orbital movements. Much like the moon in our sky, LHS 3844 b shows different faces to observers on Earth as it sweeps through its orbit: at turns, it displays its hotter dayside or its colder nightside, which subtly alters the amount of infrared radiation astronomers see emanating from the star.

The planet also passes completely behind its star for a portion of its orbit, as seen from Earth, entirely removing its heat from view and allowing scientists to determine its total contribution to the star's thermal emissions. Based on these measurements, Kreidberg's team estimated the temperature of the planet's nightside as a freezing –273 degrees Celsius and that of its days as a fiery 767 degrees C.

The presence of a regulating atmosphere should allow heat to transfer between hemispheres, reducing such extremes. But computer models suggested that LHS 3844 b's temperature differences could only arise and persist if the planet had an extremely thin atmosphere, with, at most, a tenth of the pressure of Earth's and likely none at all.

A great deal of theoretical work has already implied that worlds orbiting red dwarfs would have a hard time forming or retaining significant atmospheres because of the extreme environment, says Colin Johnstone, an astrophysicist at the University of Vienna, who was not involved in the new study. But what the characteristics of a close-in planet such as LHS 3844 b means for places such as TRAPPIST-1's worlds or Proxima Centauri b, which orbit farther from their parent star, is not entirely clear.

"It's one more piece of evidence suggesting that these stars aren't going to have habitable planets," Johnstone says, although he cautions against making sweeping judgments based on a single example.

Because LHS 3844 b is far inside the traditional habitable zone—a region around a star where a planet is sufficiently warmed by starlight to have liquid water on its surface—the null result does not much faze Tiffany Jansen, an astronomy Ph.D. candidate at Columbia University, who also was not involved in the recent work.

"The discovery of a lack of an atmosphere on this planet doesn't make it any less likely that planets in the habitable zone would have an atmosphere," she says.

But Loeb counters that what happens in the immediate vicinity of a red dwarf star is relevant to more remote planets. He has previously done theoretical calculations suggesting that red dwarfs are prone to blow away the atmospheres of exoplanets in their habitable zone. Even though LHS 3844 b is a single example and is much closer to its star than a habitable planet could be, it provides important evidence that atmospheric stripping takes place. And extrapolations imply similar outcomes can be expected farther out, Loeb says.

The discussion will probably rage on until astronomers can examine more cases. The upcoming James Webb Space Telescope (JWST), an infrared observatory whose mirror will have 6.25 times the light-collecting power of the Hubble Space Telescope, will be revolutionary in its ability to measure heat from distant exoplanets, Kreidberg says.

Other teams have already committed to using time during JWST's first year to examine the temperature of the planets TRAPPIST-1 b—found in the TRAPPIST-1 system—and Gliese 1132 b—which also orbits a red dwarf. The telescope is currently scheduled to launch in 2021, and it will be joined by powerful 30-meter-class ground-based observatories, expected to come online early next decade, that can conduct similar research.

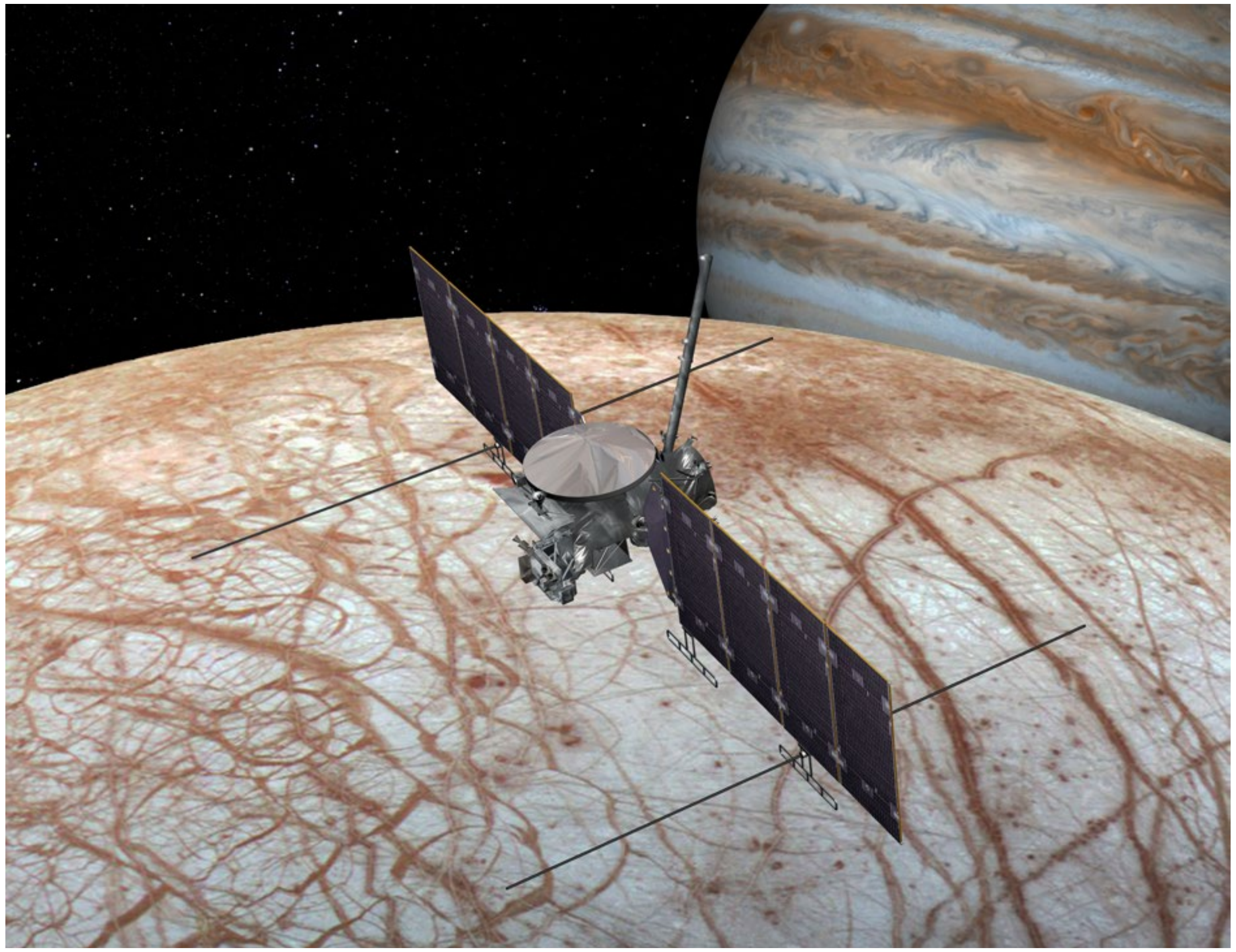
Kreidberg's preliminary disappointment about LHS 3844 b eventually dissipated. "If you were an alien looking at our solar system and saw Mercury, you'd be a little discouraged," she says, but our cosmic backyard contains a wide diversity of atmospheres.

Researchers are still coming to understand just how planetary atmospheres arise, and a great deal remains unknown. "For every idea for how to get rid of an atmosphere on a planet, there's another for how to keep it or make a new one," Kreidberg says. "I don't think this counts as a victory point for the naysayers just yet."

—Adam Mann

NASA Has Committed to a Rocket for the Europa Mission–and It Won't Be Ready on Time

Although alternatives such as SpaceX's Falcon Heavy exist, the space agency is legally required to launch its Europa Clipper spacecraft on the behind-schedule Space Launch System



Artist's rendition of NASA's Europa Clipper mission.

NASA/JPL-CALTECH

JUST WEEKS AFTER NASA's Europa Clipper mission quietly received a formal commitment to a final cost and time line from the agency, it looks increasingly like the spacecraft will not fly on its legally mandated mega rocket, the Space Launch System (SLS)—at least, not in the time line outlined by Congress—documents and experts confirm.

Because of the severe radiation challenges of the Jovian system, Europa Clipper is one of the most ambitious flagship missions ever attempted by NASA, with seismic implications for the agency's search for life beyond Earth. Europa—with its deep, ancient ocean locked beneath an icy crust—is seen by some astrobiologists as the solar system's most promising site for harboring alien biology. In search of further signs of habitability, the Europa Clipper spacecraft will enter orbit around Jupiter and encounter the moon multiple times. With each flyby, it will collect data on Europa's ice shell and subsurface ocean, remotely sounding the unseen fathoms below.

According to Curt Niebur, the mission's program scientist at NASA headquarters in Washington, D.C., Europa Clipper could answer the question of whether the right conditions exist on the icy moon to support life as we know it. If those ingredients—which include organic molecules, as well as potential energy sources such as hydrothermal vents on the ocean floor—are found on Europa, Niebur says, "we're going to want to explore further and see if life actually has arisen under the ice." A second mission, now in development, would land on Europa to excavate and collect samples in search of native organisms.

Beyond the science, the mission has an unusual political element: Europa Clipper is the first and only space mission to be married to a specific spacecraft in any appropriations bill, says former Republican representative John Culberson of Texas, a longtime Europa advocate who previously chaired the Commerce, Justice, Science, and Related Agencies subcommittee of the House Committee on Appropriations. The current appropriations bill mandates Europa Clipper use the SLS and requires a "launch no later than 2023" on the rocket.

It was a move that Culberson, an attorney and political consultant, used to ensure Europa Clipper would one day reach the launchpad. He says tying the mission to the SLS, which is being built in Alabama, garnered the support of Republican Senator Richard Shelby of Alabama, chair of the Senate Committee on Appropriations, without which the mission might not have been mandated by law. (Attempts to reach Senator Shelby for this article were unsuccessful. A staffer reported that he was unavailable for comment.)

> **"The rocket, whatever it is, has to be reliable and has to be powerful enough to get the Clipper to Europa in a timely fashion."**
>
> ***—John Culberson***

While Europa Clipper's development has proceeded apace, however, the SLS rocket has remained mired in setbacks and was arrogated by the Artemis lunar program instigated by the Trump administration. Before it could carry the Europa craft to space, the SLS would fly two Artemis moon missions—the first of which has reportedly been pushed back from 2020 to 2021, according to Senate testimony by NASA administrator Jim Bridenstine earlier this year. For Europa Clipper to launch on time, the second Artemis launch, now scheduled for 2023, would have to occur without error, with a third SLS rocket ready to go—a tall order, considering the program's lengthy development, three-year delay and zero rockets completed thus far.

A report issued this past May by NASA's Office of Inspector General supports that the SLS "is unlikely to be available" for Europa Clipper in 2023. And it adds that NASA "continues to maintain spacecraft capabilities to accommodate both the SLS and two commercial launch vehicles." Moreover, even NASA's own 2019 budget encourages "a Europa Clipper launch readiness date in 2025" and further proposes "to launch the Clipper on a commercial launch vehicle" to save money. Each SLS launch is estimated to run more than $1 billion.

In its Europa Clipper Key Decision Point-C memorandum, the formal commitment signed at NASA headquarters in August, the spacecraft is scheduled for a launch that ranges from 2023 to 2025, confirms Thomas Zurbuchen, NASA's associate administrator for the science mission directorate. But if the mission were to launch in 2025—or on something other than the SLS—it would be in violation of current law, which means the law must change or a working SLS must suddenly appear in order for Europa Clipper to take off in accordance with federal statute.

"We've been working very hard to follow the appropriation law," says Joan Salute, program executive of Europa Clipper. But she admits the mission "may or may not" be possible with the SLS in 2023. And if it's not, she says, "we can't follow that [appropriations law]."

Both Salute and Zurbuchen say forthcoming appropriations bills may need to be updated. "Congress will follow the development of the SLS, and that language should be updated as we know more about the SLS's availability to us, or not, in 2023," Salute says. And NASA will talk to Congress in order to "make sure the right solution happens for the American taxpayer," Zurbuchen adds.

Zurbuchen points out that the appropriations bill's language had been changed previously to accommodate Europa Clipper. Indeed, the 2017 appropriations bill called for a 2022 orbit and 2024 landing.

Democratic Representative Adam Schiff of California, whose district includes NASA's Jet Propulsion Laboratory, its research-and-development center, says, "When Congress returns in September, we will continue to work to pass an appropriations package across the House and Senate that preserves our strong support for [Europa Clipper's] goals and time line. We will also continue to monitor the mission's progress as part of that process, including the potential launch vehicle."

Another vehicle that could take Europa Clipper to Jupiter's moon is SpaceX's Falcon Heavy—although it would do so with an asterisk attached. Falcon Heavy has already achieved three successful launches, but using the SpaceX rocket—which is less powerful than the SLS—would add at least three years of travel time to the planned two-year mission. And while using SpaceX's rocket would save hundreds of millions of dollars on launch costs, it could add to Europa Clipper's operations budget because of its longer cruise time to Jupiter. "It's vital that the [Europa] Clipper be launched on the SLS," Culberson says.

The SLS has an undeniable advantage over Falcon Heavy: it enables a direct flight from Earth to Jupiter. Falcon Heavy will require gravity assists from other planets, and unless it uses an add-on "kicker stage"—an additional upper stage for extra loft—one of those gravity assists will require an encounter with Venus. According to Salute, a Venus flyby introduces "a riskier environment, radiation and temperature. And so we would like to avoid flying closer to Venus with this direct trajectory that SLS affords us. Right now SLS is the only launch vehicle that can give us that trajectory, and that's why it's so advantageous to us."

The idea that Europa Clipper might not run on the SLS is almost unthinkable to Culberson, who says he remains optimistic the mission will fly on the SLS in 2023. "Heaven forbid SLS is not ready in time," he says. "But in the event that it's not, the most important thing for the mission is to ensure [it arrives] safely. The rocket, whatever it is, has to be reliable and has to be powerful enough to get the Clipper to Europa in a timely fashion." *—Jillian Kramer*

Supergravity Snags Super Award: $3-Million Special Breakthrough Prize

The theory, which emerged in the 1970s as a way to unify the fundamental forces of nature, has profoundly shaped the landscape of particle physics

A SPECIAL BREAKTHROUGH Prize in Fundamental Physics, worth $3 million, has been awarded to three researchers who devised a theory in the 1970s called supergravity, which attempts to unify all of the four fundamental forces of nature. Daniel Freedman, now at the Massachusetts Institute of Technology, Sergio Ferrara, now at the University of California, Los Angeles, and Peter van Nieuwenhuizen of Stony Brook University collaborated on this approach to resolving the apparent conflicts between the two most fundamental theories of physics: quantum mechanics, which describes the microscopic world of atoms and particles, and general relativity, which describes the force of gravity and its influence on cosmic scales.

Michael Duff of Imperial College London, who has worked on quantum gravity since the 1970s, welcomes the award and calls the three recipients "worthy winners." Four decades after supergravity was devised, there is still no empirical evidence that the idea is correct. But the Breakthrough Prize in Fundamental Physics has a well-established record of rewarding ideas that still lack experimental verification, in marked distinction to the Nobel Prize's requirement that concepts be considered confirmed by observation.

SPINNING UP SUPERGRAVITY

Supergravity was born from the quest to find simplicity and unity among the particles and forces of nature. All known particles are encompassed within the theoretical framework known as the Standard Model of particle physics, which was completed in 2012 with the discovery of the Higgs boson at the Large Hadron Collider (LHC) at CERN, the European particle physics center near Geneva. Within a formulation of quantum mechanics called quantum field theory, three of the Standard

Model's fundamental forces—electromagnetism and the so-called strong and weak forces, which act inside atomic nuclei—are represented by the exchange of particles called bosons between other, interacting particles called fermions. All particles possess a quantum-mechanical property called spin, which, for bosons, has an integer value (0, 1, 2, and so on). Bosons include photons, the particles of light and the force carriers of electromagnetism, and gluons, the particles that convey the strong force. Fermions include electrons and the quarks that are the constituents of protons and neutrons in atomic nuclei. Fermions have a half-integer spin: 1/2, 3/2, and so on.

But the Standard Model does not embrace the fourth fundamental force: gravity. Even so, it has long been agreed that gravity should have a corresponding boson called the graviton, which would possess a spin of 2. The observation of gravitational waves in 2015 (which was also rewarded with a Breakthrough Prize, as well as a Nobel) essentially confirmed this picture, Ferrara says.

In the early 1970s several researchers independently proposed that bosons and fermions might be related to one another via a fundamental symmetry called supersymmetry. In this view, very early after the big bang that began our universe, a single type of particle split into these two families in a process of "symmetry breaking," rather like the branching of a river network. Supersymmetry predicts that every known particle has an as yet undetected supersymmetric partner: bosons, for example, have "bosino" siblings, such as the gluino.

In 1975 Freedman realized that supersymmetry could be extended to include gravity. That inclusion would imply that the graviton has a supersymmetric partner called the gravitino, which the theory predicts to (uniquely) have a spin of 3/2. He and van Nieuwenhuizen, working at Stony Brook, began pooling their expertise to think about the problem. The theory really began to take off when, on a visit to Paris, Freedman met Ferrara, who was then working at CERN. When he returned to the U.S. later that year, Freedman says, "I thought I'd find the rest in two weeks. But it didn't work out that way."

In fact, it took him and van Nieuwenhuizen many months of laborious calculations, some performed using the computer facilities at Brookhaven National Laboratory. For the theory to work, they needed to show that around 2,000 terms in their complex equations each canceled to precisely zero. Van Nieuwenhuizen recalls the night when the results came down the phone line from Brookhaven—all 2,000 zeros, one at a time. "My whole life was completely changed that night," he says. Freedman, van Nieuwenhuizen and Ferrara published their theory in 1976.

Physicists Peter van Nieuwenhuizen (*left*), Sergio Ferrara (*center*) and Daniel Freedman (*right*) have received a Special Breakthrough Prize in Fundamental Physics for their work on the theory of supergravity.

CERN

Some of these ideas were later used in the 1980s to develop superstring theory, a version of string theory—in which particles are represented as vibrating one-dimensional objects called strings—that incorporates supersymmetry. "Supersymmetry and supergravity were key elements in the ambitious program of using strings to make a consistent quantum theory of gravity," says particle physicist John Ellis of CERN.

Many researchers agree with Ellis that string theory is now the best hope for a theory of quantum gravity—a reason, no doubt, for the Breakthrough Prize's previous awards for string theory work. But despite intensive development of the idea, string theory has been unable to furnish any predictions amenable to experimental tests with the current generation of particle colliders—the energies needed are vastly too great. This situation has sparked heated debate about whether string theory can be considered "real science" at all.

If supersymmetric string theory is correct, however, so is supergravity: Freedman explains that the latter is what emerges from the theory at relatively low energies, rather like how Newtonian mechanics and gravity represent the low-energy limits of Einstein's special and general theories of relativity. Supergravity also underpins several other advances rewarded by previous Breakthrough Prizes, such as the late Stephen Hawking's work on black hole thermodynamics—which earned a Special Breakthrough in 2013—and the so-called anti–de Sitter/conformal field theory correspondence, a link between string theory and quantum field theory proposed in 1997 by Juan Maldacena, now at the Institute for Advanced Study in Princeton, N.J. The gravitino predicted by supergravity has also been posited as a candidate for the mysterious dark matter thought to outweigh the universe's visible matter by about a factor of five. "Supergravity was where all the action was in the late 1970s and early 1980s," says writer and former physicist Graham Farmelo, whose 2019 book *The Universe Speaks in Numbers* explores string theory.

WAITING FOR A BREAKTHROUGH

Supersymmetry has come under fire after the LHC failed to find evidence of the new particles it demands. But Duff says that failure does not, by any means, signal problems with the basic idea. "String theory is silent about the energies at which supersymmetry would reveal itself," he says—it could be that much higher energies will be needed than are currently accessible. "Supersymmetry is still alive and kicking, and supergravity was at the heart of all this progress," Duff says.

> **"I think it is good to have a spectrum of prizes that recognize different aspects of science. It's my impression that Nobel Prizes sometimes go to experimentalists rather than people who proposed the underlying theory."**
>
> ***—John Ellis***

Besides, some feel that the Nobel committee's demands for empirical proof look increasingly outdated. The Breakthrough Prize's position, Farmelo says, "will be seen as the wiser choice in the long term." Some researchers, for example, fault the Nobel for denying a prize to Hawking, whose research on black hole thermodynamics in the 1970s is widely considered to be a correct description of nature.

Andrei Linde, who, as one of the previous recipients of a Breakthrough Prize, is now part of the committee that bestows the awards, says that their purpose is to "reward extraordinary ideas." He adds, "If you have thousands of people influenced by a single bright idea," then its influence deserves recognition, whether it is experimentally proved or not. As testament to that position, he says that despite the fact that supergravity is fundamentally about particle physics, "I use it, too, even though I'm a cosmologist."

"I think it is good to have a spectrum of prizes that recognize different aspects of science," Ellis says. "It's my impression that Nobel Prizes sometimes go to experimentalists rather than people who proposed the underlying theory."

The Breakthrough Prize in Fundamental Physics was founded in 2012 by investor and philanthropist Yuri Milner. In contrast to the annual Breakthrough, the "Special" prize can be given at any time "in exceptional cases." The awards are increasingly seen as comparable to the Nobel Prizes not only in monetary value (a Nobel is worth around $1 million) but also prestige. Being conferred by a committee of world-renowned specialists, Ferrara says, makes the award "something special" and "the most important prize in my career." For Freedman, "this one takes the cake—it is the cap of my long career."

Van Nieuwenhuizen heard about the award from Ed Witten, a prominent string theorist and one of the inaugural 2012 Breakthrough Prize laureates who make up the selection committee. "I was sitting at home and saw a message on my screen from Ed," van Nieuwenhuizen says. "I was very worried he'd ask me some difficult question about supergravity to which I'd not know the answer." But when Witten then phoned to tell him the real reason for the message, he was speechless. "I'd known we might be candidates in the past," he says, "but I had completely given up hope of getting it."

One potentially controversial aspect of the decision is that the supergravity picture was also formulated independently by Bruno Zumino, a pioneer of supersymmetry, and Stanley Deser, now at Brandeis University, who also published their work in 1976—initiating disputes over priority. Zumino died in 2014, but the omission of Deser from the award seems puzzling, Duff says, given that there is no restriction on the number of recipients.

That situation aside, Linde admits that it is surprising, given the importance of supergravity, that its architects were not rewarded sooner. But what are the prospects of seeing the theory put to the test? Detection of any supersymmetric particle would strongly suggest the theory is correct, Farmelo says, because there are arguments that supersymmetry is "the one and only possible way to extend the symmetry of spacetime"—the fundamental canvas of gravity as described in general relativity—"to ensure it is quantum-mechanical."

Clinching evidence, though, would come from detection of the gravitino itself. "That would be wonderful," Freedman says. But he admits that it will be extremely hard to achieve because the gravitino should interact so weakly with any other particles. We need to be patient, Ferrara says, pointing out that the Higgs boson was not observed until five decades after it was first predicted. For supersymmetric particles such as the gravitino, he says, "we still have some decades to go" before considering it overdue.

Van Nieuwenhuizen has hopes that a new collider with greater energies than the LHC planned in China might see supersymmetric particles. He reckons on a 50 percent chance of that happening in his lifetime. To its advocates, though, supersymmetry and its concomitant supergravity seem not just likely but virtually inescapable. "I think it's inevitable that the spin-3/2 particle [gravitino] is realized in nature," Freedman says. "There is no comparable theory," Ferrara argues, "and it would be really a pity if nature has not used this one."

—Philip Ball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Mysterious Neutrinos Get New Mass Estimate

Cosmic calculations suggest how massive nature's lightest matter particle could be

By Clara Moskowitz

MARK ROSS STUDIO

Clara Moskowitz is *Scientific American*'s senior editor covering space and physics. She has a bachelor's degree in astronomy and physics from Wesleyan University and a graduate degree in science journalism from the University of California, Santa Cruz.

NEUTRINOS, SOME OF NATURE'S WEIRDEST FUNDAMENTAL particles, are nearly massless—emphasis on nearly. They were predicted to be completely massless, but experiments roughly 20 years ago found they surprisingly do have some mass. Just how much has remained a mystery. Now a new calculation based on cosmological observations places an upper limit on how heavy the lightest kind of neutrino can be.

There are many strange things about neutrinos: their unexpected heft, for one thing, and that they rarely interact with other matter and are passing through our bodies by the billions each moment. Perhaps the oddest aspect of these particles is their tendency to switch identities, cycling among the three possible "flavors," or types. In fact, it was the observation of this shape-shifting ability in the first place that told scientists the three neutrino flavors must have different masses—which means, of course, that all of their masses cannot be zero.

Scientists would desperately like to know what they actually weigh, which would be a vital clue about why they have mass, given that they do not seem to acquire it the way other particles do: through the Higgs field (associated with the Higgs boson, which was discovered in 2012). "Understanding why particles have mass is something very fundamental in how we understand physics," says physicist Joseph Formaggio of the Massachusetts Institute of Technology. "What neutrinos pose is the possibility that the mechanism we think gives rise to masses for all the particles may not apply, for some strange reason, to neutrinos. I find that exciting."

The new mass limit comes from a supercomputer calculation that combined data on the distribution of galaxies throughout the universe, the remnants of the first light released after the big bang and supernova measurements that reflect the expansion rate of the cosmos. The analysis also used laboratory data on neutrinos, such as measurements of the rates that they switch between flavors, to arrive at an estimate of the maximum weight of the smallest one: 0.086 electron volt, or 0.00000000000000000000000000000000000015 kilogram—making it at least six million times lighter than an electron.

"What they have done is really nice work," says Olga Mena of the Institute of Corpuscular Physics in Spain, who has worked on similar calculations. André de Gouvêa, a theoretical physicist at Northwestern University, says, "It's a slightly more detailed analysis of cosmological data than people had done before. It's quite a nice paper." The results, initially posted to the preprint server arXiv.org, were published on August 22 in *Physical Review Letters* (*PRL*). Another limit, calculated through similar methods by physicists Shouvik Roy Choudhury and Steen Hannestad, was also recently posted on arXiv.org and is now under peer review at the *Journal of Cosmology and Astroparticle Physics*.

COSMIC FUZZINESS

Why should far-flung measurements of galaxies and supernovae have any bearing on the mass of the lightest matter particle in the universe? Because neutrinos, though small, do have a gravitational effect on everything else through their tiny mass. As they travel through space at nearly the speed of light, they tend to pull other particles with them ever so slightly, leading to an overall blurriness in the spread of galaxies throughout the cosmos. "It's like if you're shortsighted, and you take your glasses off," says Arthur Loureiro of University College London, first author of the *PRL* study. "They make things fuzzier." And the extent of this fuzziness can tell us how much mass neutrinos have.

The estimate complements other efforts to weigh neutrinos that focus on laboratory experiments. For instance, a project in Germany called the Karlsruhe Tritium Neutrino (KATRIN) experiment aims to measure neutrino mass by observing beta decays in which a neutron transforms into a proton by releasing a neutrino and an electron. By carefully measuring the energy of the electron, scientists can infer the mass of the neutrino. In contrast to cosmology-based estimates, which include uncertainties from assumptions about unknowns such as dark matter and dark energy, this kind of experiment is more direct. “It sort of makes the least assumptions, but unfortunately, it’s the least sensitive right now,” says Formaggio, who works on KATRIN and similar experiments.

A third class of studies search for a fabled decay process known as neutrinoless double beta decay, in which two neutrons transform into two protons, releasing the expected electrons but not the corresponding neutrinos. This phenomenon could happen if neutrinos turn out to be their own antimatter partner particles—a theoretical possibility but far from a certainty. If so, the two neutrinos emitted would annihilate each other, as all matter and antimatter partners do when they meet. If neutrinoless double beta decay can be measured, the strength of the decay would be proportional to the lightest neutrino mass. So far, though, no experiment has seen it.

THE THEORY’S MISSING PIECE

Ultimately scientists must compare the results from all these different methods. “Only by combing all the possible ways of measuring the neutrino mass will we have a finite and robust answer,” Mena says. But if the estimates differ, some scientists say, all the better. “One thing that’s exciting is: What if we make a measurement from cosmology, and we get an answer that doesn’t agree with particle physics measurements?” de Gouvêa says. “That would be indicative of the fact that there’s something in this picture that’s just wrong. Maybe there’s something wrong with our understanding of the early universe. Or maybe there’s something unusual about the mechanism for neutrino masses, like the mass depends on where you are or when you make the measurement. It sounds crazy, but it’s possible.”

Even without evidence for such outlandish scenarios, finding a reliable estimate of neutrino mass would push physics in a new direction. The Standard Model of particle physics, the best theory researchers have to describe the particles and forces in the universe, predicted neutrinos were weightless. The fact that they are not presents the possibility of expanding the theory. “The Standard Model is one of the most precise theories that humanity has ever built,” Loureiro says, “but it’s missing a bit. Finding the missing piece about neutrinos could definitely be the key to understanding what dark energy and dark matter are, because they are also not in the Standard Model.”

The cosmological piece of the answer stands to get more precise in the next decade, as some eagerly awaited new telescopes come online. The European Euclid telescope, for instance, will drastically improve the precision of 3-D cosmic maps after it launches in 2022. And the Dark Energy Spectroscopic Instrument in Arizona will soon begin surveying the distances of 30 million galaxies. Finally, the Large Synoptic Survey Telescope, under construction in Chile, will image the whole sky every few nights, starting in 2022. “Everybody is very excited,” de Gouvêa says, “because in the next five-ish years, they should get to a sensitivity that they should actually see something—they will be in a position to make an observation, as opposed to just setting a bound.”


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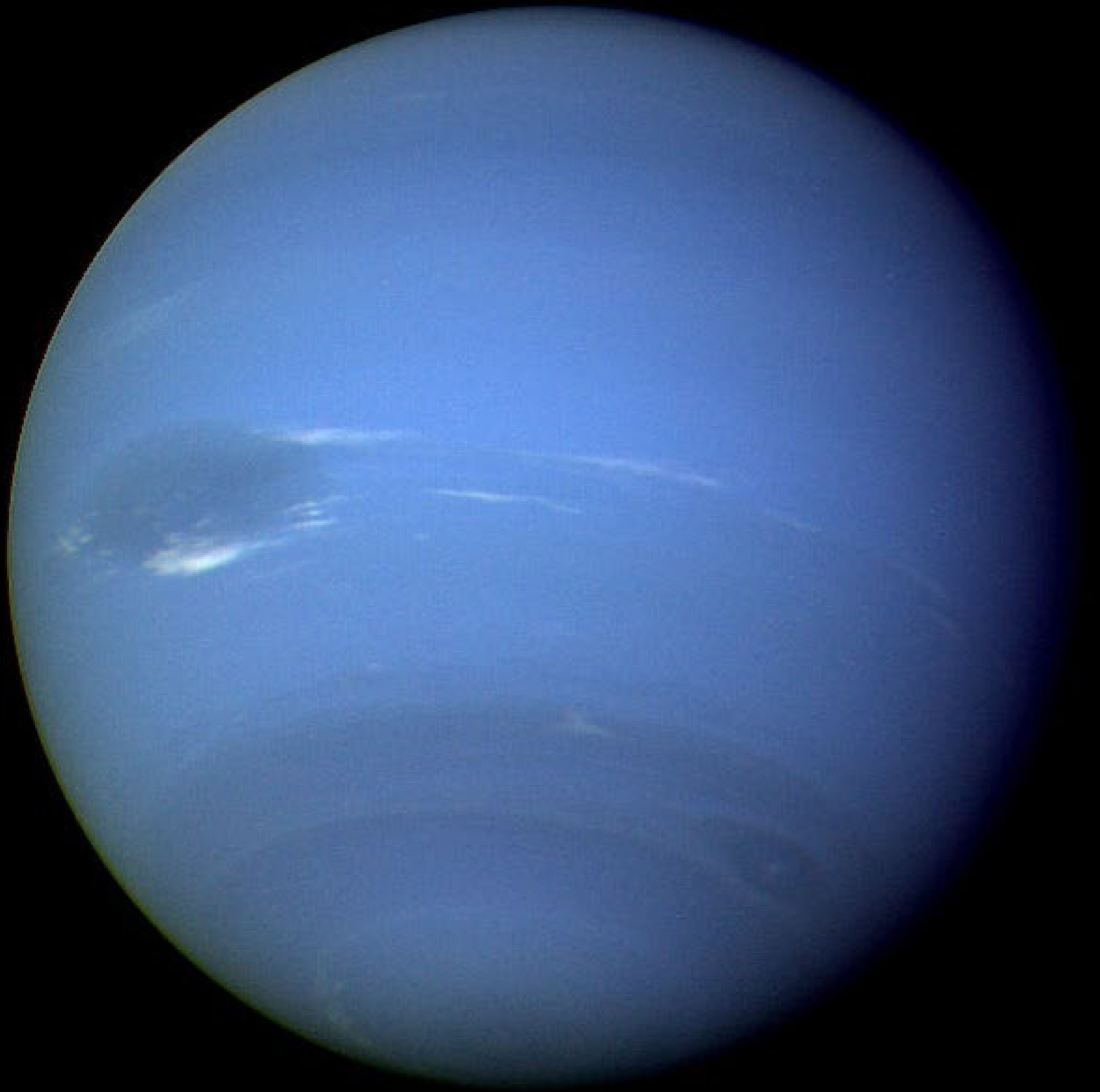
Neptune, as seen by NASA's Voyager 2 probe during its 1989 flyby of the ice-giant planet.



NASA AND JPL

The Solar System's Loneliest Planets, Revisited

Thirty years after a probe visited Neptune, many scientists say now is the time to finally return to that world and Uranus

By Shannon Hall

Shannon Hall is an award-winning freelance science journalist based in the Rocky Mountains. She specializes in writing about astronomy, geology and the environment.

ON AUGUST 25, 1989, IN PASADENA, CALIF., NASA'S JET PROPULSION LABORATORY WAS bustling with activity. Scientists, reporters and even a bona fide rock star, Chuck Berry, had flocked to the facility's mission control to commemorate the moment the Voyager 2 spacecraft flew shy of 5,000 kilometers above Neptune's north pole the previous evening—marking its closest pass to the ice giant. "The level of excitement is the highest I've ever seen here," Carl Sagan later said on a CNN television segment.

That excitement had been building for more than a year as the spacecraft slowly approached what is now considered the sun's outermost known planet. Day by day, the exhilaration grew as Voyager 2 beamed back pictures—incrementally transforming a blurry cluster of pixels into a looming, beautiful blue orb. "It got to the point where, every day, when a new set of images came down, there would be new discoveries on the planet," says Heidi Hammel, who was a member of Voyager 2's imaging science team. Hammel's logbooks from that time are filled with her sketches of those images—along with "Wow!" "Gosh!" and other exclamations scrawled in the margins.

Each image revealed an unexpectedly dynamic world—one with methane-rich clouds, violent storms larger than Earth and planetary winds that, at more than 2,000 kilometers per hour, are the fastest in the solar system. Even Neptune's large, frozen moon Triton churned with geysers and other surprising signs of geologic activity. "Every day was an adventure," Hammel recalls. "It was just a remarkable time of discovery."

But then Voyager 2 continued onward—leaving Neptune in solitude, as it had left behind our solar system's other ice giant, Uranus, after flying by it in 1986. "Our detailed knowledge of the ice giant systems is pretty much frozen at that time," says Anne Verbiscer, a planetary scientist at the University of Virginia. After 30 years, no space agency has returned to Neptune or Uranus, and the questions that Voyager 2 raised about each world remain mostly unanswered. "We think we're so busy in space, but we're busy at Mars," says Candice Hansen, a scientist who was on the Voyager imaging team during the flybys. "Once you get beyond that, there just aren't that many missions that have flown out that far. There's so much still to learn."

Luckily, the tides might soon be turning. Thanks to a renewed interest from the planetary science community and fortunate timing, a second mission might race toward those frigid and mysterious worlds relatively soon.

That is not to say that scientists have failed to study Uranus and Neptune here on Earth. On the contrary, astronomers often swivel the mirrors of giant telescopes on the ground and in orbit toward the solar system's outskirts to observe those faraway giants. But at such great distances, Uranus and Neptune each appear as minuscule blobs. As such, it has taken a number of tricks to better image them. Scientists have shot lasers into the night sky to sharpen their pictures; they have studied Triton's atmosphere as that moon passed in front of a distant star; and they have run experiments on Earth to better comprehend the odd ice that exists within these planets. But these efforts are not enough. "You just can't do the kind of science from Earth that you can do if you're in the environment itself," says Mark Showalter, a planetary astronomer at the SETI Institute.

The issue is that missions to the outer solar system, while doable, are far from easy—in part because they take at least a decade. "It is a lot easier when you can develop a mission and launch it within two years," says Hammel, now executive vice president of the Association of Universities for Research in Astronomy in Washington, D.C. "It's within a presidential funding cycle." Moreover, far from a star, a spacecraft cannot rely on solar power and instead uses nuclear fuel—such as plutonium 238, which offers a steady heat supply that makes it an ideal power source for dark voyages. But NASA's acquisition of that radioisotope has long been sporadic. That much was made painfully clear to Hansen, now a senior scientist at the Planetary Science Institute, in 2003. She was on the verge of proposing a mission to the ice giants when NASA announced it had run out of available plutonium—providing the death blow to her proposal. "It just wasn't in the cards," Hansen says. "But it was hard for me to let go of that, I have to admit." Luckily the hiatus did not last long. In 2011 Congress supplied the funds that allowed the Department of Energy to resume plutonium production for NASA—and with it, the ability to once again reach for the solar system's horizons.

NASA's nuclear rejuvenation could not arrive at a better time. To begin, there is no question that such a mission would revolutionize our understanding of the outer solar system, simply by virtue of voyaging there after three decades of further technological development and scientific discovery. What is more, in the late 2020s, the planets will be positioned so that a Neptune-bound spacecraft can get a gravity assist from Jupiter, picking up tremendous speed from swinging by the giant planet and shaving years off the travel time. Finally, a mission to Uranus needs to reach the world before 2050 in order to see its northern hemisphere for the first time. (When Voyager 2 flew past Uranus, only the planet's southern hemisphere was illuminated.) "I'm hopeful because that puts a little bit more pressure on NASA," says Mark Hofstadter, a planetary scientist at JPL. "But in the back of my mind, there's a fear that if we miss it, I'm going to miss the boat." Hofstadter is 56 years old and would therefore be in his mid-70s when—if—a mission reaches the ice giants in the late 2030s. To him and many other planetary scientists on the verge of retirement, an accepted mission would be bittersweet. "I like to joke that they'll have to reserve a rocking chair and a drooling rag for me by the time we get there," Hansen says.

> **"The challenge,**
> **of course,**
> **is that there are**
> **many fabulous places**
> **to go in**
> **our solar system."**
> ***—Heidi Hammel***

Recent findings from the Kepler space telescope add further impetus for visiting the solar system's ice giants. Based on Kepler's survey of other planetary systems in the Milky Way, scientists are now all but certain that ice giants—a distinct, unique type of world as compared with rocky planets and gas giants—are the most common planets in the galaxy. Our grasp of how worlds are born, evolve and die will remain woefully incomplete without intimately understanding these most abundant denizens of the Milky Way. Yet the ice giants defy many of our most robust models of planetary formation, which suggest such worlds should have grown into full-fledged gas giants akin to Jupiter—only they did not, and scientists are not sure why. Moreover, researchers think that water in the form of ice makes up most of a typical ice giant's interior (hence the name), but certainty on this key detail remains elusive. "We know so little about Uranus and Neptune that to really understand the exoplanets and place them into context, we really need to go back and finish the job for the ice giants," says Mark Marley, a planetary scientist at NASA's Ames Research Center, who studies exoplanets.

Because of that fact, there is a groundswell of support from the exoplanet community, Marley says. Even the last Planetary Science Decadal Survey (a report that determines NASA's exploration priorities for the coming decade) placed a mission to the ice giants third after one that would return samples from Mars and one to Jupiter's moon Europa. Given that those two higher-ranked missions are now well underway, a voyage to the ice giants just might float to the top of NASA's next bucket list.

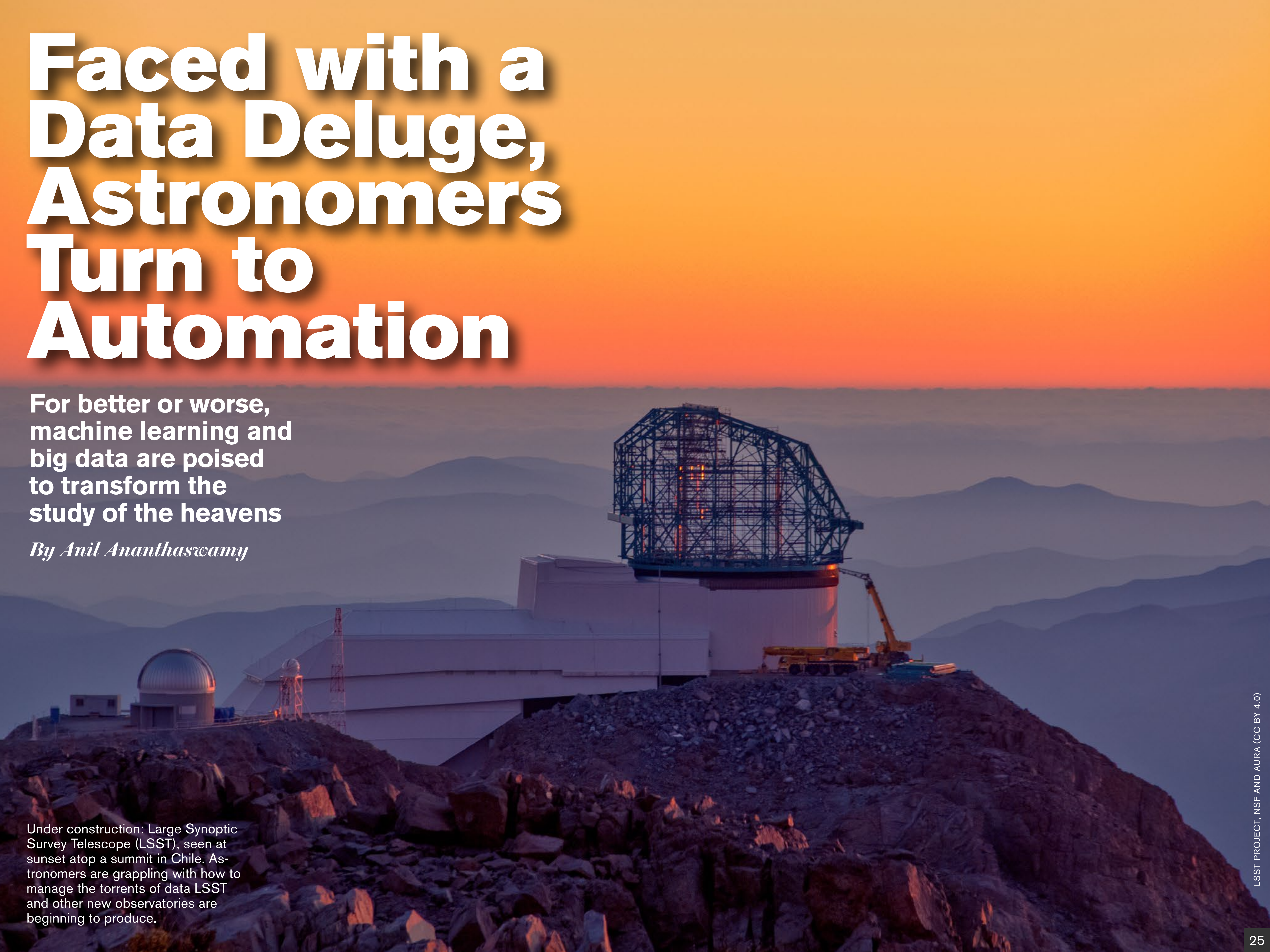
Already a team of scientists has moved to inform the next Decadal Survey, scheduled for the early 2020s, by publishing a study calling for two separate craft to the outer solar system. One would fly past Uranus, sweeping within its complex magnetic field and potentially dropping a probe into the planet's atmosphere, before leaving to explore smaller, frozen bodies even farther away from the sun. And the other would orbit Neptune, studying both the planet and the mysterious, geyser-spewing Triton.

"The challenge, of course, is that there are many fabulous places to go in our solar system," says Hammel, who admits she is biased. "But I don't want to go back to Mars again. I don't want to go back to Venus again. I don't want to go to another comet. I love them, and they're great science. But where are the mysteries? Where are the unknowns? Where are the giant question marks that we can't address without a spacecraft? To me, that's Uranus and Neptune."

Faced with a Data Deluge, Astronomers Turn to Automation

For better or worse, machine learning and big data are poised to transform the study of the heavens

By Anil Ananthaswamy



Under construction: Large Synoptic Survey Telescope (LSST), seen at sunset atop a summit in Chile. Astronomers are grappling with how to manage the torrents of data LSST and other new observatories are beginning to produce.

LSST PROJECT, NSF AND AURA (CC BY 4.0)

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

On August 18, 2017, a new age in astronomy dawned, appropriately, with a tweet: "New LIGO. Source with optical counterpart. Blow your sox off!"

One astronomer had jumped the gun, tweeting ahead of an official announcement by LIGO (the Laser Interferometer Gravitational-Wave Observatory). The observatory had detected an outburst of gravitational waves, or ripples in spacetime, and an orbiting gamma-ray telescope had simultaneously seen electromagnetic radiation emanating from the same region of space. The observations—which were traced back to a colliding pair of neutron stars 130 million light-years away—marked a pivotal moment for multimessenger astronomy, in which celestial events are studied using a wide range of wildly different telescopes and detectors.

The promise of multimessenger astronomy is immense: by observing not only in light but also in gravitational waves and elusive particles called neutrinos, all at once, researchers can gain unprecedented views of the inner workings of exploding stars, galactic nuclei and other exotic phenomena. But the challenges are great, too: as observatories get bigger and more sensitive and monitor ever larger volumes of space, multimessenger astronomy could drown in a deluge of data, making it harder for telescopes to respond in real time to unfolding astrophysical events. So astronomers are turning to machine learning—the type of technology that led to AlphaGo, the first machine to beat a professional human Go player.

Machine learning could boost multimessenger astronomy by automating crucial early phases of discovery, winnowing potential signals from torrents of noise-filled data so that astronomers can focus on the most tantalizing targets. But this technique promises more. Astrophysicists are also trying it out to weigh galaxy clusters and to create high-resolution simulations needed to study cosmic evolution. And despite concerns about just how machine-learning algorithms work, the stupendous improvements that they offer for speed and efficiency are unquestionable.

"This is like a tsunami," says Eliu Huerta, an astrophysicist and artificial-intelligence researcher at the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign. "People realize that for the big data we have [coming] in the future, we can no longer rely on what we have been doing in the past."

THE GRAVITATIONAL-WAVE HOTLINE

The past, in the case of LIGO and its European counterpart Virgo, does not extend back very far. It was only in February 2016 that those observatories announced the first ever detection of gravitational waves, produced by the merger of two black holes. Now in their third observing run, which began in April, advanced versions of LIGO and Virgo have begun sending out public alerts about new potential gravitational-wave sources as they are detected, all to better support multimessenger observations.

This practice may seem routine, but it belies the enormous effort required for each and every detection. For example, the signals being collected by LIGO must be matched by supercomputers against hundreds of thousands of templates of possible gravitational-wave signatures. Promising signals trigger an internal alert; those that survive additional scrutiny trigger a public alert so that the global astronomy community can look for electromagnetic and neutrino counterparts.

Template matching is so computationally intensive that, for gravitational waves produced by mergers, astronomers use only four attributes of the colliding cosmic objects (the masses of both and the magnitudes of their spins) to make detections in real time. From there, LIGO scientists spend hours, days or even weeks performing more processing offline to further refine the understanding of a signal's sources, a task called parameter estimation.

Seeking ways to make that labyrinthine process faster and more computationally efficient, in work published in 2018, Huerta and his research group at NCSA turned to machine learning. Specifically, Huerta and his then graduate student Daniel George pioneered the use of so-called convolutional neural networks (CNNs), which are a type of deep-learning algorithm, to detect and decipher gravitational-wave signals in real time. Deep-learning algorithms use networks made of layers. Each layer is composed of nodes modeled on the activity of neurons in the human brain. Roughly speaking, training or teaching a deep-learning system involves feeding it data that are already categorized—say, images of galaxies obscured by lots of noise—and getting the network to identify the patterns in the data correctly. The training data set can involve tens of thousands, if not millions, of instances of previously classified data. The network learns by tuning the connections between its neuronlike nodes such that it can eventually make sense of uncategorized data.

After their initial success with CNNs, Huerta and George, along with Huerta's graduate student Hongyu Shen, scaled up this effort, designing deep-learning algorithms that were trained on supercomputers using millions of simulated signatures of gravitational waves mixed in with noise derived from previous observing runs of Advanced LIGO—an upgrade to LIGO completed in 2015. These neural networks learned to find signals embedded in Advanced LIGO noise.

There are crucial differences between this approach and LIGO's standard methods. Most important, deep-learning algorithms can do both detection and parameter estimation in real time. Additionally, they can easily handle more parameters on the fly than the four that LIGO currently manages. For instance, Adam Rebei, a high school student in Huerta's group, showed in a recent study that deep learning can identify the complex gravitational-wave signals produced by the merger of black holes in eccentric orbits—something LIGO's traditional algorithms cannot do in real time. "For each black hole merger signal that LIGO has detected that has been reported in publications, we can reconstruct all these parameters in two milliseconds," Huerta says. In contrast, the traditional algorithms can take days to accomplish the same task.

> **"This is like a tsunami. People realize that for the big data we have [coming] in the future, we can no longer rely on what we have been doing in the past."**
>
> ***—Eliu Huerta***

Because of its ability to search over a larger set of parameters, a deep-learning system can potentially spot signatures that LIGO might otherwise miss. And while training requires supercomputers, once trained, the neural network is slim and supple, with an extremely small computational footprint. "You can put it on the phone and process LIGO data in real time," Huerta says.

ARTIFICIAL EYES ON THE SKY

Huerta is now working with Erik Katsavounidis, a member of the LIGO collaboration at the Massachusetts Institute of Technology, to test deep-learning algorithms in the real world. "The goal is to have some of these algorithms deployed throughout the third and fourth observing runs of the LIGO and Virgo detectors," Huerta says. "It'll be a good social experiment to see how we react to, for example, neural nets finding complex signals that are not observed by other algorithms."

If successful, such a deep-learning system will be highly efficient at generating alerts for other telescopes. The most ambitious of these telescopes, still under construction atop Cerro Pachón in Chile, is the Large Synoptic Survey Telescope (LSST). When complete, the 8.4-meter LSST will be able to observe 10 square degrees of the sky at once (equivalent in size to 40 full moons), producing 15 to 20 terabytes of raw data each night—the same amount of data generated by the Sloan Digital Sky Survey over the course of a decade. Within that massive trove, LSST's astronomers will seek out supernovae, colliding stars, and other transient or variable phenomena—sources that momentarily brighten in the electromagnetic spectrum and then fade away over hours, days or weeks. The scientific value of any given transient is typically proportional to how rapidly and thoroughly follow-up observations occur.

"We have to be able to sort through a million to 10 million alerts of places in the sky changing every night and decide in, effectively, real time what is worth using precious resources for follow-up," says Joshua Bloom, an astrophysicist and machine-learning expert at the University of California, Berkeley. "Machine learning will have a massive role in that." Such approaches are already paying dividends for precursors to LSST, including the

Zwicky Transient Facility (ZTF), which uses a camera with a field of view of 47 square degrees, installed on a 1.2-meter telescope at Palomar Observatory in California. In a preprint paper, Dmitry Duev of the California Institute of Technology and his colleagues recently reported that a system called DeepStreaks is already helping astronomers track asteroids and other fast-moving near-Earth objects. “We can improve the efficiency of detecting streaking asteroids by a couple orders of magnitude,” the researchers wrote.

“That’s almost antithetical to the way that physicists like to think about the world, which is that there are—and there ought to be—very simple mathematical functions that describe the way that the world works.”

—Joshua Bloom

Similar techniques can be used to search for other transient sources in ZTF data. “Machine learning is incredibly important for the success of the project,” Bloom says. The other important component of multimessenger astronomy is the detection of neutrinos, which are emitted alongside electromagnetic radiation from astrophysical objects such as blazars. (Blazars are quasars—highly luminous objects powered by giant black holes at the centers of distant galaxies—whose jets of high-energy particles and radiation are pointed toward Earth.)

On September 22, 2017, IceCube, a neutrino detector comprising 5,160 sensors embedded within one cubic kilometer of ice below the South Pole, detected neutrinos from a blazar. The sensors look for streaks of light made by particles called muons, which are created when neutrinos hit the ice. But the handful of neutrino-generated muons can be outnumbered by the millions of muons created by cosmic rays encountering Earth’s atmosphere. IceCube has to essentially sift through this morass of muon tracks to identify those from neutrinos—a task tailor-made for machine learning.

In a preprint paper last September, Nicholas Choma of New York University and his colleagues reported the development of a special type of deep-learning algorithm called a graph neural network, whose connections and architecture take advantage of the spatial geometry of the sensors in the ice and the fact that only a few sensors see the light from any given muon track. Using simulated data, which had a mix of background noise and signals, the researchers showed that their network detected more than six times as many events as the non-machine-learning approach that is currently being used by IceCube.

Huerta is impressed by these achievements. “If we are developing or constructing these next-generation instruments to study the universe in high fidelity, we also better design better algorithms to process these data,” he says.

EINSTEIN IN A BOX

As important as these advances are, deep-learning algorithms come with a major concern. They are essentially “black boxes,” with the specifics of their operations obscured by the interconnectivity of their layered components and the thousands to millions of tunable parameters required to make them function. In short, even experts looking in from the outside are hard-pressed to understand exactly how any given deep-learning algorithm arrives at a decision. “That’s almost antithetical to the way that physicists like to think about the world, which is that there are—and there ought to be—very simple mathematical functions that describe the way that the world works,” Bloom says.

To get a handle on interpreting what machine-learning algorithms are doing, Michelle Ntampaka, an astrophysicist and machine-learning researcher at Harvard University and her colleagues developed a CNN to analyze x-ray images of galaxy clusters. They trained and tested the network using 7,896 simulated x-ray images of 329 massive clusters, designed to resemble those generated by the Chandra X-ray Observatory. The CNN became just as good as traditional techniques at inferring the mass of a cluster. But how was that neural net doing its job?

To find out, Ntampaka and her team used a technique pioneered by Google’s DeepDream project, which enables humans to visualize what a deep-learning network is seeing. Ntampaka’s team found that the CNN had learned to ignore photons coming from the core of the clusters and was paying more attention to photons from their periphery to make its predictions. Astronomers had empirically arrived at this exact solution about a decade earlier. “It’s exciting that it learned to excise the cores because this is evidence that we can now use these neural networks to point back to the underlying physics,” Ntampaka says.

For Ntampaka, these results suggest that machine-learning systems are not entirely immune to interpretation. “It’s a misunderstanding within the community that they only can be black boxes,” she says. “I think interpretability is on the horizon. It’s coming. We are starting to be able to do it now.” But she also acknowledges that had her team not already known the underlying physics connecting the x-ray emissions from galaxy clusters to their mass, it might not have figured out that the neural network was excising the cores from its analysis.

> **“That’s like saying D^{3}M has figured out general relativity without being Einstein. That could be one interpretation. I cannot tell you what is correct. At this point, it’s nearly philosophical until we have more proof.”**
>
> ***—Shirley Ho***

The question of interpretability has come to the fore in work by astrophysicist Shirley Ho of the Flatiron Institute in New York City and her colleagues. The researchers built a deep-learning algorithm, which they call the Deep Density Displacement Model, or D^{3}M (pronounced “dee cube em”), to efficiently create high-resolution simulations of our universe. When telescopes collect data about the large-scale structure of the universe, those data are compared against our best simulations, which are themselves based on theories such as general relativity and quantum mechanics. The best matches can help cosmologists understand the physics governing the evolution of the universe. High-resolution simulations are extremely expensive, however—they can take millions or tens of millions of hours of computing time to run. So cosmologists often resort to speedier low-resolution simulations, which make simplifying assumptions but are less accurate.

Ho and her colleagues first generated 10,000 pairs of simulations, each pair consisting of a low-resolution, or low-res, simulation of the evolution of a volume of space containing about 32,000 galaxies and a high-resolution, or high-res, simulation of the same volume. They then trained D^{3}M one pair at a time, giving it a low-res simulation—which takes only milliseconds to generate—as an input and making it output the high-res counterpart. Once D^{3}M had learned to do so, it produced each high-res simulation for any given low-res simulation in about 30 milliseconds. These simulations were as accurate as those created using standard techniques, which require many orders of magnitude more time.

The staggering speedup aside, the neural net seemed to have gained a deeper understanding of the data than expected. The training data set was generated using only one set of values for six cosmological parameters (such as the amount of dark matter thought to exist in the universe). But when D^{3}M was given a low-res simulation of a universe with an amount of dark matter that was significantly different than what physicists think is present in our universe, it correctly produced a high-res simulation with the new dark matter content, despite never being explicitly taught to do so.

Ho and her team are somewhat at a loss to explain exactly why D^{3}M is successful at extrapolating high-res simulations from low-res ones despite the differing amounts of dark matter. Changing the amount of dark matter changes the forces influencing galaxies, and yet the algorithm works. Maybe, Ho says, it figured out the extrapolation for changes in only one parameter and could fail if multiple parameters are changed at once. Her team is currently testing this hypothesis.

The other “real grand possibility,” Ho adds, is that D^{3}M has stumbled on a deeper understanding of the laws of physics. “Maybe the universe is really simple, and, like humans, the deep-learning algorithm has figured out the physical rules,” she says. “That’s like saying D^{3}M has figured out general relativity without being Einstein. That could be one interpretation. I cannot tell you what is correct. At this point, it’s nearly philosophical until we have more proof.”

Meanwhile the team is working hard to get D^{3}M to fail when extrapolating to different values of the cosmological parameters. “If D^{3}M fails in certain ways in extrapolation, maybe it can give us hints about why it works in the first place,” Ho says.

Unfortunately, the use of such advanced techniques in astronomy, astrophysics and cosmology is fomenting a divide. “It’s creating a little bit of a have-and-have-nots [situation] in our community,” Bloom says. “There are those that are becoming more fluent and capable in the language of moving data and doing inference on data and those that are not.”

As the “haves” continue to develop better and better machine-learning systems, there is the tantalizing prospect that, in the future, these algorithms will learn directly from data produced by telescopes and then make inferences, without the need for training using simulated or precategorized data—somewhat like the successor to the human-conquering AlphaGo. While AlphaGo had to be taught using human-generated data, the newer version, AlphaGo Zero, taught itself how to play Go without any data from human games. If astrophysics goes the same route, the black box may become blacker.

The Road to Fusion

The construction of the International Thermonuclear Experimental Reactor, the world's largest nuclear fusion experiment, is now 60 percent complete

By Giulia Pacchioni

Technicians at the International Thermonuclear Experimental Reactor under construction in Saint-Paul-lès-Durance, France.

ANNE-CHRISTINE POUJOULAT *AFP/GETTY IMAGES*

Giulia Pacchioni is senior editor at *Nature Reviews Materials*.

Saint-Paul-lès-Durance is a small, quiet village in the south of France, but the road leading there has been widened and reinforced to support large, heavyweight vehicles.

Traveling in the dead of night to minimize travel disruptions, these heavy trucks are headed to the construction site of what will be the biggest fusion reactor in the world: the International Thermonuclear Experimental Reactor (ITER).

Nuclear fusion powers the sun. The principle is simple: two light nuclei combine to form a heavier nucleus and energy. The simplest fusion reaction to exploit involves two hydrogen isotopes, deuterium and tritium. Deuterium is abundant in seawater, and tritium can be produced

The U.S., Russia, South Korea, China, Japan, the European Union and India are all collaborating on the construction of ITER as equal partners.

PALLAVA BAGLA *CORBIS VIA GETTY IMAGES*

from lithium; thus, a fusion plant would have no shortage of fuel. Moreover, it would not produce pollutants or radioactive waste and would be intrinsically safe, because fusion is not a chain reaction. Therefore, fusion promises clean and sustainable energy.

The production of energy from fusion reactions has already been demonstrated in both tokamaks and stellarators, the two possible designs for a fusion reactor but only in small research reactors that consume more energy than they produce. The next step is demonstrating that fusion can generate energy at the power-plant scale, and that is where ITER comes into play.

ITER, which uses a tokamak design, will be a research facility. Once completed it will produce 10 times the amount of energy it needs to operate but no electricity. Despite its pivotal role, ITER will not be the end of the journey to fusion energy. It will set the stage for the construction of an industrial prototype, DEMO, which will convert the fusion energy into electricity and feed it to the electrical grid. "I don't know how fusion will work at the industrial scale, but I want to find out. My expectation is that before the second half of the century we will be able to have some fusion power plants connected to the electrical grid," explains Bernard Bigot, director general of ITER.

Employees work at the site where the tokamak confinement device will be installed.

CHRISTOPHE SIMON *AFP/GETTY IMAGES*

HEATING PLASMA UP

To trigger the fusion reaction, the electrostatic repulsion between the nuclei needs to be overcome until the strong attractive nuclear force kicks in. This is done by using extremely high temperatures: creating a plasma at 150 million degrees Celsius, 10 times the temperature of the sun.

The process starts with the injection of deuterium and tritium in the high-vacuum reaction vessel. An electric discharge separates the nuclei and electrons to create a light-density plasma. If the plasma touches the walls of the vessels, it recombines and goes back to the gas phase, hence the importance of confining it with the help of ITER's powerful magnets. The magnets are also used, along with radio-frequency and microwaves, to heat the plasma by exciting the ions. Further heating is achieved by the scattering of an injected beam of high-speed neutral deuterium.

The fusion reaction produces helium and neutrons with a higher kinetic energy than that of the original particles. Helium transfers some of its energy to the new hydrogen isotopes entering the vessel, so that the plasma is self-sustained. The chargeless neutrons escape from the magnetic confinement and transfer their kinetic energy to the walls of the vessel, generating thermal energy. In ITER this energy just heats up water, but in DEMO it will be transformed in electricity.

THE TIME LINE

Currently around 60 percent of the construction work at ITER has been completed. Once the facility is operational, it will need to be carefully tested before it can reach full power. Thus, after the first plasma is produced, which is scheduled for 2025, it will probably take until 2035 to achieve full fusion power. By 2040 the construction of DEMO should start, and the connection to the grid is forecasted for 2060. After that, companies will hopefully take the lead in building fusion power plants, with limited involvement of the research community. “It’s a long way to go, and this is why it is urgent not to lose even a single day,” Bigot says. “Think about the time it took from the first stream of oil to the oil industry: it was a century, and that was much simpler than fusion technology.”

THE BROADER FUSION LANDSCAPE

ITER, a collaboration of seven members (China, the European Union, India, Japan, Korea, Russia and the U.S.) for a total of 35 countries, with the European Union responsible for nearly half of the project, is the flagship device in the fusion world; however, it is not an isolated effort. A strong research program exists to bring to maturity the technologies needed for ITER and DEMO and eliminate risks. For example, materials will be developed and tested as part of the International Fusion Materials Irradiation Facility Project (IFMIF), for which engineering validation studies are underway in Japan, under the framework of the Broader Approach Agreement for the development of fusion energy between Europe and Japan. The resulting irradiation facility IFMIF-DONES (DEMO Oriented Neutron Source) might start operating in Europe in the next decade. The joint European torus (JET), a tokamak hosted in the U.K. that produced its first plasma in 1983 and is the most powerful fusion facility in use, is also providing an important test bed for materials and technologies for ITER.

Efforts to develop the technology behind the other possible fusion reactor design, the stellarator, are also underway. An experimental stellarator in Germany, Wendelstein 7-X, achieved the first plasma in 2016. “I think stellarators might also eventually succeed,” comments Juan Knaster, deputy head of Fusion for Energy, the organization that manages the European contribution to ITER. “They are one generation behind but are very promising, and future fusion reactors could be based on this design.”

Workers assemble the superconducting magnets to be used at ITER.

PALLAVA BAGLA *CORBIS VIA GETTY IMAGES*

MATERIALS FOR EXTREME CONDITIONS

One focus of the fusion research and development program is on the materials that will be used for the reactor vessel. In this context, multiple challenges need to be addressed. First, the tiles lining the walls of the vessel will slow down the neutrons and transform their kinetic energy in thermal energy; they will need to sustain a very high heat load. Second, because the confinement of the plasma is not perfect, there can be interactions with the plasma: high-energy neutrons can erode materials, introducing impurities in the plasma that can stop the fusion reaction. Third, radioactive tritium could be retained by the material, making it radioactive as well. Last, the plasma is so hot that most materials will melt in its proximity.

Finding the right materials for ITER is thus no easy feat, and testing of materials in operating conditions is done at JET. When it was built, JET used carbon fiber composite tiles, but carbon binds with tritium, forming a powder that needs to be removed. In 2011 new tiles were installed in JET. The new tiles for the plasma-facing wall are made of beryllium, whereas those on the exhaust system at the bottom of the vessel, the divertor (a series of cassettes in which the impurities are collected to minimize plasma contamination) are made of tungsten.

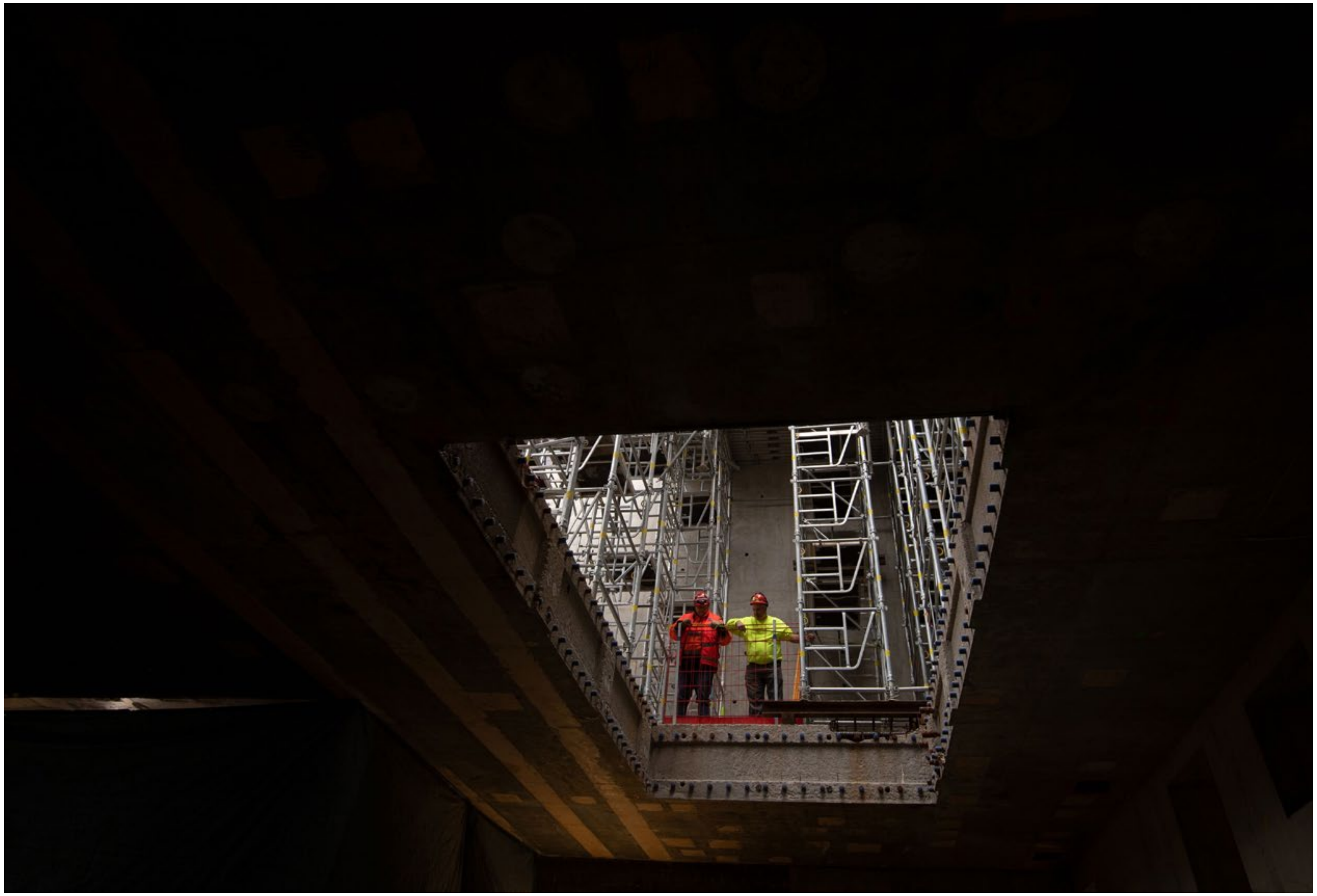
Beryllium, apart from having exceptional thermal and mechanical properties, has the advantage that it does not absorb tritium. In the divertor, however, parts of the plasma actually touch the wall, thus even the very high heat resistance of beryllium is not sufficient for its coating; the material of choice is tungsten, which has the highest melting point of all metals and is resistant to plasma erosion. Tungsten is normally brittle, so procedures to mechanically process it to increase its strength and to alloy it with other materials to prevent its embrittlement from radiation damage are being studied.

THE SUPERCONDUCTING MAGNETS

Substantial research effort also went into the design and production of ITER's magnets, which are among the world's largest and most technically sophisticated. ITER has three main magnet levels: the toroidal magnets are placed around the vacuum vessel to confine the plasma; the poloidal magnets are placed outside the toroidal system to shape the plasma, contributing to its stability; and a solenoid is placed at the center of the vacuum vessel and induces a powerful current in the plasma, heating it. Finally, there are correction coils that will compensate for possible small imperfections in the manufacturing and assembly processes. Because of the high magnetic fields that they need to generate (up to 13 Tesla), all ITER's magnets are made of superconducting material—depending on the magnet, NbTi or Nb3Sn—and will operate at liquid-helium temperatures.

A MILLION-PIECES PUZZLE

Industry and research organizations are working together to manufacture the myriad components that will be part of ITER, fostering innovation and stimulating the development of technologies that might find applications beyond nuclear fusion.



When completed, ITER will be the world's largest fusion experiment.

CHRISTOPHE SIMONAFP/GETTY IMAGES

The manufacturing of the components is distributed in all the 35 partner countries to ensure that they are all up to speed with the technological developments that will be needed when the time comes for a widespread use of fusion energy. "Huge pieces, more familiar in a shipyard, will need to be assembled with submillimeter precision: this is a big challenge," Bigot observes. "The other challenge we have to face is the integration; we have to combine a lot of different technologies: vacuum, magnetism and heat transfer. The last challenge is to manage a collaboration of 35 different countries, which we are doing by ensuring a clear decision-making process, profound integration of work and a reliable schedule."

Many of the roughly 10 million components needed to assemble ITER are already on site. The first 310-ton toroidal field coil (from Japan) and the first 440-ton vacuum vessel sector (from Korea) are among the special deliveries expected in Saint-Paul-lès-Durance in 2019.

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The Quest to Unlock the Secrets of the Baby Universe

Radioastronomers look to hydrogen for insights into the universe's first billion years

By Davide Castelvecchi

A view of part of the Murchison Widefield Array in Western Australia.

WA DEPARTMENT OF COMMERCE *FLICKR* (*CC BY-ND 2.0*)

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

TO GET AN IDEA OF WHAT THE UNIVERSE LOOKS LIKE FROM EARTH'S PERSPECTIVE, picture a big watermelon. Our galaxy, the Milky Way, is one of the seeds, at the center of the fruit. The space around it, the pink flesh, is sprinkled with countless other seeds. Those are also galaxies that we—living inside that central seed—can observe through our telescopes.

Because light travels at a finite speed, we see other galaxies as they were in the past. The seeds farthest from the center of the watermelon are the earliest galaxies seen so far, dating back to a time when the universe was just one-thirtieth of its current age of 13.8 billion years. Beyond those, at the thin, green outer layer of the watermelon skin, lies something primeval from before the time of stars. This layer represents the universe when it was a mere 380,000 years old and still a warm, glowing soup of subatomic particles. We know about that period because its light still ripples through space—although it has stretched so much over the eons that it now exists as a faint glow of microwave radiation.

The most mysterious part of the observable universe is another layer of the watermelon, the section between the green shell and the pink flesh. This represents the first billion years of the universe's history. Astronomers have seen very little of this period, except for a few, exceedingly bright galaxies and other objects.

Yet this was the time when the universe underwent its most dramatic changes. We know the end product of that transition—we are here, after all—but not how it happened. How and when did the first stars form, and what did they look like? What part did black holes play in shaping galaxies? And what is the nature of dark matter, which vastly outweighs ordinary matter and is thought to have shaped much of the universe's evolution?

An army of radioastronomy projects small and large is now trying to chart this terra incognita. Astronomers have one simple source of information—a single, isolated wavelength emitted and absorbed by atomic hydrogen, the element that made up almost all ordinary matter after the big bang. The effort to detect this subtle signal—a line in the spectrum of hydrogen with a wavelength of 21 centimeters—is driving astronomers to deploy ever more sensitive observatories in some of the world's most remote places, including an isolated raft on a lake on the Tibetan Plateau and an island in the Canadian Arctic.

Last year the Experiment to Detect the Global Epoch of Reionization Signature (EDGES), a disarmingly simple antenna in the Australian outback, might have seen the first hint of the presence of primordial hydrogen around the earliest stars. Other experiments are now on the brink of reaching the sensitivity that is required to start mapping the primordial hydrogen—and therefore the early universe—in 3-D. This is now the "last frontier of cosmology," says theoretical astrophysicist Avi Loeb of the Harvard-Smithsonian Center for Astrophysics (CfA). It holds the key to revealing how an undistinguished, uniform mass of particles evolved into stars, galaxies and planets. "This is part of our genesis story—our roots," Loeb says.

A FINE LINE

Some 380,000 years after the big bang, the universe had expanded and cooled enough for its broth of mostly protons and electrons to combine into atoms. Hydrogen dominated ordinary matter at the time, but it neither emits nor absorbs photons across the vast majority of the electromagnetic spectrum. As a result, it is largely invisible.

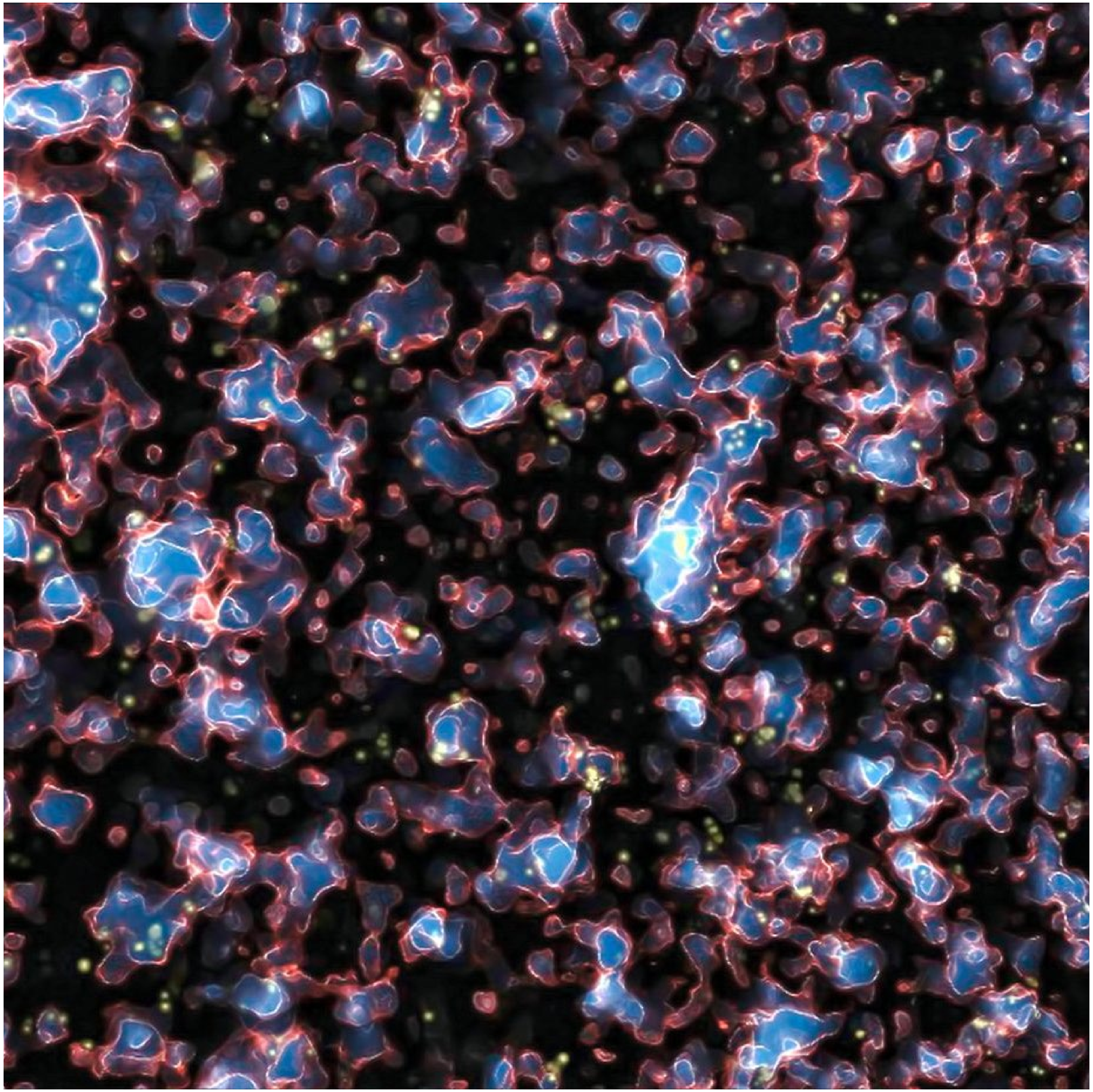
But hydrogen's single electron offers an exception. When the electron switches between two orientations, it releases or absorbs a photon. The two states have almost identical energies, so the difference that the photon makes up is quite small. As a result, the photon has a relatively low electromagnetic frequency and so a rather long wavelength, of slightly more than 21 centimeters.

It was this hydrogen signature that, in the 1950s, revealed the Milky Way's spiral structure. By the late 1960s Soviet cosmologist Rashid Sunyaev, now at the Max Planck Institute for Astrophysics in Garching, Germany, was among the first researchers to realize that the line could also be used to study the primordial cosmos. Stretched, or redshifted, by the universe's expansion, those 21-centimeter photons would today have wavelengths ranging roughly between 1.5 and 20 meters—corresponding to 15 to 200 megahertz (MHz).

Sunyaev and his mentor, the late Yakov Zeldovich, thought of using the primordial hydrogen signal to test some early theories for how galaxies formed. But, he tells *Nature*, "When I went to radioastronomers with this, they said, 'Rashid, you are crazy! We will never be able to observe this.' "

The problem was that the hydrogen line, redshifted deeper into the radio spectrum, would be so weak that it seemed impossible to isolate from the cacophony of radio-frequency signals emanating from the Milky Way and from human activity, including FM radio stations and automotive spark plugs.

The idea of mapping the early universe with 21-centimeter photons received only sporadic attention for three decades, but technological advancements in the past few years have made the technique look more tractable.



A simulation of the epoch of reionization in the early universe. Ionized material around new galaxies (*bright blue*) would no longer emit 21-centimeter radiation. Neutral hydrogen, still glowing at 21 centimeters, appears dark.

M. ALVAREZ, R. KAEHLER AND T. ABEL/ESO

The basics of radio detection remain the same; many radio telescopes are constructed from simple materials, such as plastic pipes and wire mesh. But the signal-processing capabilities of the telescopes have become much more advanced. Consumer-electronics components that were originally developed for gaming and mobile phones now allow observatories to crunch enormous amounts of data with relatively little investment. Meanwhile theoretical cosmologists have been making a more detailed and compelling case for the promise of 21-centimeter cosmology.

DARKNESS AND DAWN

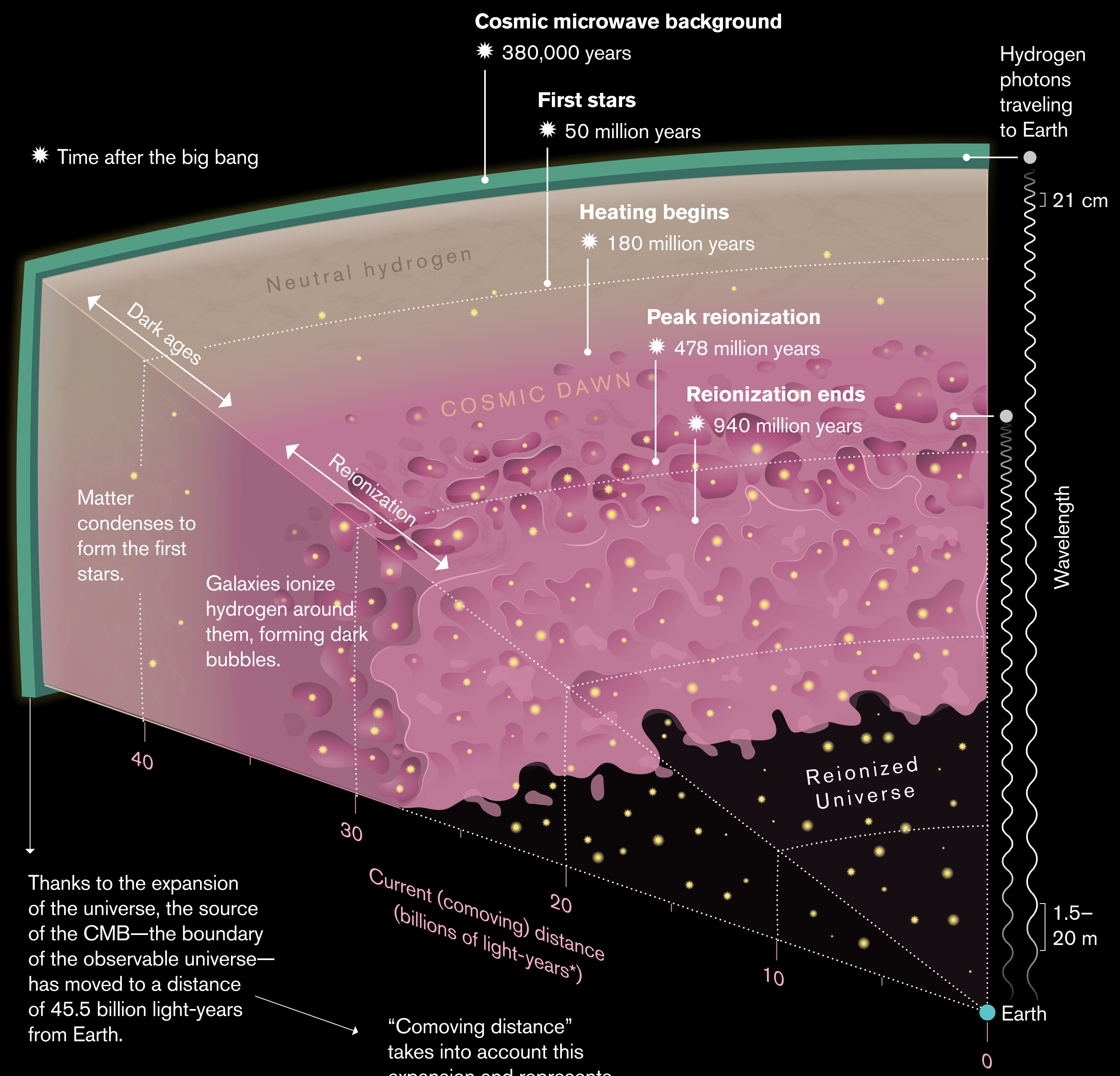
Right after atomic hydrogen formed in the aftermath of the big bang, the only light in the cosmos was that which reaches Earth today as faint, long-wavelength radiation coming from all directions—a signal known as the cosmic microwave background (CMB). Some 14 billion years ago this afterglow of the big bang would have looked uniformly orange to human eyes. Then the sky would have reddened, before slowly dimming into pitch darkness; there was simply nothing else there to produce visible light, as the wavelengths of the background radiation continued to stretch through the infrared spectrum and beyond. Cosmologists call this period the dark ages.

Over time, theorists reckon that the evolving universe would have left three distinct imprints on the hydrogen that filled space. The first event would have begun some five million years after the big bang, when the hydrogen became cool enough to absorb more of the background radiation than it emitted. Evidence of this period should be detectable today in the CMB spectrum as a dip in intensity at a certain wavelength, a feature that has been dubbed the dark-ages trough.

A second change arose some 200 million years later, after matter had clumped together enough to create the first stars and galaxies. This “cosmic dawn” released

AN EARTH’S-EYE VIEW OF THE EARLY UNIVERSE

The deeper astronomers look into the night sky, the further back in time they see. The oldest observable light is the cosmic microwave background (CMB)—radiation left over from the big bang that was emitted when the universe was just 380,000 years old. Atomic hydrogen formed at that time, and researchers can follow its activities in the early universe by looking for signs of the radiation that it emitted or absorbed. Hydrogen does this at a characteristic 21-centimeter wavelength, and that radiation has stretched over time as the universe has expanded. Evidence of that 21-centimeter signal charts the evolution of the universe from the dark ages, before the first stars emerged, through to the galaxy-studded cosmos we see today.



Thanks to the expansion of the universe, the source of the CMB—the boundary of the observable universe—has moved to a distance of 45.5 billion light-years from Earth.

“Comoving distance” takes into account this expansion and represents the distance light has traversed from objects that disappeared long ago.

Although the early cosmos is long gone, its light is only now reaching Earth. The first billion years of cosmic history, still largely unstudied, represent a good 80 percent of the universe’s observable volume.

* 1 light year = 0.3 parsecs.

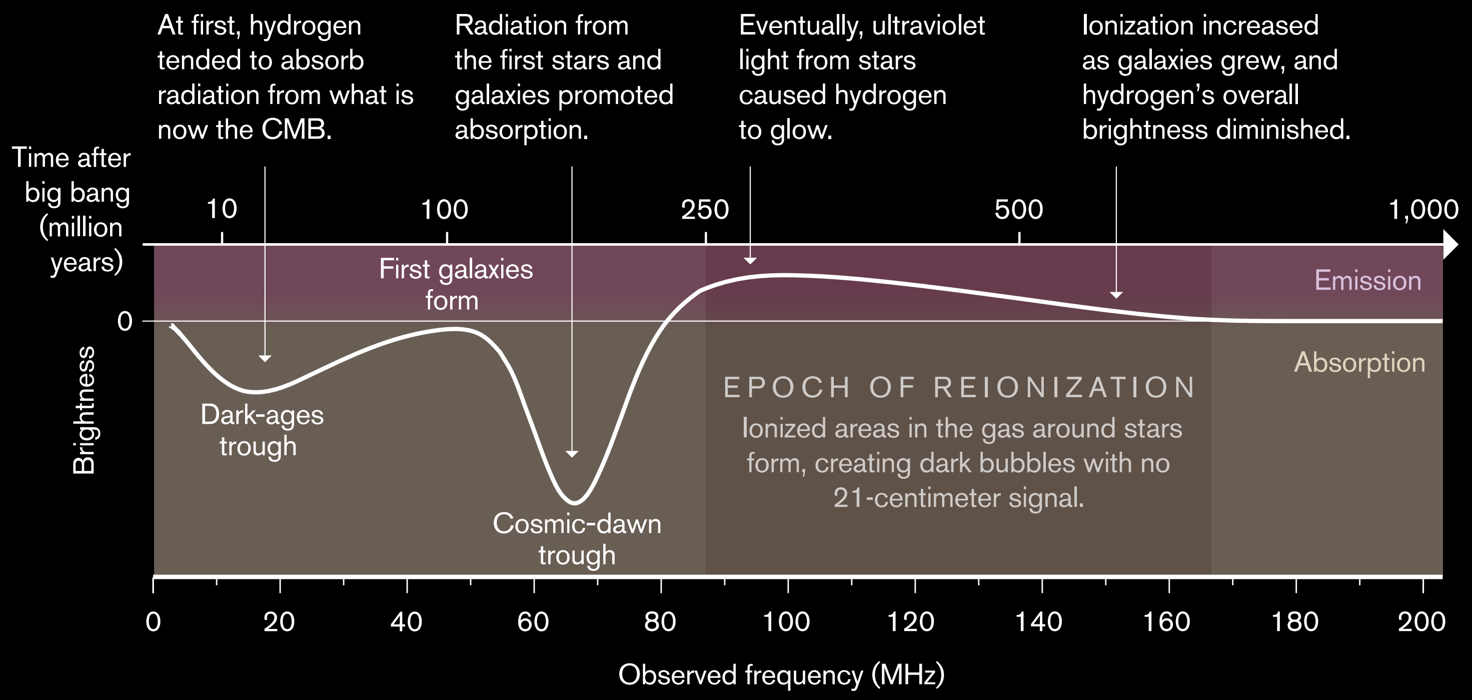
NIK SPENCER *NATURE*

ultraviolet radiation into intergalactic space, which made the hydrogen there more receptive to absorbing 21-centimeter photons. As a result, astronomers expect to see a second dip, or trough, in the CMB spectrum at a different, shorter wavelength; this is the signature that EDGES seems to have detected.

Half a billion years into the universe's existence, hydrogen would have gone through an even more dramatic change. The ultraviolet radiation from stars and galaxies would have brightened enough to cause the universe's hydrogen to fluoresce, turning it into a glowing source of 21-centimeter photons. But the hydrogen closest to those early galaxies absorbed so much energy that it lost its electrons and went dark. Those dark, ionized bubbles grew bigger over roughly half a billion years, as galaxies grew and merged, leaving less and less luminous hydrogen between them. Even today the vast majority of the universe's hydrogen remains ionized. Cosmologists call this transition the epoch of reionization, or EOR.

IMPRINT OF AN ATOM

This curve represents the overall brightness of hydrogen's 21-centimeter signal during the first billion years of the universe's history.



The EOR is the period that many 21-centimeter radio-astronomy experiments, either ongoing or in preparation, are aiming to detect. The hope is to map it in 3-D as it evolved over time, by taking snapshots of the sky at different wavelengths, or redshifts. "We'll be able to build up a whole movie," says Emma Chapman, an astrophysicist at Imperial College London. Details of when the bubbles formed, their shapes and how fast they grew, will reveal how galaxies formed and what kind of light they produced. If stars did most of the reionization, the bubbles will have neat, regular shapes, Chapman says. But "if there are a lot of black holes, they start to get larger and more free form or wispy," she says, because radiation in the jets that shoot out from black holes is more energetic and penetrating than that from stars.

The EOR will also provide an unprecedented test for the current best model of cosmic evolution. Although there is plenty of evidence for dark matter, nobody has identified exactly what it is. Signals from the EOR would help to indicate whether dark matter consists of relatively sluggish, or "cold," particles—the model that is currently favored—or "warm" ones that are lighter and faster, says Anna Bonaldi, an astrophysicist at the Square Kilometer Array (SKA) Organization near Manchester, England. "The exact nature of dark matter is one of the things at stake," she says.

Although astronomers are desperate to learn more about the EOR, they are only now starting to close in on the ability to detect it. Leading the way are radio telescope arrays, which compare signals from multiple antennas to detect variations in the intensity of waves arriving from different directions in the sky.

One of the most advanced tools in the chase is the Low-Frequency Array (LOFAR), which is scattered across multiple European countries and centered near the Dutch town of Exloo. Currently the largest low-frequency radio observatory in the world, it has so far only been able to put limits on the size distribution of the bubbles, thereby excluding some extreme scenarios, such as those in which the intergalactic medium was particularly cold, says Leon Koopmans, an astronomer at the University of Groningen in the Netherlands, who leads the EOR studies for LOFAR. Following a recent upgrade, a LOFAR competitor, the Murchison Widefield Array (MWA) in the desert of Western Australia, has further refined those limits in results due to be published soon.

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In the short term, researchers say the best chance to measure the actual statistical properties of the EOR—as opposed to placing limits on them—probably rests with another effort called the Hydrogen Epoch of Reionization Array (HERA). The telescope, which consists of a set of 300 parabolic antennas, is being completed in the Northern Cape region of South Africa and is set to start taking data in September. Whereas the MWA and LOFAR are general-purpose long-wavelength observatories, HERA's design was optimized for detecting primordial hydrogen. Its tight packing of 14-meter-wide dishes covers wavelengths from 50 to 250 MHz. In theory, that should make it sensitive to the cosmic-dawn trough, when galaxies first began to light up the cosmos, as well as to the EOR.

As with every experiment of this kind, HERA will have to contend with interference from the Milky Way. The radio-frequency emissions from our galaxy and others are thousands of times louder than the hydrogen line from the primordial universe, cautions HERA's principal investigator Aaron Parsons, a radioastronomer at the University of California, Berkeley. Fortunately, the galaxy's emissions have a smooth, predictable spectrum, which can be subtracted to reveal cosmological features. To do so, however, radioastronomers must know exactly how their instrument responds to different wavelengths, also known as its systematics. Small changes in the surrounding environment, such as an increase in soil moisture or pruning of a nearby bush, can make a difference—just as the quality of an FM radio signal can change depending on where you sit in a room.

If things go well, the HERA team might have its first EOR results in a couple of years, Parsons says. Nichole Barry, an astrophysicist at the University of Melbourne in Australia and a member of the MWA collaboration, is enthusiastic about its chances: “HERA is going to have enough sensitivity that, if they can get the systematics under control, then boom! They can make a measurement in a short amount of time.”

> **“HERA is going to have enough sensitivity that, if they can get the systematics under control, then boom! They can make a measurement in a short amount of time.”**
>
> ***—Nichole Barry***

Similar to all existing arrays, HERA will aim to measure the statistics of the bubbles, rather than produce a 3-D map. Astronomers' best hope for 3-D maps of the EOR lie in the U.S.$785-million SKA, which is expected to come online in the next decade. The most ambitious radio observatory ever, the SKA will be split between two continents, with the half in Australia being designed to pick up frequencies of 50 to 350 MHz, the band relevant to early-universe hydrogen. (The other half, in South Africa, will be sensitive to higher frequencies.)

CRO-MAGNON COSMOLOGY

Although arrays are getting bigger and more expensive, another class of 21-centimeter projects has stayed humble. Many, such as EDGES, collect data with a single antenna and aim to measure some property of radio waves averaged over the entire available sky.

The antennas these projects use are “fairly Cro-Magnon,” says CfA radioastronomer Lincoln Greenhill, referring to the primitive nature of the equipment. But researchers spend years painstakingly tweaking instruments to affect their systematics or using computer models to work out exactly what the systematics are. This is a “masochistic obsession,” says Greenhill, who leads the Large-Aperture Experiment to Detect the Dark Ages (LEDA) project in the U.S. He often takes solo field trips to LEDA's antennas in Owens Valley, Calif., to do various tasks. These might include laying a new metal screen on the desert ground underneath the antennas, to act as a mirror for radio waves.

Such subtleties have meant that the community has been slow to accept the EDGES findings. The cosmic-dawn signal that EDGES saw was also unexpectedly large, suggesting that the hydrogen gas that was around 200 million years after the big bang was substantially colder than theory predicted, perhaps 4 kelvins instead of 7 kelvins. Since the release of the results in early 2018, theorists have written dozens of papers proposing mechanisms that could have cooled the gas, but many radioastronomers—including the EDGES team—warn that the experimental findings need to be replicated before the community can accept them.

LEDA is now attempting to do so, as are several other experiments in even more remote and inaccessible places. Ravi Subrahmanyan at the Raman Research Institute in Bengaluru, India, is working on a small, spherical antenna called SARAS 2. He and his team took it to a site on the Tibetan Plateau, and they are now experimenting with placing it on a raft in the middle of a lake. With freshwater, “you are assured you have a homogeneous medium below,” Subrahmanyan says, which could make the antenna's response much simpler to understand, compared with that on soil.

Physicist Cynthia Chiang and her colleagues at the

> **“The 21-centimeter signal offers today the biggest data set on the universe that will ever be accessible to us.”**
>
> ***—Avi Loeb***

University of KwaZulu-Natal in Durban, South Africa, went even farther—halfway to Antarctica, to the remote Marion Island—to set up their cosmic-dawn experiment, called Probing Radio Intensity at High-Z from Marion. Chiang, who is now at McGill University, is also traveling to a new site, Axel Heiberg Island in the Canadian Arctic. It has limited radio interference, and the team hopes to be able to detect frequencies as low as 30 MHz, which could allow them to detect the dark-ages trough.

At such low frequencies, the upper atmosphere becomes a serious impediment to observations. The best place on Earth to do them might be Dome C, a high-elevation site in Antarctica, Greenhill says. There the auroras—a major source of interference—would be below the horizon. But others have their eyes set on space or on the far side of the moon. “It’s the only radio-quiet location in the inner solar system,” says astrophysicist Jack Burns of the University of Colorado Boulder. He is leading proposals for a simple telescope to be placed in lunar orbit, as well as an array to be deployed by a robotic rover on the moon’s surface.

Other, more conventional techniques have made forays into the first billion years of the universe’s history, detecting a few galaxies and quasars—black hole-driven beacons that are among the universe’s most luminous phenomena. Future instruments, in particular the James Webb Space Telescope that NASA is due to launch in 2021, will bring more of these findings. But for the foreseeable future, conventional telescopes will spot only some of the very brightest objects and therefore will be unable to do any kind of exhaustive survey of the sky.

The ultimate dream for many cosmologists is a detailed 3-D map of the hydrogen not only during the EOR but all the way back to the dark ages. That covers a vast amount of space: thanks to cosmic expansion, the first billion years of the universe’s history account for 80 percent of the current volume of the observable universe. So far the best 3-D surveys of galaxies—which tend to cover closer, and thus brighter, objects—have made detailed maps of less than 1 percent of that volume, says Max Tegmark, a cosmologist at the Massachusetts Institute of Technology. Loeb, Tegmark and others have calculated that the variations in hydrogen density before the EOR contain much more information than the CMB does, which so far has been the gold standard for measuring the main features of the universe. These include its age, the amount of dark matter it contains and its geometry.

Mapping this early hydrogen will be a huge technical challenge. Jordi Miralda-Escudé, a cosmologist at the University of Barcelona in Spain, says that with current technology, it is so challenging as to be a “pipe dream.”

But the payoff of producing such maps would be immense, Loeb says. “The 21-centimeter signal offers today the biggest data set on the universe that will ever be accessible to us.”

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

LIFE, UNBOUNDED

Tardigrades Were Already on the Moon

It may not be smart to add more, but nature probably beat us to it anyway

C. SCHARF 2019

In August a number of headlines have pointed to a previously obscure fact about a recent attempt at placing a lander on the moon by the nonprofit Israeli SpaceIL organization. That mission, which unfortunately failed to softly deposit a lander called Beresheet on the lunar surface on April 11, seems to have been carrying a set of thousands of dehydrated tardigrades as passengers.

In fact, when Beresheet crashed onto the moon it was carrying a novel repository of human history and information, along with a bunch of human DNA samples (in the form of hair follicles and blood) and the tardigrades. You can read more about the interesting motivations for this complement of terrestrial material, a product of the Arch Mission Foundation based out of Los Angeles, elsewhere.

Now, though, the specter of "deliberate" biocontamination of the moon is getting some scrutiny. Tardigrades, the tiny "water bears," are extraordinarily resilient life-forms. For a field like astrobiology, looking for life beyond Earth, one of the biggest challenges in our solar system is to avoid creating false positives by allowing terrestrial biomarkers or actual organisms into alien environments, whether the moon, Mars or elsewhere. There is also a sensible consensus that we don't want to mess up any alien ecosystems—especially if they might be delicate and vulnerable to invasive life.

Since the dawn of the space age, there have been internationally vetted protocols and broad agreements about this kind of planetary protection. But it is a tricky business. We know that our efforts to sterilize spacecraft are imperfect, and we know that human spacefarers are an enormous potential cross-contamination problem. On the moon there are already about 100 baggies of, well, astronaut poop, from the Apollo landings. And if the far-flung ambitions of SpaceX are ever realized, we will see hundreds, perhaps thousands, of microbe-oozing humans deposited on the surface of Mars.

None of this appears helpful when seen through the lens of astrobiology's search for other life. But at the same time, we know that nature has been busy cross-contaminating worlds for the past four billion years. And hardy little critters like tardigrades have likely already been deposited far beyond Earth.

The mechanism involves asteroid impacts and so-called impact ejecta. A large literature exists on both theoretical and experimental work tracking the possibilities. The bottom line is that largish asteroid impacts (that is, roughly one-kilometer-diameter objects and up) tend to spall (shedding of surface material) stuff from a planet and eject some of it with escape velocity or higher. Furthermore, it appears that microbial life and tough organisms like tardigrades have a decent chance of withstanding the pressure and temperature extremes during these shockingly violent launches.

Big impacts can send billions of centimeter-scale chunks from the surface of the Earth out across the solar system. Some of those pieces may take thousands of years to drop onto other planetary bodies, wending their way through an unseen web of orbital pathways, but they will get there. Indeed, computer modeling of impact ejecta suggests that even far-flung places like Titan around Saturn should—albeit rarely—be recipients of pieces of Earth over time. Places like Mars, or the moon, get far more detritus.

From the point of view of seeking clues to the deep history of life on Earth, this kind of lithopanspermia is fascinating. It may well be that scattered across the surface of the moon are fossil-like samples taken sporadically throughout life's terrestrial history. It is also possible that there are samples, even if millions of years old, that contain naturally dehydrated animals like the tardigrade. It is also, of course, possible (albeit with an unknown probability) that there is a happy ecosystem on Mars populated by descendants of terrestrial life.

There have also been many debates about whether life on Earth got its origins elsewhere before being transported here by impact ejecta. We're probably a long way from knowing the answer to that. But it is conceivable that any life in our solar system has spent the past few billion years in a merry game of natural cross-contamination—mixing it up on a regular basis.

Does any of this mean it's a good idea to be incautious about flinging terrestrial biology onto places like the moon? No, we should step very carefully. But like all things, there has to be a balance between big ideas, exploration, science and a sense of cosmic ethics.

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Robin Wordsworth is an associate professor of environmental science and engineering at Harvard University.

OBSERVATIONS

Can Mars Be Made Habitable in Our Lifetime?

It could be possible, at least to some degree, with a novel system involving aerogel

NASA, JPL-CALTECH AND MSSS

It's a very poorly kept secret in planetary science that many of us first got inspired to join the field by reading science fiction. For many of us who study Mars, Kim Stanley Robinson's 1990s Mars trilogy, which describes the colonization and eventual terraforming of the Red Planet, was particularly influential. But rereading these books in 2019, I noted that much of what he imagined looks pretty far-fetched—we're still a long way from landing the first human on Mars, and terraforming the planet to make it habitable seems like a very distant dream.

Serious scientific ideas for transforming Mars into an Earth-like planet have been put forward before, but they require vast industrial capabilities and make assumptions about the total amount of accessible carbon dioxide on the planet that have been criticized as unrealistic. When we started thinking about this problem a few years ago, therefore, we decided to take a different approach. One thing you learn quickly when you study Mars's past climate, as we do in our usual research, is that while it was intermittently habitable in the past, it was never really like Earth—it has always been a unique and alien world. So when we're thinking about how to make Mars habitable in the future, perhaps we should also be taking inspiration from the Red Planet itself.

One natural process on Mars—the so-called solid-state greenhouse effect—is of particular interest, as it is capable of intensely heating layers of ice just below the surface in Mars's polar caps every summer. This effect occurs when visible light is transmitted into the interior of a thermally insulating material, after which the heat becomes trapped and dramatic warming can occur.

Inspired by this process, as well as by a question I posed a few years ago for a graduate class on planetary climate (never say that teaching can't help with research!), we set out to see how much warming could be created on Mars by thin layers of translucent solid material on the surface. To do our experiments, we used silica aerogel, an exotic material that is incredibly insulating, very low density (it's over 97 percent air) and almost transparent to visible light, making it an ideal candidate for creating strong solid-state greenhouse warming.

Silica aerogel is already used by NASA to insulate the insides of Mars rovers, among other things. As we show in our paper via a combination of lab experiments, modeling and first-principles theory, we found that a two- to three-centimeter-thick layer of this stuff placed on or not far above the Martian surface would be sufficient to keep the layer below permanently warm enough to grow algae or plants and to block most hazardous UV radiation. If we're happy to start locally, making Mars habitable might therefore be a far more achievable goal than has previously been thought.

What are the next steps? Our paper demonstrates that the basic physics of this idea is sound, but there is still lots of work to be done in understanding how actual habitats could be constructed on Mars with this approach. Silica aerogel is quite fragile, so to allow for robust shields and control interior pressure it would need to be modified or combined with some other materials. There is also the question of how to supply silica aerogel on Mars. It's very light, which is favorable for transporting it from Earth, but eventually we'd want to make it on the surface.

One standard industrial approach involves a high-pressure CO_2 drying step, which could use CO_2 supplied from the atmosphere. But it is notable that some organisms on Earth are incredibly proficient at manipulating silica on nanoscales (glass sponges and diatom phytoplankton are just two examples). Speculatively, it is therefore possible that organisms could eventually be adapted to produce silica-aerogel-like material themselves, leading to a biosphere that helps to sustain its own habitable environment.

In practical terms, we next plan to focus on improving the range and sophistication of our laboratory experiments and on performing initial tests in the field. Mars is unique, but there are some inhospitable locations on Earth that are rather like it, including the Atacama Desert in Chile and the Dry Valleys in Antarctica. If we can demonstrate the feasibility of our idea at sites like these in the field, that'll go a long way toward demonstrating that it can work for real on the Martian surface.

After that, the biggest remaining hurdle will be planetary protection: any plans to put life on Mars must avoid contaminating places where there could be life already. This will be much more easily done with the regional, scalable approach we are proposing than in any global terraforming scenario, but it is still a major issue that requires very careful consideration in the future.

We're still a long way from making viable self-sufficient habitats on other planets. But for the first time, our research opens up a plausible pathway to achieve this decades in the future, rather than centuries, if we choose to do so. And we think that's something worth getting excited about.

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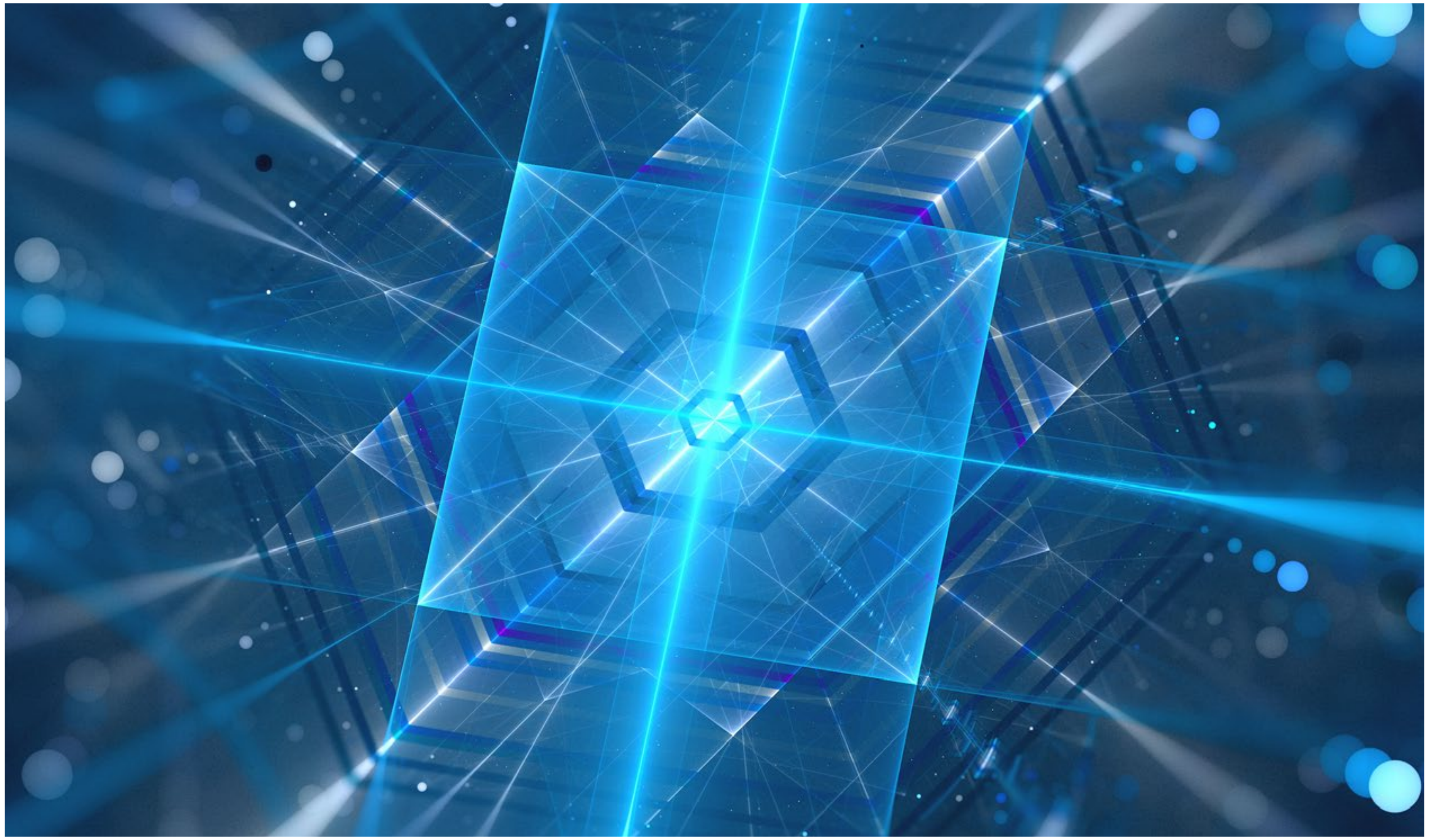
Christopher Monroe is Bice Zorn Professor of Physics and Distinguished Professor at the University of Maryland and co-founder and chief scientist of IonQ, a quantum computing start-up.

OBSERVATIONS

The Quantum Computing Party Hasn't Even Started Yet

But your company may already be too late



GETTY IMAGES

If you pay even a little attention to technology news, you've undoubtedly heard about the amazing potential of quantum computers, which exploit the unusual physics of the smallest particles in the universe. While many have heard the buzz surrounding quantum computing, most don't understand that you can't actually buy a quantum computer today, and the ones that do exist can't yet do more than your average laptop.

Don't let that discourage you from digging deeper into the promising field. If your organization uses advanced scientific or mathematical models, the time to start building your quantum computing capabilities may be now.

Why now? Because quantum computers that are powerful enough to shake up some of the world's largest industries will begin to hit the market in just three to five years. And it will take you at least that long to build the expertise required to take advantage of them for your own business benefit.

The key to understanding quantum computers is that they are nothing like the computers we have now. Conventional computers are linear and deterministic. Double the number of transistors or bytes of memory, and you should expect to double the computing power. They represent data as distinct numbers and execute programs step by step. Quantum computers are parallel and probabilistic. Add a single quantum bit to the system, and its power generally doubles. Information is represented as the odds that something might be true, and quantum algorithms can evaluate myriad potential scenarios at the same time.

As it happens, a lot of the hardest problems organizations face today involve making sense of complex systems of interconnected yet uncertain events, often in the form of mathematical models that cannot generally be solved. Think about predicting the economy a year from now. Or plotting the best routes for a nationwide delivery company in a blizzard. Or even simulating the behavior of large molecules used in pharmaceuticals and advanced materials. All of these problems stump even the most powerful supercomputers we have now.

So if your company deals with complexity—big or small—quantum computers may be the key to breakthrough discoveries and significant improvements in efficiency. But you'll need completely new algorithms, written by people with very different skills than you have now.

Here's what you can do to be ready:

Create a formal effort to explore quantum computing applications. It needs people and resources, but not many to start. Treat it as a research and development expense with a high probability of paying off in three to five years.

Identify where quantum computers can help your company most. These are likely to involve optimizing complex systems that are difficult or impossible to model today. There are other applications, such as cryptography, that you may discover in your field.

Build relationships with quantum computer makers. As companies refine their hardware, they are eager to help potential future customers develop software. Some make online access to quantum computers available through the cloud. Others have published simulators for some of the growing numbers of quantum programming environments. Even though you can't buy a quantum computer now, you can get access to tools to develop applications.

Cultivate emerging talent. The biggest problem that many companies will face as quantum computers become available is the shortage of software engineers who know how to use them. Now is the time to build relationships with universities that have cutting-edge quantum computer programs. Get to know the faculty and students. Sponsor events. Hire interns. You need help with your R&D now, and you'll need a lot more soon enough.

Build prototype quantum applications in your field. What you can do with them today may seem trivial. What's important is that you create new algorithms that use the distinctive mathematics of quantum computers. After you develop the right approach, you'll be ready to use more powerful hardware as it becomes available.

For example, at IonQ, the company I co-founded to build quantum computer hardware, we used our first-generation machine to simulate a key measure of the energy of a water molecule. Why get excited when ordinary computers can handle the same calculation without breaking a sweat?

The excitement is what comes next. Water only has 10 electrons to consider with just thousands of configurations. In a few years more powerful hardware can use the algorithms we wrote to understand molecules with hundreds of electrons, having more configurations than there are atoms in the universe! Calculating properties of such molecules will be needed for breakthroughs in drugs, fertilizers, batteries and other materials.

For ours and the other companies building quantum computers, it's an exciting time. It's taken decades of work to learn how to build working machines that can handle a few dozen quantum bits of information (qubits). It will take a few more years of engineering for us to build capacity in the hundreds of qubits, but I am confident that we will and that those computers will deliver on the amazing potential of quantum technology.

The choice facing technology leaders in many industries is whether to start working today on the quantum software that will use the next generation of computers or whether to wait and watch the breakthroughs be made by more agile competitors.

> **The key to understanding quantum computers is that they are nothing like the computers we have now.**

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!

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Astronomical Events

October—November 2019

October	Event
3	Evening sky: moon is upper left of Jupiter in constellation Ophiuchus
5	Moon: first quarter
	Moon reaches southernmost declination
	Evening sky: moon is lower left of Saturn in constellation Sagittarius
10	Moon at apogee (405,899 km), apparent diameter 29´ 04´´
13	Full moon
20	Mercury in greatest elongation east (25°)
	Moon reaches northernmost declination
21	Moon: last quarter
26	Dawn: waning crescent moon is 5° upper left of Mars one hour before sunrise
	Moon at perigee (361,311 km), apparent diameter 33´ 10´´
28	New moon
	Uranus at opposition
29	Dusk: waxing crescent moon 5° upper left of Venus 30 minutes after sunset
31	Dusk: waxing crescent moon left of Jupiter
	Mercury stationary

October— November 2019: Visibility of the planets

The astronomical highlight of these two months is the transit of Mercury on November 11. But to observe this phenomenon, telescopes equipped with approved solar filters are necessary. The bright planets Venus, Jupiter and Saturn can be seen in the evening sky.

Mars was in conjunction with the sun on September 2 and reappears in the morning sky at the end of October. The Red Planet moves eastward through the constellation Virgo and passes its brightest star, Spica, on the morning of November 10. The best time to look for the planet is about one hour before sunrise.

Mercury, the innermost planet of our solar system, was in superior conjunction (i.e., behind the sun) on September 4 and is slowly moving eastward away from the sun until it reaches its greatest elongation 25° east of the sun on October 20. Therefore, during October when the sun sets, Mercury is still about 7 degrees above the western horizon. But it is impossible to spot the planet in the bright twilight. If you see a bright object setting about 40 minutes after the sun, it is Venus, not Mercury. It is possible, however, to see Mercury on November 11, when the planet transits the sun's disk as a tiny dark spot between 12h 35m and 18h 04m UT. But you need a telescope with a special approved solar filter to protect your eyes from the sun's glare. Never look into the sun with an optical instrument that is not equipped with such a solar filter! Please contact your nearest astronomy club, planetarium or observatory for advice if you want to observe the Mercury transit, which is a rare astronomical event. (The next transit of Mercury will take place in 2032.) Mercury reappears in the morning sky just a few days after the transit, because its western elongation quickly increases, and the ecliptic—the sun's apparent path in the sky—rises steeply in the eastern morning sky.

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Astronomical Events

October—November 2019

November	Event
1	Evening sky: moon is lower right of Saturn in constellation Sagittarius
2	Moon reaches southernmost declination
4	Moon: first quarter
7	Moon at apogee (405,058 km), apparent diameter 29´ 20˝
11	Mercury in inferior conjunction
	Transit of Mercury
12	Full moon
16	Moon reaches northernmost declination
19	Moon: last quarter
20	Mercury stationary
23	Moon at perigee (366,716 km), apparent diameter 32´ 34˝
24	Dawn: waning crescent moon left of Mars and above Mercury one hour before sunrise
	Dusk: Venus 1.5° south of Jupiter 30 minutes after sunset
26	New moon
27	Neptune stationary
28	Mercury greatest elongation west (20°)
	Dusk: waxing crescent moon left of Venus and Jupiter 30 minutes after sunset
29	Moon reaches southernmost declination
	Dusk: moon below Saturn in constellation Sagittarius

October— November 2019: Visibility of the planets

The astronomical highlight of these two months is the transit of Mercury on November 11. But to observe this phenomenon, telescopes equipped with approved solar filters are necessary. The bright planets Venus, Jupiter and Saturn can be seen in the evening sky.

Venus is much brighter than Mercury but somewhat closer to the sun and therefore also hard to see in October. At the end of the month Venus sets about one hour after sunset. The visibility improves in the second half of November, when the planet gains more height and the sun sets earlier. In this fortnight Venus passes Jupiter, which is also low in the west at the beginning of the night. The best time to observe this conjunction is about 40 to 60 minutes after sunset. The two planets have a distance of only 1.5° on the evening of November 23 and 24.

Saturn just crosses the meridian when the sun sets in early October, leaving about four hours of observation time until the ringed planet sets in the southwest. The first-quarter moon is to the lower left of Saturn on the evening of October 5. On the evening of November 1 the moon—a waxing crescent—is to the lower right of Saturn. A third conjunction occurs at dusk of October 29, when a very thin crescent is just 2° left of Saturn.

Jupiter is shining bright in the low southwest evening sky low after sunset. The planet slowly moves eastwards through the constellation Ophiuchus (the Serpent-bearer) and then into Sagittarius in mid-November. Because the sun comes continuously closer, Jupiter's visibility period is about to end in early December. But before vanishing from sight in the sun's glare, Jupiter is joined by bright Venus. Both planets form a close pair on the evenings of November 23 and 24. We can see the waxing crescent moon near Jupiter on October 3, October 31 and November 28.

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SKY REPORT

October

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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November

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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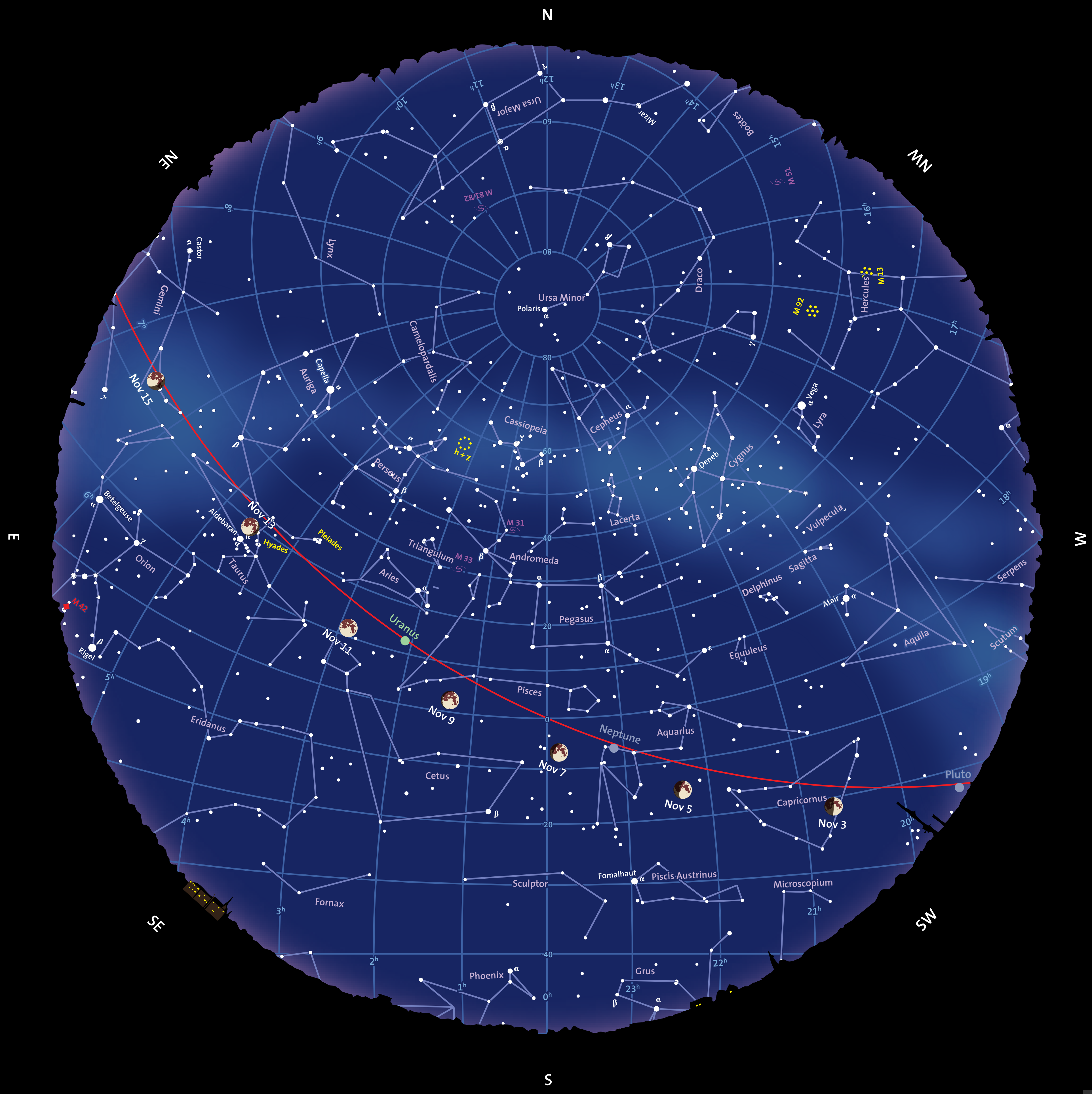
●	●	●	•	•	·	·
–1	0	1	2	3	4	5

Apparent magnitudes

- ⁘ Open cluster
- ⁙ Globular cluster
- ௵ Galaxy
- 🟥 Nebula



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