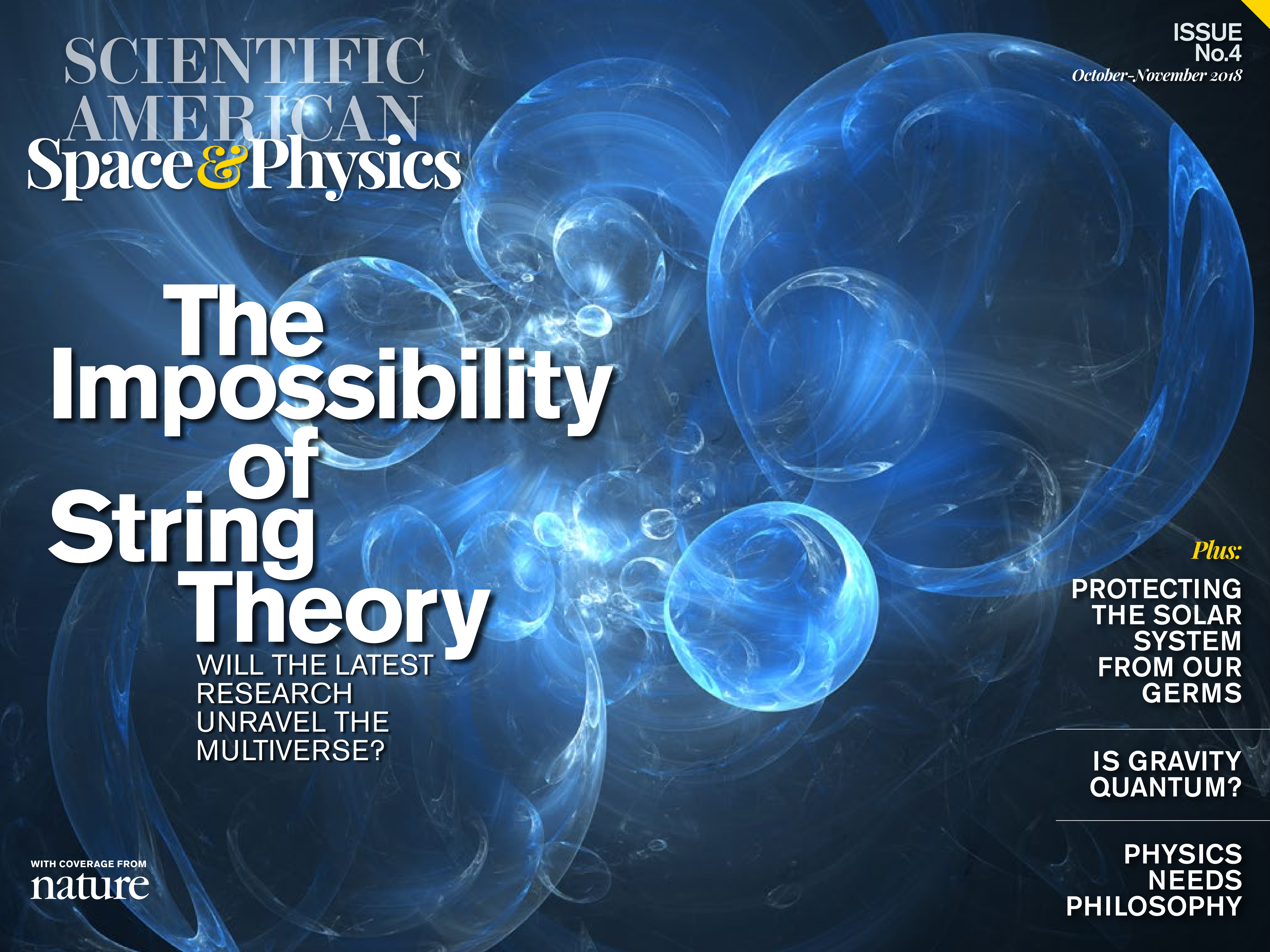

SCIENTIFIC AMERICAN Space & Physics

ISSUE No.4
October-November 2018

The Impossibility of String Theory

WILL THE LATEST RESEARCH UNRAVEL THE MULTIVERSE?

Plus:

PROTECTING THE SOLAR SYSTEM FROM OUR GERMS

IS GRAVITY QUANTUM?

PHYSICS NEEDS PHILOSOPHY

WITH COVERAGE FROM
nature

LIZ TORMES

Problems with the Multiverse

In the moments after the big bang, spacetime expanded so rapidly that, in addition to our own, many—maybe infinite—universes exploded into existence (I envision these universes as bubbles that surge up when you blow air through a straw into your glass). So goes the “multiverse” component of string theory. To be sure, the multiverse is decidedly centered in the pop physics zeitgeist, capturing the minds of the public in books, comics and film. Now a view of string theory posits that the infinite number of universes predicted cannot accommodate the stable dark energy required in any universe. But this may not necessarily be a bad thing for string theory research. Read more in “String Theory May Create Far Fewer Universes Than Thought,” by Clara Moskowitz. For better or worse, ours may be a more singular universe after all.

Elsewhere in this issue, scientists worry that human exploration of the solar system may unwittingly spread our pathogens to other worlds, possibly to the moon or Mars (see “Should the Moon Be Quarantined?” by David Warmflash). And physics experiments in search of a fundamental particle of gravity—the graviton—are employing some new tools such as microscopic superconductors, free-falling crystals and the cosmic background radiation (see “Is Gravity Quantum?” by Charles Q. Choi).

As always, we’d love to hear what you think!

Andrea Gawrylewski
Collections Editor
editors@sciam.com

Your Opinion Matters!

Help shape the future of this digital magazine. Let us know what you think of the stories within these pages by emailing us: editors@sciam.com.

On the Cover

According to string theory, innumerable universes formed, perhaps like bubbles, in the moments after the Big Bang.

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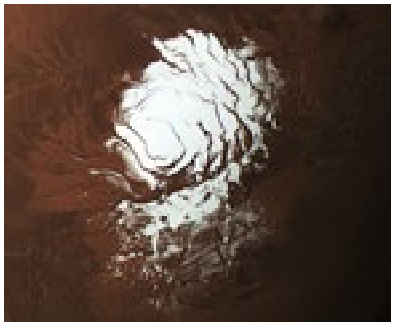

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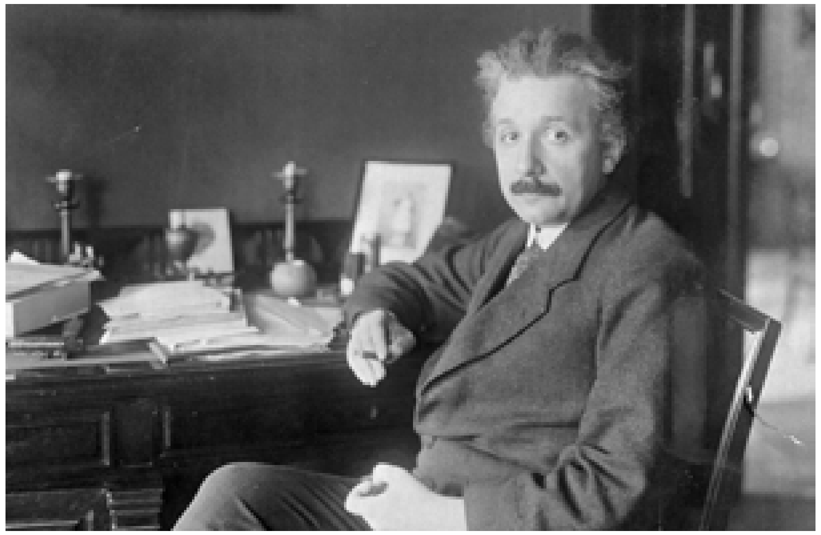

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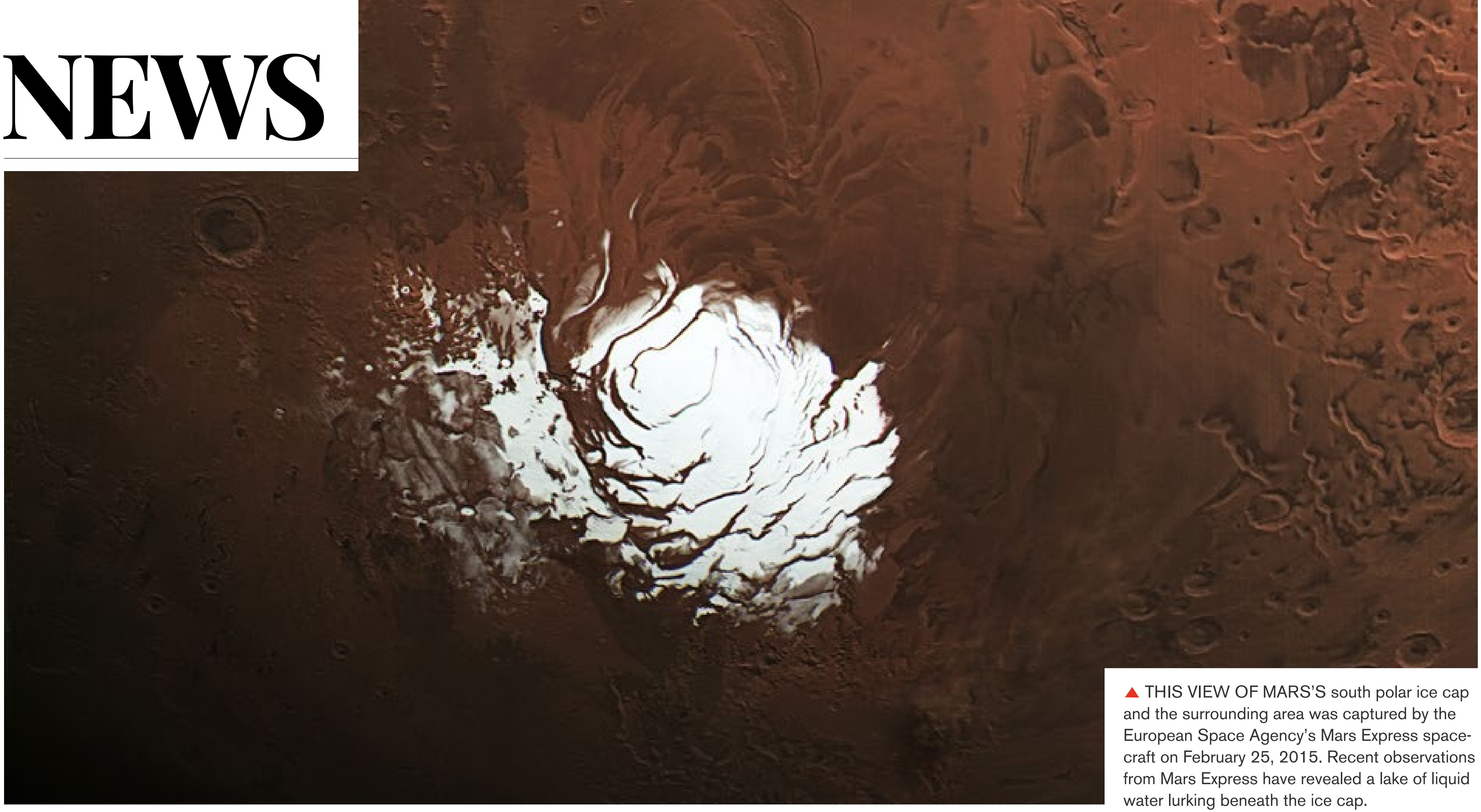


▲ THIS VIEW OF MARS'S south polar ice cap and the surrounding area was captured by the European Space Agency's Mars Express spacecraft on February 25, 2015. Recent observations from Mars Express have revealed a lake of liquid water lurking beneath the ice cap.

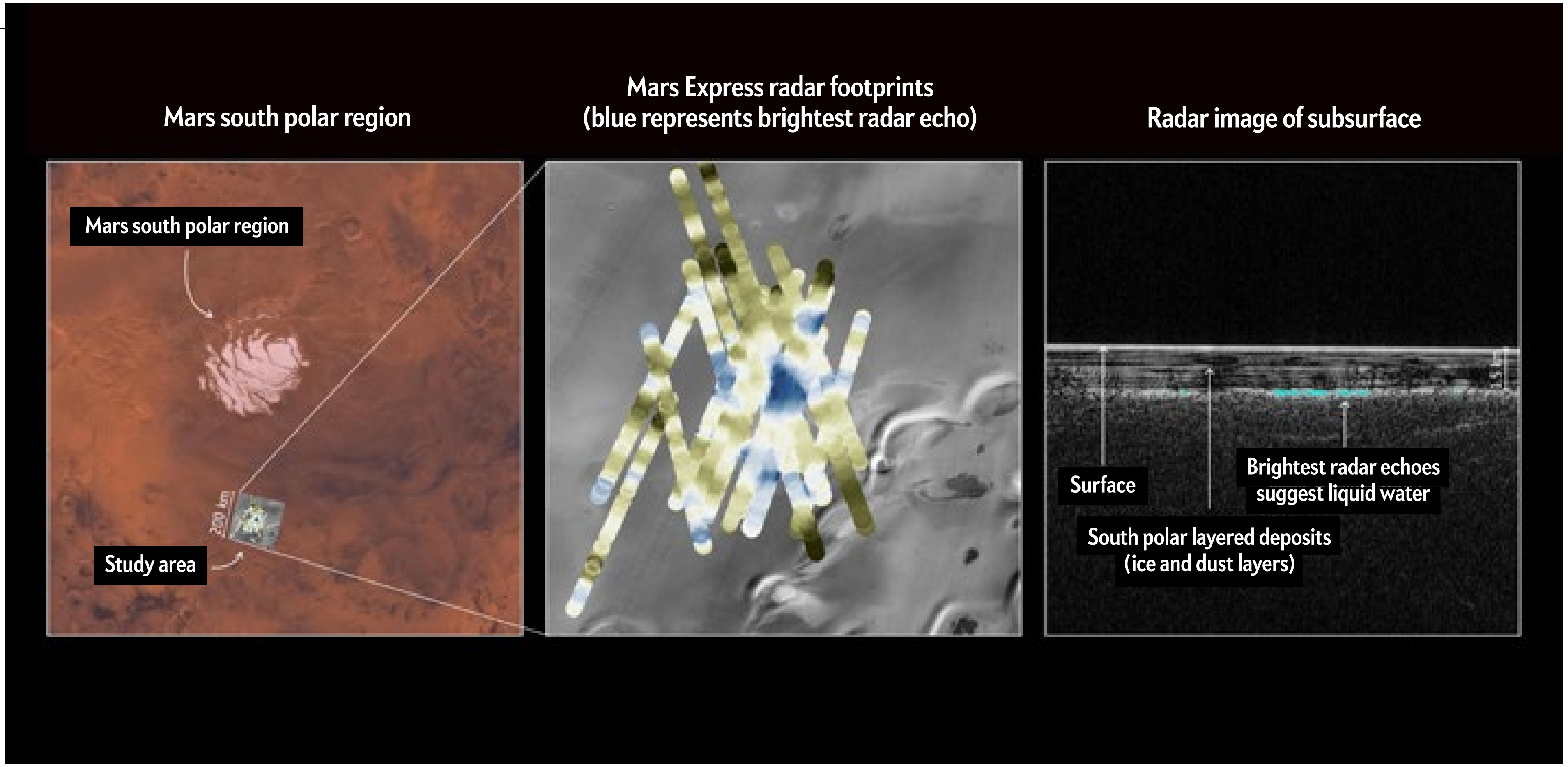
ESA, DLR AND FU BERLIN

Deep within Mars, Liquid Water Offers Hope for Life

Radar observations have revealed what appears be a buried lake on Mars, the first-ever stable reservoir of liquid water found on the Red Planet

Located at the edge of a more than three-billion-year-old ice cap covering Mars's south pole, the region known as Planum Australe would rank high on any list of the Red Planet's least interesting locales. Frozen, flat and featureless, it seemingly offers little more than windblown dust and drifts of crystallized carbon dioxide for any aspiring explorer to see. Unless, that is, one could somehow peer deep beneath its frigid surface to the base of the ice cap some 1.5 kilometers below, where a lake of liquid water nearly three times larger than the island of Manhattan may lurk.

Discovered by a team of Italian scientists using three years' worth of data from the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on the European Space Agency's Mars Express orbiter, the potential lake is at least a few meters deep, and might be a fixed, steady feature of the subsurface. If confirmed, this



▲ Radar studies of Mars's Planum Australe (*left panel*) have revealed evidence of a lake (*large blue spot in central panel*) buried beneath 1.5 kilometers of ice and dirt (*right panel*).

CONTEXT MAP: NASA AND VIKING; THEMIS BACKGROUND: NASA, JPL-CALTECH AND ARIZONA STATE UNIVERSITY; MARSIS DATA: ESA, NASA, JPL, ASI AND UNIV. ROME; R. OROSEI ET AL 2018

would be the first known reservoir of liquid water on present-day Mars—a keystone in the search for past or even present life on the Red Planet, potentially offering fresh clues about how Earth's neighbor so profoundly transformed billions of years ago from a warmer, wetter world to its current freeze-dried state. Announced at a press conference in Rome, the results are detailed in a study appearing in the July 26 edition of *Science*. Although this is just one detection, the team wrote, "there is no reason to conclude that the presence of subsurface water on Mars is limited to a single location."

"The presence of a body of liquid water beneath Mars's south polar cap has various implications, opening new possibilities for the existence of microorganisms in the Martian environment," says Sebastian Lauro, a study co-author based at Roma Tre University in Rome. "Moreover, it provides a valuable confirmation that the water that once flowed abundantly over the Martian surface in the form of seas, lakes and rivers filled the voids in the subsurface."

For the past 12 years MARSIS has mapped the Martian underground using beams of low-frequency radar pulses, which can penetrate up to several kilometers beneath the surface. Although they pass relatively unscathed through most substances, these pulses reflect back up to the spacecraft each time they encounter boundaries between different materials, such as the interface of ice and bedrock. That reflection is particularly strong at interfaces with liquid water, and shows up as a distinctively bright spot in visualizations of the data.

Following up on preliminary detections of bright spots beneath Mars's southern ice cap dating back to 2007, the Italian team reprogrammed MARSIS to employ a more intensive scanning mode, then surveyed Planum Australe 29 times with the instrument between 2012 and 2015. Time and time again across the entire observing campaign the new MARSIS readings revealed a consistent 20-kilometer-wide bright spot nestled in a bowl-like depression beneath the ice cap in Planum Australe—a feature consistent with a sizable body of liquid water (or, to be fair, with water-saturated sediments more akin to subterranean sludge). The team then spent almost a year analyzing the data, and another two years writing their paper and attempting to rule out nonaqueous explanations for what they had seen.

Billions of years ago, Mars was a much more Earth-like place where water pooled in seas, carved enormous canyons and bubbled from hot springs. Life, many astrobiologists speculate, may have had no difficulty getting started there. But early in its promising existence the planet somehow lost its way, transforming into a desiccated orb of dried-up ocean-, river- and lakebeds. Robotic missions to the planet's surface still find surprising echoes of that bygone time, such as patches of water-ice frost forming on rocks as well as water droplets condensing like dew on a lander's leg. Orbiters, too, have glimpsed what might be rivulets of water flowing down sun-bathed crater walls at the height of Martian summer. Perhaps life, too, has managed to endure in some diminished, limited way. But if so, it would have to contend with a world in which all moisture quickly vanishes in the thin, cold air, leaving the surface dry as a bone. Still, the water that once flowed across the land had to go somewhere. Some of it was likely lost to space, due to Mars's diminutive gravitational field, but a significant fraction of the planet's aqueous inventory never really left, instead just freezing below ground. Now it appears not all of that buried watery wealth is frozen after all.

"The really exciting thing is that this is a stable body of liquid water that was observed in the radar data over three years, not just droplets that have been observed over a short period of time," says Anja Diez, a glaciologist at the Norwegian Polar Institute who wrote an accompanying commentary about the discovery. The subsurface lake, Diez says, may be similar those found via radar sounding on Earth beneath ice sheets in Antarctica and Greenland.

Whether below an Earthly glacier or a Martian ice cap, the mechanism for melting is much the same: heat trickling up from below combines with the immense bulk of an insulating blanket of material pressing down from above to form lakes of meltwater. On Earth those lakes are often connected by channels, forming branching riverlike networks of water that extend across vast spaces beneath the ice. In the late 1980s, Steve Clifford, a researcher now at the Planetary Science Institute, began exploring how similar hydrological activity could occur under both Mars's southern and northern polar caps and whether it might feed meltwater into worldwide aquifers he hypothesized should exist beneath the planet's permafrost. Clifford's models suggest huge amounts of liquid water could still be hidden in the planet's depths, providing a globe-spanning refuge for any life that retreated from the ever more inhospitable surface long ago.

"This finding is potentially of enormous significance," says Clifford, who was not involved with the study. "Based on analogy with Earth, if water still exists in the subsurface, there is no reason to believe that life which arose on Mars and evolved for underground conditions could not persist there into the present day…. If you do have liquid water as shallow as 1.5 kilometers beneath the surface [at Planum Australe], then liquid water is also likely to be present at greater depths here. And if you have conditions for life in one area of the planet that is in hydraulic continuity with other areas where liquid water also exists, you could have a very substantial subsurface biosphere that has survived since the planet's early history."

That life, however, would have to contend with another key factor making its aquatic environs possible: mineral salts that leach out of rocks and sediments to act as antifreeze. Suffusing the meltwater, the salts would create brines that remain liquid far below the typical freezing point of pure water. Such salts are known to exist in abundance in some Martian rocks, and are the most likely cause of the dewlike droplets and crater-wall rivulets previously observed on the planet's surface. But Clifford holds out hope subsurface geothermal hotspots like those that power volcanoes and hot springs on Earth could sufficiently heat portions of the Martian underworld to allow liquid reservoirs to exist there without the need for life-sabotaging salt levels. Such a hot spot could, in fact, be responsible for the MARSIS team's newfound lake.

These conjectures must, for now, remain untested. The MARSIS instrument lacks sufficient sensitivity and resolution to clearly determine the thickness of this deposit or whether it is in fact connected to other similar bodies, although studies using more advanced radar instruments on an as yet unbuilt next generation of orbiters could clarify such details. For that matter, the detection itself is as yet uncorroborated: another radar-sounding instrument called SHARAD (for shallow radar) onboard NASA's Mars Reconnaissance Orbiter has also repeatedly scanned Planum Australe and other regions in search of buried water, but its beams cannot penetrate as deeply, and it has not replicated MARSIS's detection. Even so, according to Bruce Campbell, a SHARAD team member and senior scientist at the Smithsonian Institution, "it is possible that a targeted effort [by SHARAD] to collect data on more tracks across this region could build up enough echo strength to detect the reflector seen by MARSIS."

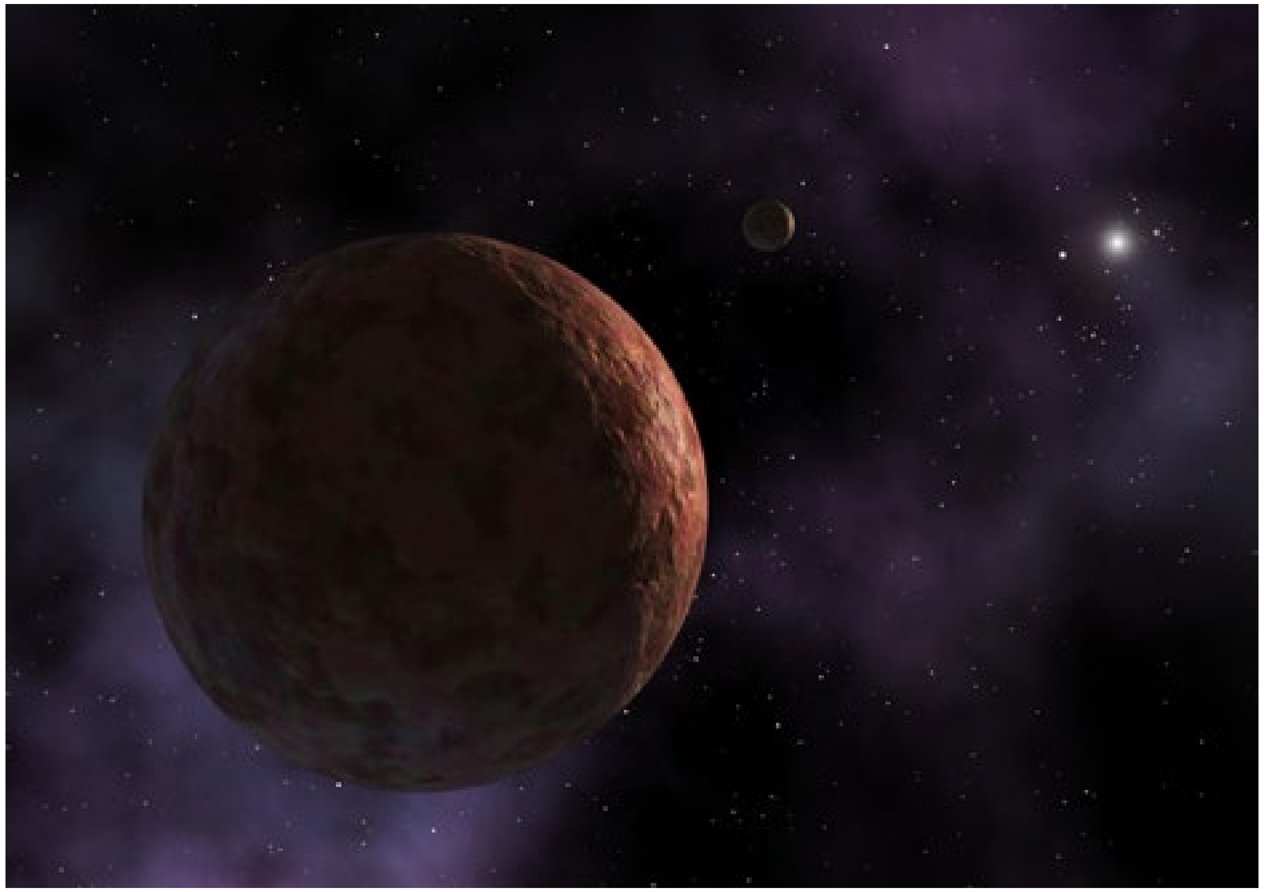
Ultimately, "ground truth" may be required to solve the mystery of just how much water is locked away in Mars's underworld. But there are at present no public or private plans to build or launch missions, robotic or human, that would be capable of drilling or melting down to the depths probably required to directly sample meltwater anywhere on the planet—which, Clifford says, might be for the best.

"The possibility that life could currently exist somewhere beneath the polar ice reinforces the point that we must take care that our investigations do not needlessly contaminate Mars," he says. "That could not only make the result of any life-detection experiment ambiguous but could also contaminate a habitat that may be interconnected on a global basis, leading to a very serious impact on any native biosphere. I worry that unless we are very careful, we could end up responsible for the extinction of the very first life we ever detect on another planet."

—Lee Billings

Did a Stellar Intruder Deform Our Outer Solar System?

New results suggest a massive star once swung dangerously close to our sun—helping to shape the mysterious features we see today



▲The odd orbit of the dwarf planet Sedna (*shown here in an artist's conceptualization*) and other outer solar system objects suggests a visiting star may have swerved too close to the sun long ago.

NASA AND JPL-CALTECH

There is a mystery brewing in the far reaches of our solar system.

Astronomers have long thought the eight planets orbit in nearly perfect circles because they once formed within the swirling disk of dust and gas that surrounded the young sun. But in 2003 scientists discovered something strange: a dwarf planet known as Sedna whose elongated orbit takes it from twice Pluto's distance to more than 20 times its distance from the sun. And it is not alone. In the years since, astronomers have uncovered nearly two dozen distant icy objects whose orbits are oblong and strangely tilted compared to the plane of the solar system. To explain such oddities, scientists speculated that maybe these worlds are scars from a violent past, a sign something—perhaps a passing star—knocked them off course in our solar system's infancy. Or maybe there is a distant ninth planet whose gravity sculpts their peculiar orbits.

The latter hypothesis has gained traction over the past several years, leaving the first in the dust, says Susanne Pfalzner, an astronomer at the Max Planck Institute for Radio

Astronomy in Germany. Anomalies in the orbits of some small outer solar system objects have amassed evidence for a "Planet Nine" roughly 10 times Earth's mass. Meanwhile a stellar interloper has been considered too unlikely—until now. Pfalzner and her colleagues recently published a paper to the preprint server arXiv that has been accepted by *The Astrophysical Journal* showing stars might buzz our solar system far more often than previously thought. Not only do the results lend credibility to a stellar flyby, but they just might also explain how the elusive Planet Nine would have landed in its odd orbit in the first place.

Astronomers know the sun has not always been so solitary. It was born within a cluster of hundreds to perhaps tens of thousands of stars that dispersed only 10 million years later. So while the sun was still entombed within that cluster, stars would have rocked to and fro in a dizzying dance that easily could have brought one waltzing into our nascent solar system. But after the cluster broke apart the likelihood of such an encounter dropped nearly to zero, or so the thinking went. Pfalzner and her colleagues now argue the odds of an encounter remained quite high after the cluster had started to disperse. After many long computer simulations they found there is a 20 to 30 percent chance a star perhaps as massive as the sun would swing nearly as close as Pluto at 50 to 150 astronomical units. (One AU is the mean distance from Earth to the sun, or 93 million miles.) And there is no doubt such a close approach would shake our young solar system.

Although the large planets would remain unbothered (much as the sun is only slightly jostled by the minor gravities of the eight planets), the encounter would perturb the solar system's smaller objects—tossing them around and placing them in odd orbits in the distant reaches of the solar system. What is more, the simulations also re-created a second trend astronomers have observed in the solar system: that outer objects tend to cluster together in space. They travel together in tight-knit groups that all cross the plane of the solar system at roughly the same spot before swinging outward to the same distant point. In short, simulations including a stellar interloper can perfectly re-create the observations to date. "But whether they'll last for 4.5 billion years," or over the solar system's entire life span, "is the million-dollar question," says Scott Kenyon, an astronomer at Harvard-Smithsonian Center for Astrophysics who was not involved in the research. And Pfalzner agrees. She would like to model the long-term behavior next to see whether those changes will hold over the solar system's entire lifetime. It could be that a flyby clusters objects for a cosmic moment before they randomize again. If that is the case, then a planet is the best explanation for the observations.

Scientists are eagerly tracking down more data with a number of different observing campaigns. A handful of teams, for example, are already scouring large chunks of the heavens in search of more oddities in the outer solar system. Scott Sheppard, an astronomer at the Carnegie Institution for Science who was not involved in the study, cannot contain his excitement over the upcoming Large Synoptic Survey Telescope—an 8.4-meter-wide scope that will likely uncover hundreds of new solar system rocks. "That's really going to open up the floodgates for trying to discover these distant objects," he says.

Meanwhile Kenyon is hopeful the Gaia spacecraft, which is in the process of charting one billion stars to unprecedented accuracy, will help find our sun's long-lost siblings. That will allow scientists to better understand the stellar cluster in which our young solar system formed, along with the likelihood another star zoomed too close. "Gaia is the new savior on the block," he says. A recent Gaia study even traced the paths of nearby stars into the past and projected those paths into the future, only to find that 25 stars speed dangerously close to home over a 10-million-year time period. That tally is seven times as much nearby stellar traffic as previously thought. Then, of course, there are a number of surveys searching for the elusive Planet Nine itself.

But Pfalzner argues the discovery of another major member of the solar system will not rule out a stellar flyby. "It's not an either-or scenario," she says. "If Planet Nine exists, this would not be in any way a contradiction to the flyby model, but possibly even a point in favor for it." Her team argues Planet Nine's predicted orbit, which is also both eccentric (stretched out) and inclined (tilted from the solar system's plane), was likely shaped by the stellar interloper itself. So she and others will continue to hunt for both Planet Nine and further oddities.

And although astronomers might disagree over the specifics of our solar system's origin story, they are all certain the treasure trove of objects already discovered in the outer solar system is only the beginning. Sedna was the tip of the iceberg, Sheppard says. "There's just so much sky we haven't covered to date that it's more likely than not there's something pretty big out there."

–Shannon Hall

Neutrinos on Ice: Astronomers' Long Hunt for Source of Extragalactic "Ghost Particles" Pays Off

Along with gravitational waves, the find adds more options for "multimessenger" astronomy, which does not solely rely on light to gather data

▲ In this artistic composition, based on a real image of the IceCube Lab at the South Pole, a distant source emits neutrinos that are detected below the ice by IceCube sensors, called DOMs.

ICECUBE, NSF

Ever since the 1950s, when physicists first dreamed up the idea of doing astronomy with neutrinos, the holy grail has been to observe the first object outside our solar system that emits these ghostly particles. A handful were collected from a nearby supernova in 1987, but that was a rare event and the instruments that made the detection were hardly telescopes; they could not discern much more than up from down or left from right.

Three papers released in July (two in *Science* and one on the preprint server arXiv) announced the culmination of this 60-year quest. IceCube, a strange telescope made of deep glacial ice at the South Pole, has detected neutrinos from a distant, luminous galaxy.

The neutrino is nearly massless and flies through space at almost the speed of light. Its nickname, "ghost particle," points to the fact it rarely interacts with any form of matter and is therefore devilishly difficult to detect. Like the photon (particle of light), the neutrino carries no electric charge, so it is not diverted by electromagnetic fields: its arrival direction will point directly back to its source. Unlike the photon, however, it can pass through planets, stars, galaxies, veils of interstellar dust as easily as a bullet passes through fog and can therefore bring us news from regions that are opaque to light, at the edge of the universe and from the earliest times.

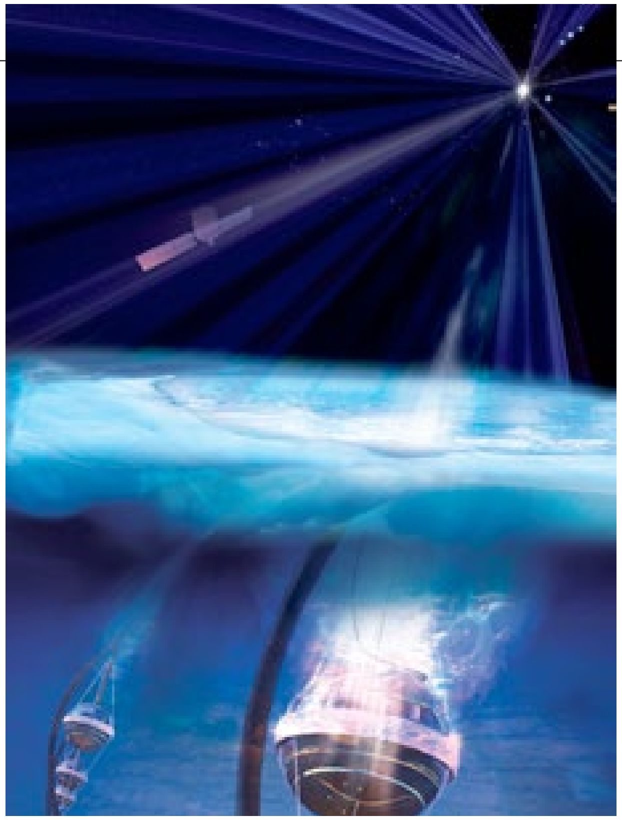
The latest discovery represents only the second time—after the near-miraculous supernova—scientists have identified neutrinos and light coming from the same extragalactic object. It also provides a clue to the long-standing mystery of how the charged particles known as cosmic rays, which constantly bombard our planet from space, are accelerated to the highest energies that have ever been observed. "It's incredibly exciting and what we were always hoping for from the neutrino detectors," says Alan Watson, a cosmic ray physicist from the University of Leeds in England who was not involved in these studies.

Observatory in the Ice

IceCube can tell the direction of some neutrinos to better than a quarter of a degree. It consists of a billion tons of diamond-clear Antarctic ice about two kilometers deep, monitored by more than 5,000 light detectors. In 2013 it detected the first high-energy neutrinos coming from beyond our atmosphere. But that breakthrough was not entirely satisfying because those neutrinos had rained in uniformly across the sky: there was no indication of the specific objects that may have emitted them—no "point source."

This past September IceCube detected a neutrino carrying about 20 times the energy of any particle that could possibly be created by the most powerful man-made accelerators. This meant it had probably come from outer space. The instrument broadcast an automated alert.

IceCube's alerts generate a lot of interest among astronomers, because the neutrino represents the third arrow in the quiver of the newborn field of multimessenger astronomy. Astrophysicists have long dreamed of employing messengers besides light to reveal the inner workings of the many unfathomable wonders in the cosmos. And the dream had come true only one month earlier, when three gravitational-wave observatories had detected the merger of two neutron stars and optical telescopes had tied that merger to a gamma-ray burst: a brief flash of the most energetic form of light. No neutrinos were seen, however.



◀ NASA's Fermi (*top left*) has achieved a new first—identifying a monster black hole in a far-off galaxy as the source of a high-energy neutrino seen by the IceCube Neutrino Observatory (*sensor strings, bottom*).

NASA, FERMI AND AURORE SIMONNET AND SONOMA STATE UNIVERSITY

A Blazar Seen in Texas

Several days after IceCube's alert, astronomer Yasuyuki Tanaka, who works at Kanata ("faraway" in Japanese), an optical/near-infrared telescope operated by Hiroshima University, realized the neutrino was pointing within two tenths of a degree of a known blazar named TXS 0506+056, which had first been observed by a radio telescope in Texas four decades ago.

Blazars are among the most violent creatures in the astronomical zoo: giant elliptical galaxies with rapidly spinning, supermassive black holes at their cores that gobble up nearby stars and other material in a sort of continuous cosmic earthquake and send out laserlike jets of light and other particles from their north and south poles. What differentiates blazars from other galaxies with such so-called active nuclei is that one of the jets points in Earth's direction, making these objects extremely bright. Blazars occasionally flare, brightening by factors of 10 or more for periods of minutes to years. Because they are so cataclysmic and give off very energetic gamma rays, they have long been suspected of emitting not only high-energy neutrinos but also mysterious ultrahigh-energy cosmic rays.

Tanaka also works on the Fermi Gamma-ray Space Telescope, which has been taking images of the entire gamma-ray sky every three hours for about 10 years. Searching its catalogues, he discovered TXS had been flaring since the previous April. He sent out a second alert encouraging "observations of this source" across the optical spectrum.

TXS had not distinguished itself among the 4,000 or so known blazars until that moment, so little was known about it—even how far away it was. In the excitement after Tanaka's alert the astronomical community made up for lost time. One group determined TXS is about 4.5 billion light-years away. That makes it one of the most luminous objects in the cosmos.

Six days after Tanaka's alert, the operators of MAGIC, the Major Atmospheric Gamma Imaging Cherenkov telescope on the La Palma Canary Island, announced the observation of very high-energy gammas coming from TXS. Because MAGIC sees to higher energies and has finer angular resolution than Fermi, this finding strengthened the connection to the neutrino—but not quite enough. In the first of the recent papers IceCube and the 15 collaborations that followed up on its alert conclude there is about one chance in a thousand the coincidence in direction and time between the single neutrino and the flaring blazer was just that, a coincidence. In this business, you need one chance in three million to claim discovery.

But IceCube's principal investigator, Francis Halzen, a physicist at the University of Wisconsin–Madison, points out there is more to the science of this matter than statistics. He quotes the great experimentalist Ernest Rutherford: "If your experiment needs a statistician, you need a better experiment," and adds, "We did that."

Looking Back in Time

IceCube's point source group, led by astrophysicist Chad Finley of Stockholm University, looked through the experiment's historical data and discovered IceCube had detected a spectacular "neutrino flare" from TXS—about 13 particles in all—during a four-month period starting in October 2014. Perplexingly, however, Fermi had observed no corresponding flare in gamma rays.

Another IceCubist, Elisa Resconi, an astrophysicist at the Technical University of Munich, gathered a small team to investigate more closely. Synthesizing all the observations that had ever been made of TXS, they discovered it actually had flared in gammas in 2014, but in a subtle way. Although it had not given off more gamma-ray energy altogether, its spectrum had shifted toward higher-energy gammas exactly when it had flared in neutrinos. And the shapes of the optical and neutrino spectra shifted in complementary ways during both flares. It all holds together," Watson says. "I believe the whole story, but it took all three papers to convince me. This is the first convincing direct evidence for the acceleration of a hadronic component [a particle made of quarks] in any source."

Basic particle physics says these neutrinos can only have been produced by hadrons, which would primarily have been protons, emerging in the blazar jet and colliding with other particles, including photons, on their way out. Because the cosmic rays that bombard Earth are made up predominantly of protons and heavier nuclei, the simple fact a blazar has now been shown to produce high-energy neutrinos is the first solid clue to a possible source of ultrahigh-energy cosmic rays. The reason it is difficult to identify the sources of cosmic rays is that they carry electric charge, so their trajectories are bent by interstellar magnetic fields and their arrival directions do not point back to their origins. Because the neutrinos IceCube detected must have traveled in straight lines and must have been produced by hadrons, they indicate high-energy hadrons must have been emitted from the same blazar source.

The various models for neutrino emission from blazars, developed in blissful theoretical isolation, have now had their first encounter with real data, and none can explain the exact details seen. Theorist Eli Waxman of the Weizmann Institute of Science in Israel believes the models "will require a complete modification."

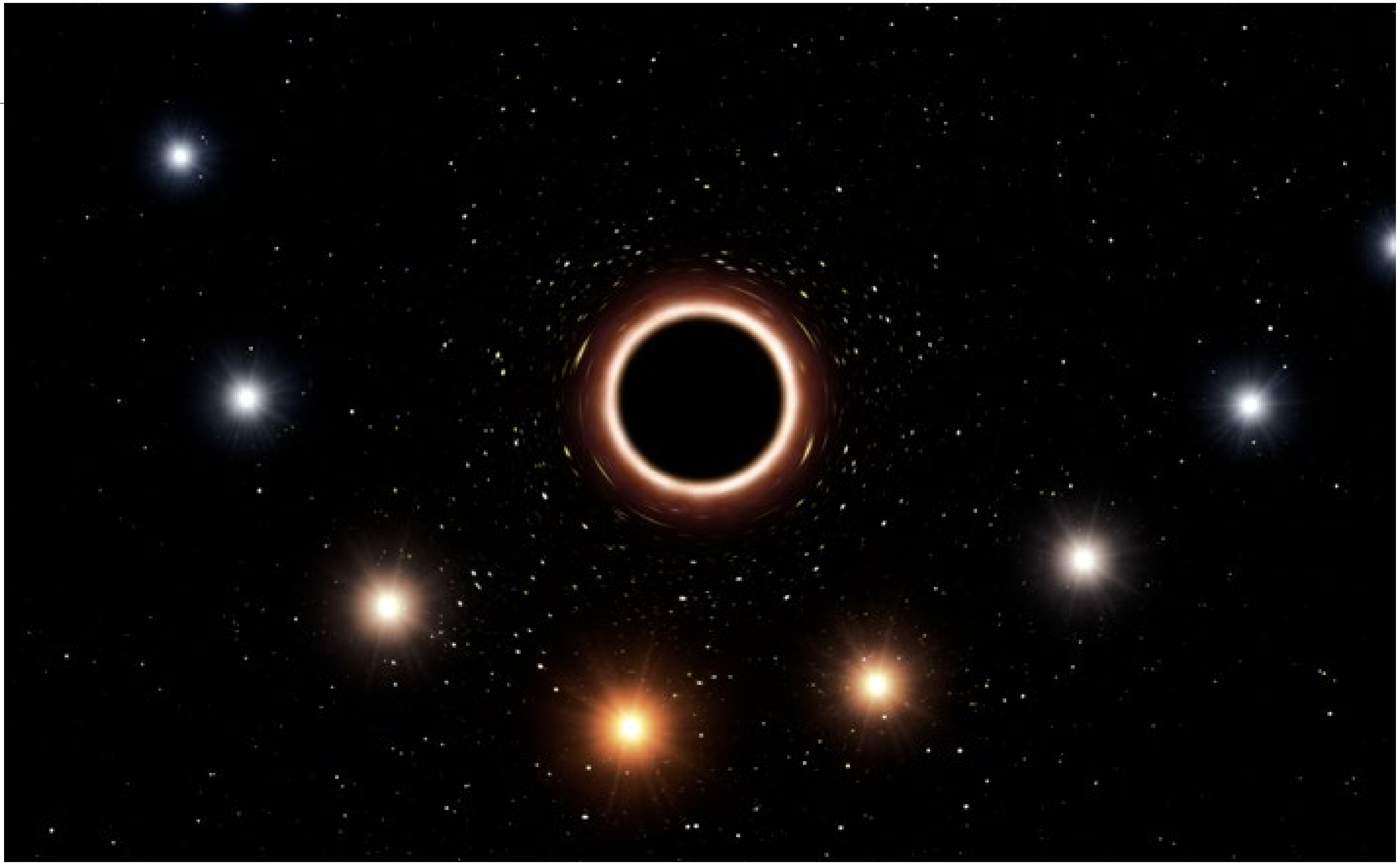
This discovery also gives a shot in the arm to the nascent field of neutrino astronomy. Both Waxman and Watson now hunger for next-generation instruments. The IceCube collaboration has proposed an upgrade that stands to improve sensitivity by an order of magnitude, and similar instruments are planned for deployment in the Mediterranean Sea and Lake Baikal, Siberia.

Meanwhile, this remarkable telescope continues to watch the neutrino sky from its deep, icy abode. IceCube almost certainly has more surprises in store.

—Mark Bowen

Milky Way's Black Hole Provides Long-Sought Test of Einstein's General Relativity

An observation decades in the making confirms predictions about how light behaves in an immense gravitational field



▲ This artist's impression shows the orbit of the star S2 as it passes close to the supermassive black hole at the center of the Milky Way. The black hole's powerful gravitational field causes the star's color to shift slightly to the red in precise concordance with predictions of Einstein's theory of general relativity.

ESO/M. KORNMESSER

Astronomers have caught the giant black hole at our galaxy's center stretching the light emitted by an orbiting star—nearly three decades after they first starting tracking the star. The long-sought phenomenon, known as gravitational redshift, was predicted by Einstein's general theory of relativity, but until now it had never been spotted in the environs of a black hole.

"It's another big step in getting closer to understanding the black hole," says Heino Falcke, an astronomer at Radboud University in Nijmegen, the Netherlands, who was not involved in the research. "This is just amazing, to be able to see these effects."

A team led by Reinhard Genzel of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, announced the discovery in July at a press conference and reported the results in *Astronomy & Astrophysics*. The group includes scientists from universities and research institutions in Germany, France, Portugal, Switzerland, the Netherlands, the United States and Ireland.

Genzel and his colleagues have tracked the journey of this star, known as S2, since the early 1990s. Using telescopes at the European Southern Observatory in Chile, the scientists watch it as it travels in an elliptical orbit around the black hole, which lies 26,000 light-years from Earth in the constellation Sagittarius. With a mass of 4 million times the sun, the black hole generates the strongest gravitational field in the Milky Way. That makes it an ideal place to hunt for relativistic effects.

On May 18 this year, S2 passed as close as it ever does to the black hole. The researchers pointed instruments including GRAVITY, an instrument called an interferometer that combines light from four 8-meter telescopes and became operational in 2016. "With our measurements the door is wide open to black-hole physics," says team member Frank Eisenhauer, an astronomer at the Max Planck institute.

GRAVITY measured S2's movement across the sky; at its fastest, the star whizzed along at more than 7,600 kilometers a second, or nearly 3 percent the speed of light. Meanwhile, a different instrument studied how fast S2 moved towards and away from Earth as it swung past the black hole. Combining the observations allowed Genzel's team to detect the star's gravitational redshift—its light being stretched to longer wavelengths by the black hole's immense gravitational pull, which is consistent with the predictions of general relativity.

"What we measured cannot be described by Newton any more," says Odele Straub, an astrophysicist at the Paris Observatory. Future observations of S2 might confirm other Einstein predictions, such as how the spinning black hole drags spacetime around with it.

"Their data look beautiful," says Andrea Ghez, an astronomer at the University of California, Los Angeles, who leads a competing team that uses the Keck telescopes in Hawaii to measure the star's path around the galactic center.

It takes 16 years for S2 to make a complete orbit around the black hole, so both groups have been eagerly awaiting this year's close passage. But Ghez says that her team plans to wait until later in the year to publish their results.

In April, S2 experienced its maximum velocity in the line of sight from Earth. In May, it made that closest approach to the galactic center. And in late August and early September, it experienced the minimum velocity in the line of sight from Earth. "It's taken us 20 years to get to this moment," Ghez says. "We're going to wait until the end of the passage, until the star will be done with whatever it's going to do."

S2 has already begun slowing down, in the direction of travel as seen from Earth, as it transitions towards the third event. And both the U.S. and European teams are watching it closely. "We're in the thick of it," says Ghez. "It's super-exciting."

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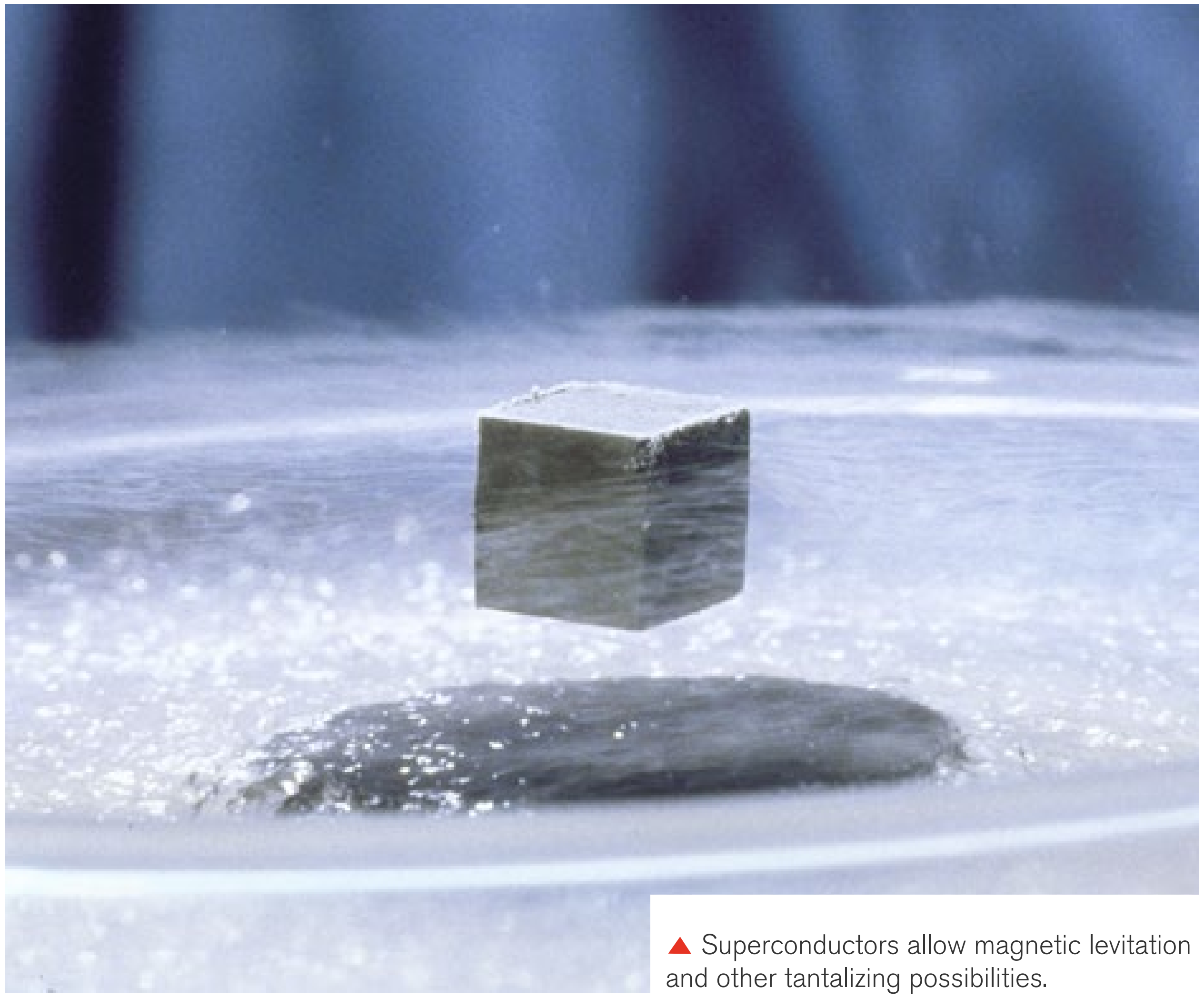
—Alexandra Witze

A Superconductor Scandal? Scientists Question a Nobel Prize–Worthy Claim

Scientists claim to have achieved superconductivity at room temperature, but other physicists say the data looks doctored

The discovery would change the world. From power grids that never lose energy to magnetically levitating trains, finding a material that is superconductive at room temperature would bring a range of fantastical technologies to life. And it is not as far-fetched as it sounds. Although superconductors—materials that can transmit electricity with



▲ Superconductors allow magnetic levitation and other tantalizing possibilities.

BILL PIERCE GETTY IMAGES

zero resistance—exist only at extremely frigid temperatures today, there is no physical reason why they cannot also work at room temperature. It could simply be that no one has stumbled upon the magical formula yet. That might be about to change. In a study posted to the arXiv in late July, Dev Kumar Thapa and Anshu Pandey, two scientists from the Indian Institute of Science, suggest a concoction of gold and silver nanoparticles achieves the Nobel Prize–worthy goal. The finding, from a reputable team, was initially met with both excitement and skepticism as physicists cautiously took a closer look. But the story has since prompted disbelief and even a little drama.

Despite physicists' hope, those in the field know that numerous previous claims of warm superconductors have all fizzled out. Many initially worried that Thapa and Pandey's find would turn out to be one more erroneous report—dubbed a USO, or unidentified superconducting object. But that natural skepticism transformed into suspicion when Brian Skinner, a physicist at MIT, found something unnerving. In one of the paper's figures, which shows how well the superconductor repels different magnetic fields at various temperatures, he noticed that the data for two different values of the magnetic field have the exact same pattern of noise, albeit slightly offset from each other. Every time one pattern veers up or down, the other follows—perfectly in sync. But noise is random by definition. It should not repeat itself on separate trials done under different magnetic fields.

That correlation is alarming alone. But it also echoed one of the biggest scandals in modern physics. In the early 2000s, scientists discovered that prominent physicist Jan Hendrik Schön, who also worked on superconductors among other topics, had falsified data from several experiments. It was a move that eventually stripped him of his doctoral degree and led to the retraction of several papers. And, yes, the discovery was sparked when scientists noticed that the noise pattern within one of his published graphs looked eerily similar to the noise pattern within another.

It is a story that scientists know extremely well. "It's sort of like a bedtime fable," Skinner says, told to teach students to be scrupulously honest. And it made Skinner hesitant to publish his finding. He knew that the repeated noise pattern would bring Schön to the forefront of everyone's minds—making his claim sound like an accusation against Thapa and Pandey. Skinner deliberated for more than a week, pulling other scientists aside—from technicians to senior experimentalists—to ask whether this could be an honest mistake. Although that is still possible, everyone agreed that the noise patterns had no obvious explanation. Skinner knew he had an obligation to go public. So, in a short note published to the arXiv, he pointed out the repeated noise pattern and asked for an explanation, without suggesting the data were fraudulent. And Peter Armitage, a physicist from Johns Hopkins University, agrees it was the correct move. "I think that's a really important observation and he's done a true service to the field by not only pointing it out—but having the nerve to do so publicly," he says.

> **"I think that's a really important observation and he's done a true service to the field by not only pointing it out—but having the nerve to do so publicly."**
>
> *—Peter Armitage*

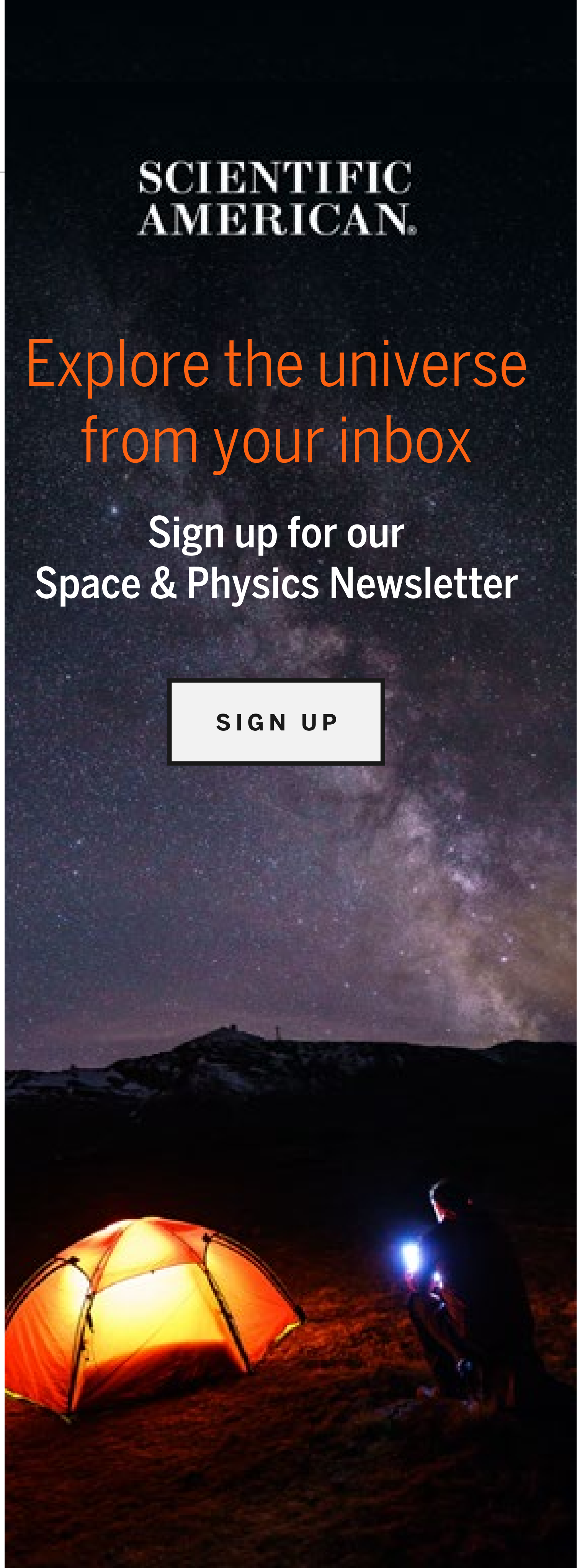
Despite Skinner's careful attempt to not accuse the team, his finding caused quite the debate. "When I looked at Skinner's paper and I saw the curve, I thought 'game over,'" says David Muller, a physicist at Cornell University. "It's not hard evidence … but I know which way I would take a bet." The original paper's authors have not addressed the noise correlation and say they are waiting for outside validation of their results. Pratap Raychaudhuri, a physicist at the Tata Institute of Fundamental Research in India, set out to find the most plausible explanation for the correlation. After much thought, he argues that the noise is not noise at all but a signal that arises from the natural rotation of particles within a magnetic field. The signal simply looks random and therefore masquerades as noise. What is more, this pattern can repeat itself after independent runs—thus explaining why the two curves match. Although Raychaudhuri admits that he does not fully believe his rationalization, he says it can be easily tested at any professional lab—should the authors send their samples along.

The issue is that Thapa and Pandey have done no such thing. “This kind of silence from the authors is not a healthy practice,” Raychaudhuri says. “It is against the spirit of science.” And while Pandey insists that his results are being validated by independent experts, that brings no comfort to Raychaudhuri, who worries the checks cannot truly be independent. “Getting this validated by your friend, by your next-door colleague and so on, is not independent validation,” he says. He and others in the field would like the team to send their superconducting material to outside labs that can test the results.

In the meantime, the story has taken a wild turn: in August, Raychaudhuri received an e-mail that appeared to come from T.V. Ramakrishnan, a physicist at the Indian Institute of Science, asking him not to criticize the authors on social media. (Raychaudhuri had posted his findings to Facebook.) But Ramakrishnan never sent such an e-mail. It did not take long before the two realized that a fake e-mail address had been set up in Ramakrishnan’s name. “The purpose of the e-mail seems to be to stir up discord between him and me,” Ramakrishnan says. The odd events do not end there. The same name attached to the encrypted e-mail address is also attached to a Facebook profile that attempted to befriend both Skinner and Raychaudhuri shortly after the e-mail scandal. The profile has zero friends and the timeline reads: "Remember: Julius Caesar went too far!"

Both the e-mail address and the Facebook profile have been deleted. Some suspect that it was the work of a disgruntled student, but Raychaudhuri thinks it is far too early to venture a guess. At the moment, he is surprisingly thankful that so much scientific discourse has happened over social media. Not only did Raychaudhuri post several Facebook posts last week, but Skinner also posted a Twitter thread—events that brought the scientific process into the public sphere. “This is a very good thing, because it connects people,” Raychaudhuri says. “The research community is normally very esoteric and detached from society at large.” He is even optimistic that no matter what happens—whether Thapa and Pandey’s results hold up or their work turns out to be incorrect—that the events will help the public understand this is how the scientific method works to verify (or reject) claims in order to slowly inch forward.

—Shannon Hall



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String Theory May Create Far Fewer Universes Than Thought

SOME PHYSICISTS CLAIM THE POPULAR LANDSCAPE OF UNIVERSES IN STRING THEORY MAY NOT EXIST

By Clara Moskowitz

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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.

THE PROBLEM WITH STRING THEORY, ACCORDING to some physicists, is that it makes too many universes. It predicts not one but some 10^{500} versions of spacetime, each with its own laws of physics. But with so many universes on the table, how can the theory explain why ours has the features it does?

Now some theorists suggest most—if not all—of those universes are actually forbidden, at least if we want them to have stable dark energy, the supposed force accelerating the expansion of the cosmos. To some, eliminating so many possible universes is not a drawback but a major step forward for string theory, offering new hope of making testable predictions. But others say the multiverse is here to stay, and the proposed problem with all those universes is not a problem at all.

The debate was a hot topic at the end of June in Japan, where string theorists convened for the conference Strings 2018. "This is really something new and it's led to a controversy within the field," says Ulf Danielsson, a physicist at Uppsala University in Sweden. The conversation centers on a pair of papers posted on the preprint server arXiv in June taking aim at the so-called "landscape" of string theory—the incomprehensible number of potential universes that result from the many different solutions to string theory's equations that produce the ingredients of our own cosmos, including dark energy. But the vast majority of the solutions found so far are mathematically inconsistent, the papers contend, putting them not in the landscape but in the so-called "swampland" of universes that cannot actually exist. Scientists have known many solutions must fall in this swampland for years, but the idea that most, or maybe all, of the landscape solutions might live there would be a major change. In fact, it may be theoretically impossible to find a valid solution to string theory that includes stable dark energy, says Cumrun Vafa, a Harvard University physicist who led the work on the two papers.

LOST IN THE MULTIVERSE

String theory is an attempt to describe the whole universe under a single "theory of everything" by adding extra dimensions of spacetime and thinking of particles as minuscule vibrating loops. Many string theorists contend it is still the most promising direction for pursuing Albert Einstein's dream of uniting his general theory of relativity with the conflicting microscopic world of quantum mechanics. Yet the notion of a string theory landscape that predicts not just one universe but many has put some physicists off. "If it's really the landscape, in my view it's death for the theory because it loses all predictive value," says Princeton University physicist Paul Steinhardt, who collaborated on one of the recent papers. "Literally anything is possible." To Steinhardt and others, the newfound problems with dark energy offer string theory a way out. "This picture with a big multiverse could be mathematically wrong," Danielsson says. "Paradoxically this makes things much more interesting because that means string theory is much more predictive than we thought it was."

Some string theorists such as Savdeep Sethi of the University of Chicago welcome the reevaluation that is happening now. "I think this is exciting," he says. "I've been a skeptic of the landscape for a long time. I'm really happy to see the paradigm shift away from this belief that we have this proven set of solutions." But not everyone buys the argument that the landscape actually belongs in the swampland—especially the research team that established one of the earliest versions of the landscape in the first place back in 2003, which goes by the acronym KKLT after the scientists' last names. "I think it's very healthy to make these conjectures and check what other things could be going on but I don't see either theoretical or experimental reasons to take such a conjecture very seriously," says KKLT member Shamit Kachru of Stanford University. And Eva Silverstein, a Stanford physicist who also helped build the early landscape models, likewise doubts Vafa and his colleagues' argument. "I think the ingredients KKLT use and the way they put them together is perfectly valid," she says. Juan Maldacena, a theorist at the Institute for Advanced Study, says he also still supports the idea of string theory universes with stable dark energy.

And many theorists are perfectly happy with the string theory multiverse. "It is true that if this landscape picture is correct, the bit of the universe we're in compared to the multiverse will be like our solar system within the universe," Kachru says. And that is a good thing, he adds. Johannes Kepler originally sought a fundamental reason for why Earth lies the distance it does from the sun. But now we know the sun is just one of billions of stars in the galaxy, each with its own planets, and the Earth-sun distance is simply a random number rather than a result of some deep mathematical principle. Likewise, if the universe is one of trillions within the multiverse, the particular parameters of our cosmos are similarly random. The fact these numbers seem perfectly fine-tuned to create a habitable universe is a selection effect—humans will of course find themselves in one of the rare corners of the multiverse where it is possible for them to have evolved.

THE ACCELERATING UNIVERSE

If it is true string theory cannot accommodate stable dark energy, that may be a reason to doubt string theory. But to Vafa it is a reason to doubt dark energy—that is, dark energy in its most popular form, called a cosmological constant. The idea originated in 1917 with Einstein and was revived in 1998 when astronomers discovered that not only is spacetime expanding—the rate of that expansion is picking up. The cosmological constant would be a form of energy in the vacuum of space that never changes and counteracts the inward pull of gravity. But it is not the only possible explanation for the accelerating universe. An alternative is "quintessence," a field pervading spacetime that can evolve. "Regardless of whether one can realize a stable dark energy in string theory or not, it turns out that the idea of having dark energy changing over time is actually more natural in string theory," Vafa says. "If this is the case, then one can measure this sliding of dark energy by astrophysical observations currently taking place."

So far all astrophysical evidence supports the cosmological constant idea, but there is some wiggle room in the measurements. Upcoming experiments such as Europe's Euclid space telescope, NASA's Wide-Field Infrared Survey Telescope (WFIRST) and the Simons Observatory being built in Chile's desert will look for signs dark energy was stronger or weaker in the past than the present. "The interesting thing is that we're already at a sensitivity level to begin to put pressure on [the cosmological constant theory]," Steinhardt says. "We don't have to wait for new technology to be in the game. We're in the game now." And even skeptics of Vafa's proposal support the idea of considering alternatives to the cosmological constant. "I actually agree that [a changing dark energy field] is a simplifying method for constructing accelerated expansion," Silverstein says. "But I don't think there's any justification for making observational predictions about the dark energy at this point."

> **"We don't have to wait for new technology to be in the game. We're in the game now."**
>
> *—Paul Steinhardt*

Quintessence is not the only other option. In the wake of Vafa's papers, Danielsson and colleagues proposed another way of fitting dark energy into string theory. In their vision our universe is the three-dimensional surface of a bubble expanding within a larger-dimensional space. "The physics within this surface can mimic the physics of a cosmological constant," Danielsson says. "This is a different way of realizing dark energy compared to what we've been thinking so far."

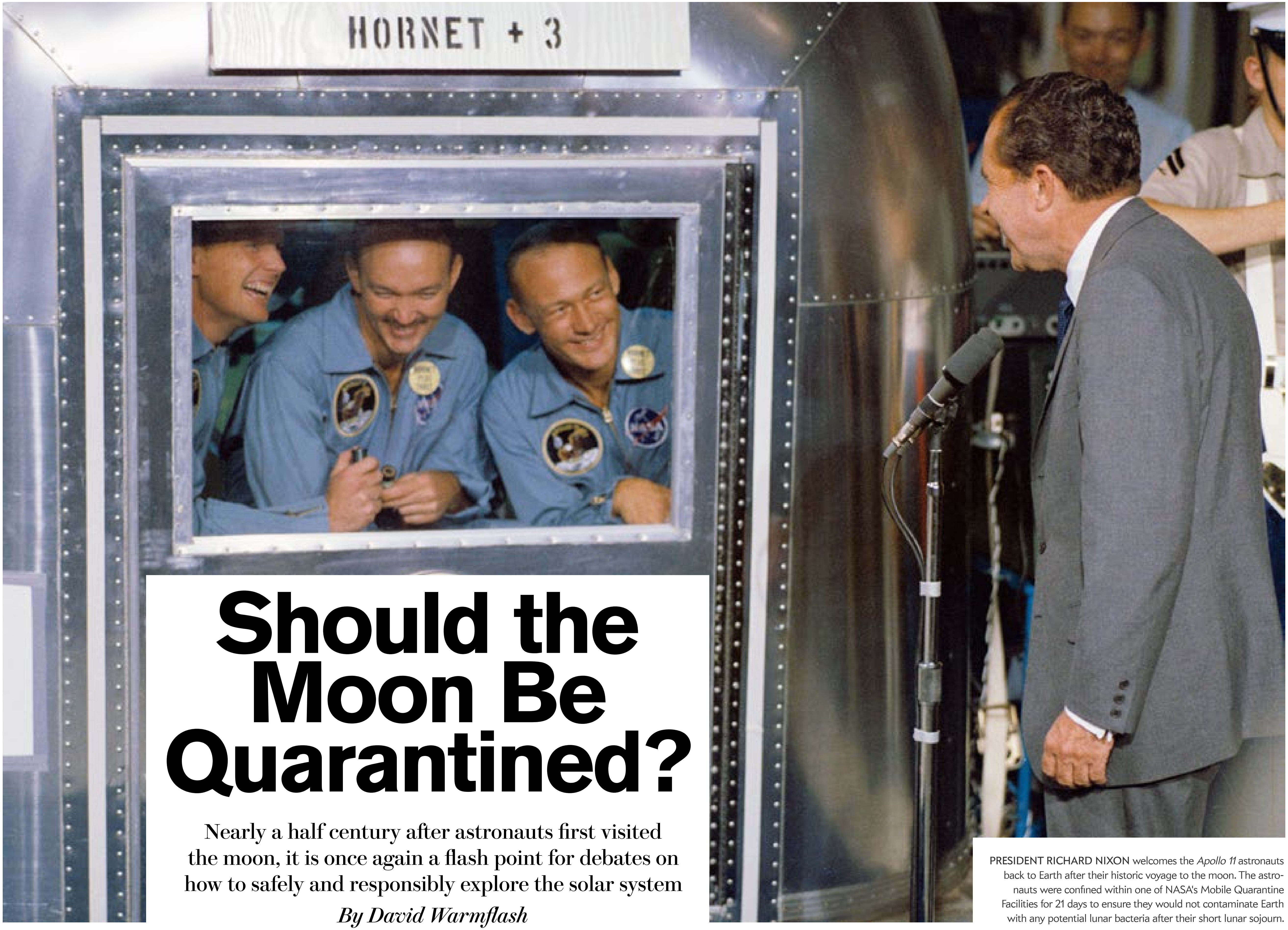
A BEAUTIFUL THEORY

Ultimately the debate going on in string theory centers on a deep question: What is the point of physics? Should a good theory be able to explain the particular characteristics of the universe around us or is that asking too much? And when a theory conflicts with the way we think our universe works, do we abandon the theory or the things we think we know?

String theory is incredibly appealing to many scientists because it is "beautiful"—its equations are satisfying and its proposed explanations elegant. But so far it lacks any experimental evidence supporting it—and even worse, any reasonable prospects for gathering such evidence. Yet even the suggestion string theory may not be able to accommodate the kind of dark energy we see in the cosmos around us does not dissuade some. "String theory is so rich and beautiful and so correct in almost all the things that it's taught us that it's hard to believe that the mistake is in string theory and not in us," Sethi says. But perhaps chasing after beauty is not a good way to find the right theory of the universe. "Mathematics is full of amazing and beautiful things, and most of them do not describe the world," physicist Sabine Hossenfelder of the Frankfurt Institute for Advanced Studies wrote in her recent book, *Lost in Math: How Beauty Leads Physics Astray* (Basic Books, 2018).

Despite the divergence of opinions, physicists are a friendly bunch and are united by their common goal of understanding the universe. Kachru, one of the founders of the landscape idea, worked with Vafa, the landscape's critic, as his undergraduate advisor—and the two are still friends. "He asked me once if I'd bet my life these [landscape solutions] exist," Kachru says. "My answer was I wouldn't bet my life but I'd bet his!"

—Additional reporting by Lee Billings



NASA

Should the Moon Be Quarantined?

Nearly a half century after astronauts first visited the moon, it is once again a flash point for debates on how to safely and responsibly explore the solar system

By David Warmflash

PRESIDENT RICHARD NIXON welcomes the *Apollo 11* astronauts back to Earth after their historic voyage to the moon. The astronauts were confined within one of NASA's Mobile Quarantine Facilities for 21 days to ensure they would not contaminate Earth with any potential lunar bacteria after their short lunar sojourn.

David Warmflash, M.D., is an astrobiologist, science writer, physician, and citizen of the cosmos.

THE MOON AND THE WORD "ASTROBIOLOGY" DON'T OFTEN appear in the same sentence—even with a handful of government space agencies and private corporations planning crewed forays to the lunar surface for the first time since NASA's *Apollo 17* mission in 1972. That final *Apollo* lunar landing took place after it became clear the moon was lifeless—a shift from the initial landings, which subjected their crews to quarantine after returning to Earth. Those early precautions, now called "planetary protection," were meant to prevent back contamination—the potentially catastrophic introduction of extraterrestrial organisms to Earth's biosphere. But by the end of the *Apollo* program, moon-walking astronauts were only quarantined prior to leaving Earth, simply to ensure they were not incubating an infectious disease that could manifest during their high-risk missions.

Keeping Earth's germs from journeying to the moon proved to be a tall order, however. At least one bacterial species, *Streptococcus mitis*, found its way inside the *Surveyor 3* camera that had spent some 2.5 years on the moon before the astronauts of *Apollo 12* retrieved and returned it to Earth. Experts now believe Surveyor 3's *S. mitis* came from post-return contamination by human investigators, rather than surviving lunar conditions. Even so, subsequent research has conclusively shown certain terrestrial organisms—*Deinococcus radiodurans* and *Bacillus subtilis* bacteria as well as tiny invertebrates called tardigrades—can indeed survive extended exposure to the harsh conditions of space. Both then and now forward contamination—the transfer of Earthly lifeforms to other worlds—is the most vexing challenge of planetary protection.

Forward contamination is a familiar concern for mission planners seeking to preserve the environments of Mars and ocean-bearing icy moons of the outer solar system (such as Saturn's Enceladus and Jupiter's Europa) so astrobiologists can identify native life there—should it exist. But how should planetary protection's prohibitions and restrictions apply to the moon, and what lessons from the *Apollo* era might be applicable in the coming years as we aim to go back?

"Biological precautions during *Apollo* were concerned only with preventing back contamination from putative lunar organisms," says Andy Spry, a senior scientist at the SETI Institute and a planetary protection consultant for NASA. Even before the first *Apollo* landings the possibility of lunar life was still considered remote. But precautions against back contamination were still put in place, given that unlikely scenario's potentially catastrophic consequences. Astronauts and lunar samples—plus a recovery engineer and flight surgeon who met returning crews—were all quarantined for 21 days after *Apollo*s *11, 12* and *14*. (*Apollo 13* failed to land on the moon, so quarantine was not necessary.) Beginning with *Apollo 15*, however, there were no post-mission quarantines because analysis of lunar samples brought back by *Apollos 11* and *12* indicated the moon was lifeless.

Beginning in the 1980s the Committee on Space Research (COSPAR) began beefing up protocols aimed at preventing forward contamination to better protect off-Earth environments. Those guidelines have evolved over time as scientific knowledge has increased—for both good and ill. Although today we know more than ever before about the potentials for life on other worlds, the lack of actual alien organisms to study means our burgeoning knowledge tends to raise more questions than it answers. Unlike during the *Apollo* era, today the question of whether or not a celestial body requires any protection at all is no longer a simple matter of yes or no.

"There are five COSPAR planetary protection categories," Spry says, "category I being that no precautions are needed to protect a target body. The 'requirement' is merely to demonstrate that your mission does not require any particular protection precautions." Since

2008 the moon has been considered category II, meaning that although it is not a target in the search for life, exploration there merits a modicum of caution. This is because the satellite's largely untrammeled surface offers unique clues about the history of our solar system—and perhaps the origins and evolution of life on Earth.

The quarantines and other planetary protection safeguards of *Apollo*s *11, 12* and *14* had a few things in common with today's category V, which applies to missions in which equipment or samples are returned to Earth from a potentially habitable (or maybe even inhabited!) world such as Mars, Europa or Enceladus. In such cases one goal is to prevent back contamination; another is to keep returned samples pristine, just like during the *Apollo* lunar landing missions. Of course, category V missions also must prevent forward contamination—a goal that was not given priority during *Apollo*.

One proposed solution for handling modern category V scenarios would be to return equipment and samples not to Earth but rather to purpose-built labs on the moon or in orbit. There, the reasoning goes, the diverted material could be analyzed without the risk of contaminating Earth. But such approaches would be very expensive, and off-Earth facilities would lack the big, heavy instruments currently needed to maximize the scientific payback from sample-return missions. And that is not the only problem.

Moving people, equipment and material freely throughout the Earth-moon system without high-category planetary protection requirements should be a priority, Spry says: "We don't want to revive the old quarantine protocol from *Apollo* exactly, but returning samples and astronauts to an isolation facility located on Earth is a reasonable approach." The logistical details of such an Earth-based receiving plan still need to be worked out, but Spry envisions a containment facility with what is called "biosafety level 4 capability" (the highest safety level for working with dangerous, disease-causing organisms on Earth, such as smallpox or Ebola viruses). Such a facility would also require added measures to keep any samples pristine, just as most *Apollo* samples were.

Another way to look at the problem of protecting the moon is that our lifeless lunar neighbor could best be treated as a kind of test bed for missions to more astrobiologically delicate locales—namely Mars. "As we continue to develop and refine planetary protection requirements for Mars exploration, lunar exploration provides an opportunity to assess those requirements before applying them in a microbially sensitive environment," says Julie Mitchell, curator of ices and organics in the Astromaterials Research and Exploration Science Division at NASA's Johnson Space Center (JSC). For example, she adds, an outpost on the moon could yield new insights about how a space habitat's microbiome can change over time, and could lead to better methods for preventing dust and other contaminants from intruding into a facility from the alien world outside.

The lifeless and sterile moon could also offer an ideal proving ground for "synthetic biology" experiments before they could be unleashed elsewhere in the solar system. The term refers to sophisticated genetic modifications of terrestrial organisms such as the deliberate engineering of photosynthetic algae known as cyanobacteria to purify a habitat's air or even to produce rocket fuel. "Human space exploration is not possible without the application of cyanobacteria," says Igor Brown, a microbiologist who researched lunar applications of synthetic biology with the late astrobiology pioneer David McKay at JSC.

Could such a visionary synthetic biology–enhanced program of human interplanetary exploration throughout the solar system ever mesh with the strict tenets of planetary protection? The answer, if it is to be found at all, will likely emerge when, how and if we return to the moon.

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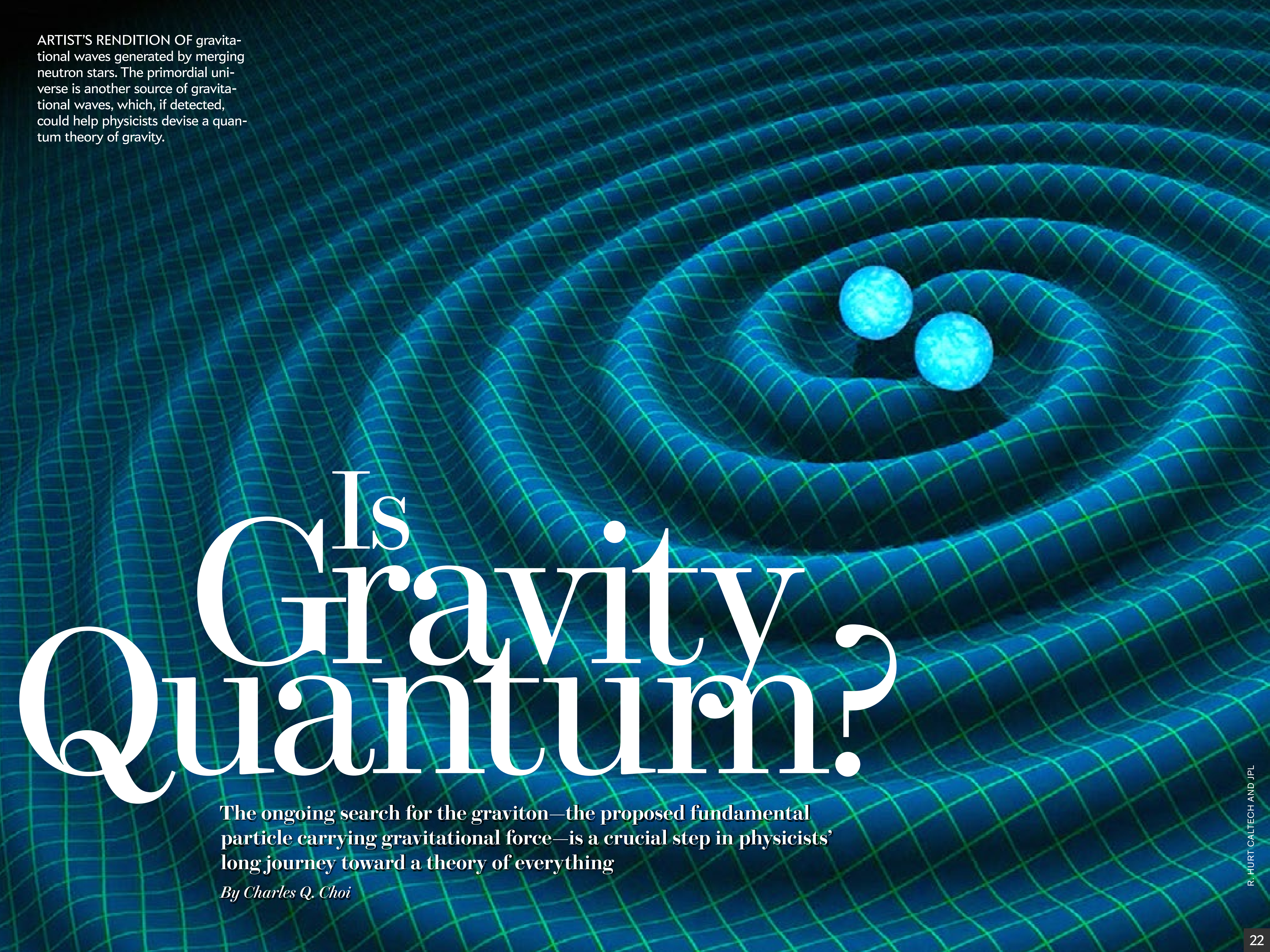

ARTIST'S RENDITION OF gravitational waves generated by merging neutron stars. The primordial universe is another source of gravitational waves, which, if detected, could help physicists devise a quantum theory of gravity.

R. HURT CALTECH AND JPL

Is Gravity Quantum?

The ongoing search for the graviton—the proposed fundamental particle carrying gravitational force—is a crucial step in physicists' long journey toward a theory of everything

By Charles Q. Choi

Charles Q. Choi is a frequent contributor to *Scientific American*. His work has also appeared in *The New York Times*, *Science*, *Nature*, *Wired*, and *LiveScience*, among others. In his spare time, he has traveled to all seven continents.

ALL THE FUNDAMENTAL FORCES OF THE UNIVERSE ARE KNOWN TO FOLLOW THE LAWS OF QUANTUM mechanics, save one: gravity. Finding a way to fit gravity into quantum mechanics would bring scientists a giant leap closer to a “theory of everything” that could entirely explain the workings of the cosmos from first principles. A crucial first step in this quest to know whether gravity is quantum is to detect the long-postulated elementary particle of gravity, the graviton. In search of the graviton, physicists are now turning to experiments involving microscopic superconductors, free-falling crystals and the afterglow of the big bang.

Quantum mechanics suggests everything is made of quanta, or packets of energy, that can behave like both a particle and a wave—for instance, quanta of light are called photons. Detecting gravitons, the hypothetical quanta of gravity, would prove gravity is quantum. The problem is that gravity is extraordinarily weak. To directly observe the minuscule effects a graviton would have on matter, physicist Freeman Dyson famously noted, a graviton detector would have to be so massive that it collapses on itself to form a black hole.

“One of the issues with theories of quantum gravity is that their predictions are usually nearly impossible to experimentally test,” says quantum physicist Richard Norte of Delft University of Technology in the Netherlands. “This is the main reason why there exist so many competing theories and why we haven’t been successful in understanding how it actually works.”

In 2015, however, theoretical physicist James Quach, now at the University of Adelaide in Australia, suggested a way to detect gravitons by taking advantage of their quantum nature. Quantum mechanics suggests the universe is inherently fuzzy—for instance, one can never absolutely know a particle's position and momentum at the same time. One consequence of this uncertainty is that a vacuum is never completely empty, but instead buzzes with a “quantum foam” of so-called virtual particles that constantly pop in and out of existence. These ghostly entities may be any kind of quanta, including gravitons.

Decades ago, scientists found that virtual particles can generate detectable forces. For example, the Casimir effect is the attraction or repulsion seen between two mirrors placed close together in vacuum. These reflective surfaces move due to the force generated by virtual photons winking in and out of existence. Previous research suggested that superconductors might reflect gravitons more strongly than normal matter, so Quach calculated that looking for interactions between two thin superconducting sheets in vacuum could reveal a gravitational Casimir effect. The resulting force could be roughly 10 times stronger than that expected from the standard virtual-photon-based Casimir effect.

Recently, Norte and his colleagues developed a microchip to perform this experiment. This chip held two microscopic aluminum-coated plates that were cooled almost to absolute zero so that they became superconducting. One plate was attached to a movable mirror, and a laser was fired at that mirror. If the plates moved because of a gravitational Casimir effect, the frequency of light reflecting off the mirror would measurably shift. As detailed online July 20 in *Physical Review Letters*, the scientists failed to see any gravitational Casimir effect. This null result does not necessarily rule out the existence of gravitons—and thus gravity’s quantum nature. Rather, it may simply mean that gravitons do not interact with superconductors as strongly as prior work estimated, says quantum physicist and Nobel laureate Frank Wilczek of the Massachusetts Institute of Technology, who did not participate in this study and was unsurprised by its null results. Even so, Quach says, this “was a courageous attempt to detect gravitons.”

Although Norte’s microchip did not discover whether gravity is quantum, other scientists are pursuing a variety of approaches to find gravitational quantum effects. For example, in 2017 two independent studies suggested that if gravity is quantum it could generate a link known as “entanglement” between particles, so that one particle instantaneously influences another no matter where either is located in the cosmos. A tabletop experiment using laser beams and microscopic diamonds might help search for such gravity-based entanglement. The crystals would be kept in a vacuum to avoid collisions with atoms, so they would interact with one another through gravity alone. Scientists would let these diamonds fall at the same time, and if gravity is quantum the gravitational pull each crystal exerts on the other could entangle them together.

> **“Experimentalists all over the world are curious to take the challenge up.”**
> ***—Anupam Mazumdar***

The researchers would seek out entanglement by shining lasers into each diamond’s heart after the drop. If particles in the crystals’ centers spin one way, they would fluoresce, but they would not if they spin the other way. If the spins in both crystals are in sync more often than chance would predict, this would suggest entanglement. “Experimentalists all over the world are curious to take the challenge up,” says quantum gravity researcher Anupam Mazumdar of the University of Groningen in the Netherlands, co-author of one of the entanglement studies.

Another strategy to find evidence for quantum gravity is to look at the cosmic microwave background radiation, the faint afterglow of the big bang, says cosmologist Alan Guth of M.I.T. Quanta such as gravitons fluctuate like waves, and the shortest wavelengths would have the most intense fluctuations. When the cosmos expanded staggeringly in size within a sliver of a second after the big bang, according to Guth’s widely supported cosmological model known as inflation, these short wavelengths would have stretched to longer scales across the universe. This evidence of quantum gravity could be visible as swirls in the polarization, or alignment, of photons from the cosmic microwave background radiation.

However, the intensity of these patterns of swirls, known as B-modes, depends very much on the exact energy and timing of inflation. “Some versions of inflation predict that these B-modes should be found soon, while other versions predict that the B-modes are so weak that there will never be any hope of detecting them,” Guth says. “But if they are found, and the properties match the expectations from inflation, it would be very strong evidence that gravity is quantized.”

One more way to find out whether gravity is quantum is to look directly for quantum fluctuations in gravitational waves, which are thought to be made up of gravitons that were generated shortly after the big bang. The Laser Interferometer Gravitational-Wave Observatory (LIGO) first detected gravitational waves in 2016, but it is not sensitive enough to detect the fluctuating gravitational waves in the early universe that inflation stretched to cosmic scales, Guth says. A gravitational-wave observatory in space, such as the Laser Interferometer Space Antenna (LISA), could potentially detect these waves, Wilczek adds.

In a paper recently accepted by the journal *Classical and Quantum Gravity*, however, astrophysicist Richard Lieu of the University of Alabama, Huntsville, argues that LIGO should already have detected gravitons if they carry as much energy as some current models of particle physics suggest. It might be that the graviton just packs less energy than expected, but Lieu suggests it might also mean the graviton does not exist. “If the graviton does not exist at all, it will be good news to most physicists, since we have been having such a horrid time in developing a theory of quantum gravity,” Lieu says.

Still, devising theories that eliminate the graviton may be no easier than devising theories that keep it. “From a theoretical point of view, it is very hard to imagine how gravity could avoid being quantized,” Guth says. “I am not aware of any sensible theory of how classical gravity could interact with quantum matter, and I can't imagine how such a theory might work.”

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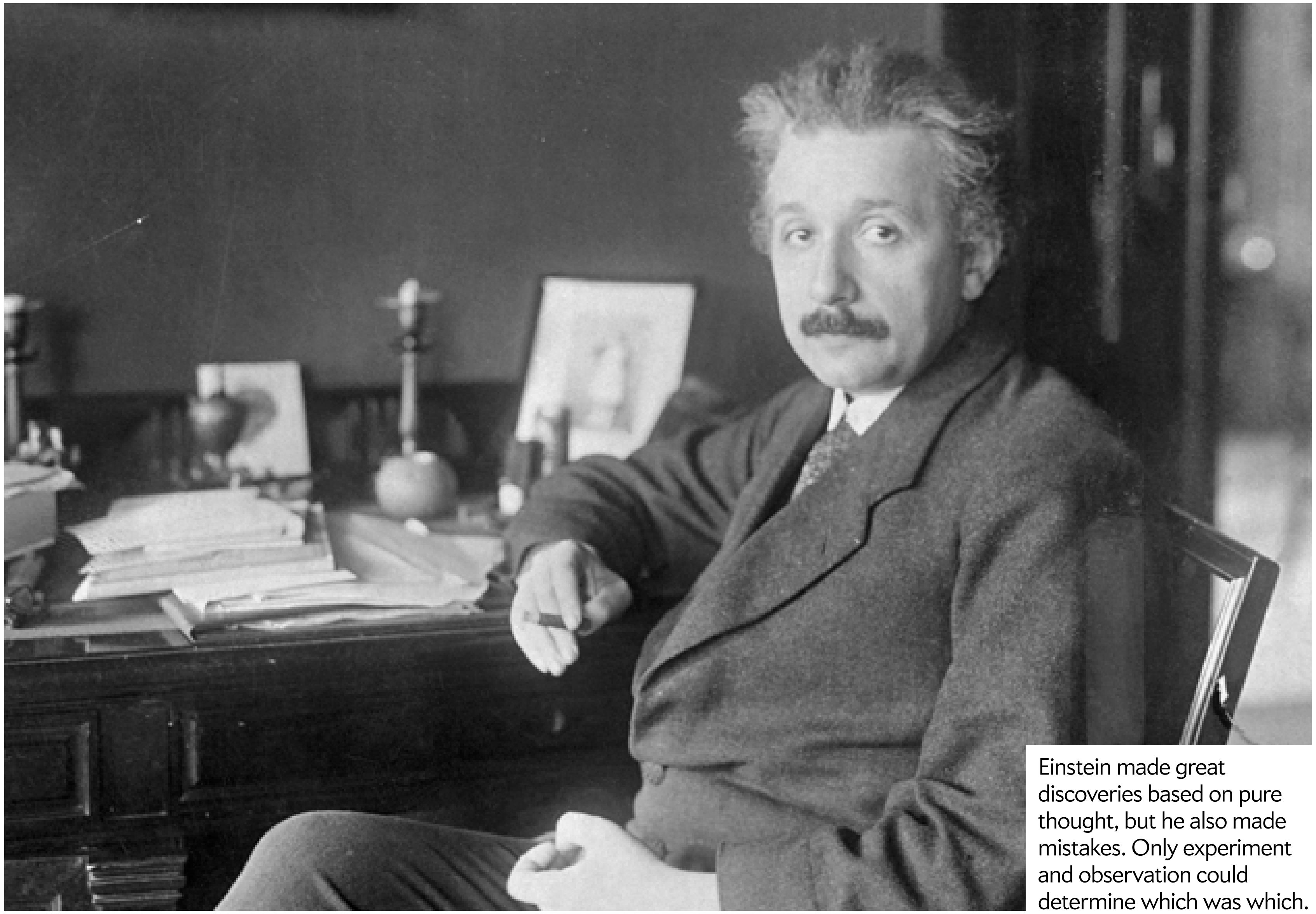
Abraham Loeb is chair of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the advisory board for the Breakthrough Starshot project.

PHYSICS

Theoretical Physics Is Pointless without Experimental Tests

Our discipline is a dialogue with nature, not a monologue, as some theorists would prefer to believe



Einstein made great discoveries based on pure thought, but he also made mistakes. Only experiment and observation could determine which was which.

GETTY IMAGES

A NEW DEBATE has recently emerged as to whether string theory admits even a single rigorous solution that includes a cosmological constant, as we find observationally in the real universe. The debate follows on a period of several decades during which the mathematical richness of the theory has been advanced considerably but with very limited connection to experimental testing. This experience inspired a new culture of doing theoretical physics without the need for experimental verification.

Given our academic reward system of grades, promotions and prizes, we sometimes forget that physics is a learning experience about nature rather than an arena for demonstrating our intellectual power. As students of experience, we should be allowed to make mistakes and correct our prejudices.

Albert Einstein is admired for pioneering the use of thought experiments as a tool for unraveling the truth about the physical reality. But we should keep in mind that he was wrong about the fundamental nature of quantum mechanics as well as the existence of gravitational waves and black holes—which he dismissed late in his career, and which were both confirmed observationally by LIGO in 2015, exactly a century after he formulated the general theory of relativity.

Given this humbling historical lesson, theoretical physicists should be careful of premature hubris in celebrating conjectures and accept the final verdict of experimental guillotines in setting the fate of untested speculations.

The feedback from experimental data is essential. At its foundation, physics is a dialogue with nature, not a monologue as some theorists would prefer to believe. On my daily route to work, I am often reminded of the need for empirical verification by the sight of the beautiful house purchased by Charles Ponzi in 1920, just months before his arrest for the fraudulent investment operations now commonly associated with his last name.

Ponzi made his fortune by promising investors guaranteed revenues, a desirable theoretical scheme that was socially acceptable until it was brought to an experimental test by the investors asking to cash out their funds. Their shock at the time signified the need for testing theoretical schemes before giving them the stamp of approval as descriptions of reality.

Similar to the way physicians are obliged to take the Hippocratic Oath, physicists should take a “Galilean Oath” in which they agree to gauge the value of theoretical conjectures in physics based on how well they are tested by experiments within their lifetime.

The risk for physics stems primarily from mathematically beautiful “truths,” such as string theory, accepted prematurely for decades as a description of reality just because of their elegance. This is a judgment often guided by a social trend within physics to feed off mathematical sophistication and prestige. It is widely accepted today that the study of extra dimensions is part of the mainstream in theoretical physics even though there is no evidence for any extra dimension beyond the 3+1 we witness in our daily life.

Many of the same scientists who consider the study of extra dimensions as mainstream regard the search for extraterrestrial intelligence (SETI) as speculative. This mindset fails to recognize that SETI merely involves searching elsewhere for something we already know exists on Earth, and the knowledge that a quarter of all stars host a potentially habitable Earth-size planet around them. This search should be considered well within the boundaries of mainstream research, whereas the conjecture of extra dimensions should be regarded as highly speculative.

The experience of subjecting a theoretical conjecture to an experimental test is humbling. If the conjecture turns out to be wrong, it must be adjusted. Becoming a physicist brings with it the privilege of retaining your childhood curiosity throughout your adult life. There is no need to pretend you know more than you actually do, and you can admit mistakes if proven wrong by experience, just like a child who is seeking to learn about the world. Doing pure theory without worrying about experimental verification actually deprives you from the pleasure of learning something new about nature.

Identifying the boundaries of our knowledge is more exciting than taking pride in past knowledge. And only our contact with reality itself through experimentation can direct our notions into new realms. No one, not even Einstein, would have imagined quantum mechanics without the experimental data that led us to this unexpected notion of reality.

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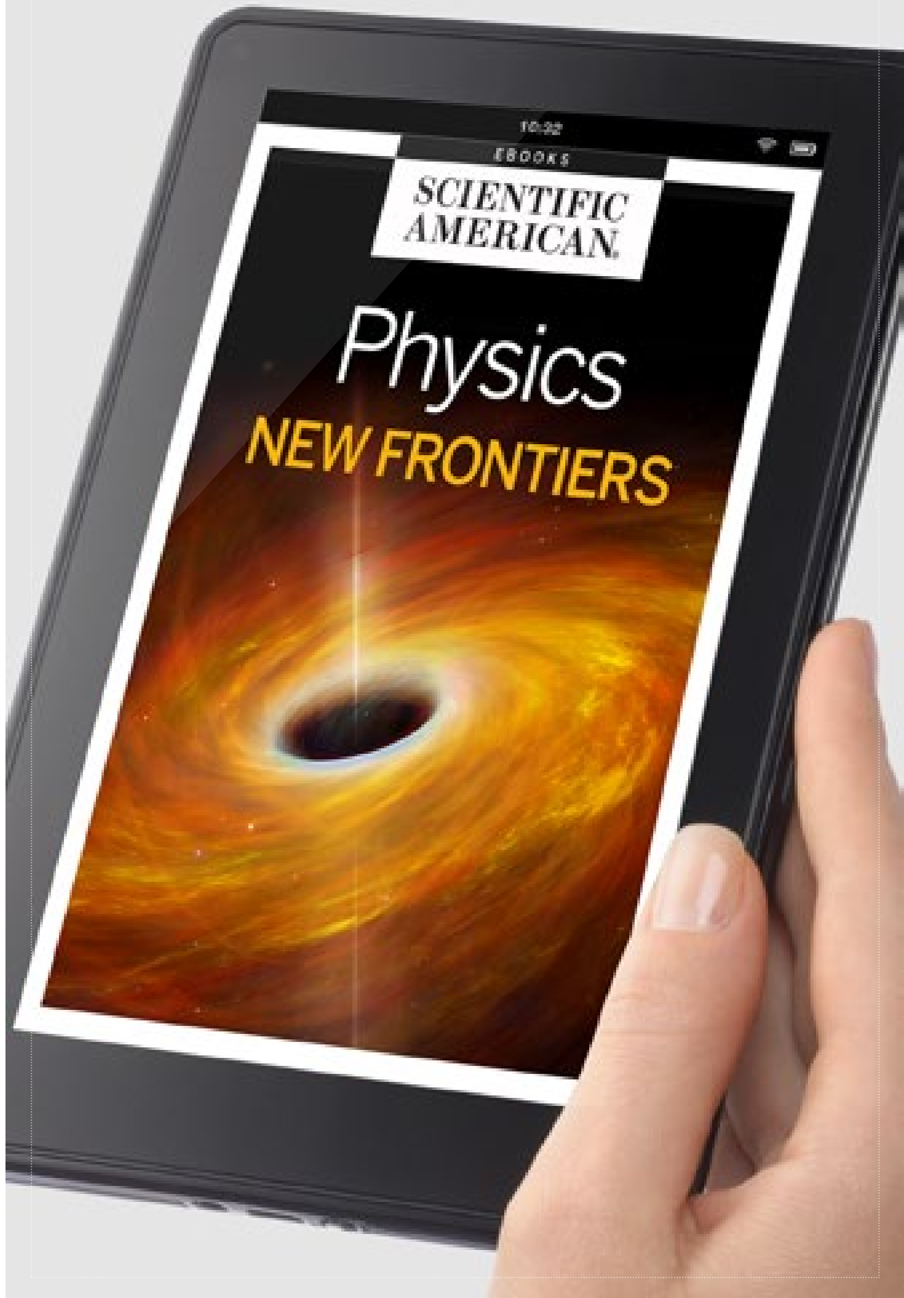

Steven J. Dick is the former NASA chief historian and the former Baruch S. Blumberg NASA/Library of Congress Chair in Astrobiology. He is the author or editor of 20 books, including, most recently, *Astrobiology, Discovery,* and *Societal Impact* (Cambridge, 2018). In 2006 Dick received the LeRoy E. Doggett Prize from the American Astronomical Society for a career that has significantly influenced the field of the history of astronomy. Minor planet 6544 Stevendick is named in his honor.

SPACE

Astroethics and Cosmocentrism

As astronomers forge ahead in their search for alien life, the ethical questions a discovery would raise are becoming more urgent

ANYUR ZAKIROV PIXABAY

WITH THE RECENT ANNOUNCEMENT of a large subsurface lake on Mars, ongoing investigations of the oceans of Europa and Enceladus (complete with shooting geysers!), the discovery of exoplanets numbering in the thousands and the $100-million Breakthrough Listen SETI program well underway, the paradigm-shattering discovery of life beyond Earth could be made any day. NASA is showing renewed interest in SETI (it is sponsoring a meeting on technosignatures in September), and a few intrepid organizations such as METI International are actually sending messages to the stars (METI stands for "messaging extraterrestrial intelligence").

In recent months both Breakthrough Listen and the SETI Institute have sponsored both real and virtual meetings to examine the societal impact should their programs prove successful. Anthropologists, historians, ethicists, philosophers and others are joining the interdisciplinary conversation in a serious way, impelled by the increasing possibility of discovery.

All of this activity gives new urgency to a whole series of ethical questions. Does Mars belong to the Martians, even if the Martians are only microbes? What do we say in response to an alien message, and who speaks for Earth? How do we treat aliens, either remotely or in a "close encounter of the third kind"? In short, whether we discover alien microbes or advanced alien life, we will immediately be faced with the problem of how to interact. Welcome to the world of astroethics—the contemplation and development of ethical standards for a variety of outer space issues, including terraforming the planets, resource utilization, near-Earth asteroid threats, space exploration, planetary protection—and the discovery of extraterrestrial life.

The problems involving E.T. life are particularly fraught, especially if it talks back to us. Before we can act in any situation that involves life, it is first important to assess the moral status of the organisms involved. This is no easy task, since we are ambiguous about relations with animals on Earth, on the one hand sheltering them as beloved pets, on the other hand and rather arbitrarily hunting, eating and exterminating them. But a good deal of thought has been given to the subject of the moral status of Earth organisms and the idea of intrinsic value on which it is often based. Contemplating encounters with alien life tremendously expands our ethical horizons.

The case of intelligent aliens also encompasses not just the problem of how we might treat them but also how they might act or react. In other words, it is not just a question of our ethics. What about their ethics? Is there any basis for inferring whether alien intelligence might be good or bad? On Earth we exhibit a mix of altruism and evil, but is there any reason to believe altruism has triumphed among extraterrestrials? Might there be such a thing as a universal ethics in the form of a universal Golden Rule or a reverence for life? Or is *Star Trek*'s "Prime Directive" of nonintervention a naive one-way street, a recipe for our own extinction? Does the arc of the moral universe indeed bend toward justice?

There are obviously many more questions than answers. Nonetheless, answers to these questions will inform our actions in real-world contacts with alien life under different scenarios. As I argue in my new book *Astrobiology, Discovery and Societal Impact,* by contemplating these issues, and certainly by putting them into practice in the event of the discovery of life beyond Earth, we will not only address what the World Economic Forum has called one of the "X-factors" in our near or far future but also transform our thinking by moving from an anthropocentric ethic toward a "cosmocentric" one that establishes the universe and all or part of its life as a priority rather than just humans or even terrestrial life in general.

Let's look at some specific issues, beginning with microbes, which many consider most likely to be the first discovery of life beyond the Earth. Microbes have always been a focus of attention in the context of Mars exploration, but now the focus is expanded to other water worlds of our solar system, such as Jupiter's moon Europa or Saturn's Enceladus. At first the issues might seem straightforward: NASA has a robust planetary protection program whose goal is to protect all of the planets all of the time from contamination or back contamination.

Beyond that, however, the scary fact is that no guidance exists on what to do if microbial life is actually discovered. In the context of microbes, it matters whether we adopt an anthropocentric or ratiocentric ethic that confers intrinisic value only on reasoning beings, or a biocentric ethic that values all living things. It matters whether we consider microbes only of scientific value or whether they are considered to have intrinsic value, in which case microbes have rights too—rights that we do not give their counterparts on Earth. Planetary contamination policies seem to confer rights on any microbes we may find on other worlds; the central goal of those policies, after all, is to protect from contamination any planets that might harbor life. That is a kind of biocentric ethic.

But it is an unstable and inconsistent one, since by necessity on Earth we stamp out pathogenic microbes while at the same time realizing the microbiome is essential to human health. Thus, the status of microbes is one of many ethical dilemmas we will face if and when extraterrestrial microbes are discovered. One has the feeling that even if a biocentric ethic is adopted in principle, human health will always take priority.

While the policy issues involved with the discovery of microbes are serious enough, the issues become even more daunting for extraterrestrial intelligence. Once again they depend on the discovery scenario, most urgently in connection with current programs for indirect contact via SETI or METI, and most spectacularly in terms of impact if we ever make direct contact with aliens on Earth or in our solar system, even in the form of alien artifacts. The question of what to do in the event of success in SETI has received considerable attention in the form of SETI protocols adopted three decades ago, which basically boil down to "confirm and then tell everybody."

In other words, no false positives and no secrets. While these protocols have been adopted by a number of international organizations such as the International Astronomical Union, they have not been adopted by the United Nations and are not legally enforceable. Moreover, they have already been broken. When a reporter calls an astronomer to ask about a rumored detection, astronomers admirably tend not to lie, even before confirmation. Beyond that, there are no principles for dealing with a successful SETI detection.

And despite attempts, there are no protocols for the messaging in METI, although there has been a great deal of heated discussion about the ethics of initiating messages, both in terms of consultation and message content. Opponents have gone so far as to suggest METI should be banned, and readers of Cixin Liu's disturbing *Three-Body Problem* trilogy might tend to agree as they witness the Trisolaran fleet heading to Earth from the Alpha Centauri system. In contrast, I argue that when it comes to METI—and all of astrobiology—we are a part of the universe and cannot isolate ourselves from it. We will have to deal with microbes and aliens for good or ill in the same way we have had to deal with terrestrials for good and ill. Certainly, we can have consultations about message construction, content and other burning issues bound to arise.

But it is good to recall that METI is just one step ahead of SETI. If SETI is successful, we will reply, and all the questions METI practitioners are now dealing with will immediately come to the fore. In my view, not only is it unrealistic to think we will restrain ourselves from replying, it is also undesirable. An Earth where we have to limit our curiosity is not the kind of place I want to live. We should take all necessary precautions, feel at home in the universe and deal with the problems and the promise as they come.

The questions we have been asking go to the very core of the concepts of intrinsic value, moral status and their meaning for practical ethics. They raise the issue of whether an anthropocentric ethic is enough for an astroethics dealing with alien life, even when extended to environmental ethics and deep ecology, or whether we need something even broader: a “cosmocentric ethic,” as NASA engineer, biologist and philosopher Mark Lupisella and space policy analyst John Logsdon suggested two decades ago.

I would argue that we do, in the sense that at a minimum we should apply a *basic cosmocentric ethic* stipulating that our increasing cosmic consciousness requires us to consider our place in the biological universe when we make ethical judgments. We are, after all, part of the cosmos and perhaps not the most important part when it comes to life—the central question of astrobiology. In this view, when we ask about the rights of Martian life or how to treat alien intelligence, we should certainly avoid an anthropocentric stance that only humans have moral status.

Perhaps you think this is all rather esoteric, a subject for elites to contemplate while most people deal with the more pressing problems of daily life. In my view, you would be wrong. Yes, we have plenty of problems on Earth to deal with, but extraterrestrial contact may soon be one of them. Preparing for discovery is important to maximize the chances for a beneficial outcome. And we should never forget that Earth is part of the universe, and the cosmic view of astroethics and an accompanying cosmocentric ethic might just give us a perspective on our problems that will help solve them. In addition, astroethics has the potential to influence multitudes with the rise of the related discipline of astrotheology, the study of alien behavior, now also a hot topic and the subject of many books. But that is another question.

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Carlo Rovelli is a theoretical physicist at Aix-Marseille University in France and one of the developers of loop quantum gravity.

PHYSICS

Physics Needs Philosophy; Philosophy Needs Physics

Philosophy has always played an essential role in the development of science, physics in particular, and is likely to continue to do so

DIMITRI OTIS GETTY IMAGES

CONTRARY TO CLAIMS ABOUT the irrelevance of philosophy for science, philosophy has always had, and still has, far more influence on physics than commonly assumed. A certain current antiphilosophical ideology has had damaging effects on the fertility of science. The recent momentous steps taken by experimental physics are all rebuttals of today's freely speculative attitude in theoretical physics. Empirical results such as the detection of the Higgs particle and gravitational waves and the failure to detect supersymmetry where many expected it challenge the validity of philosophical assumptions common among theoretical physicists, inviting us to engage in a clearer philosophical reflection on scientific method.

"Against Philosophy" is the title of a chapter in *Dreams of a Final Theory*, written by one of the great physicists of the last generation, Steven Weinberg.[1] Weinberg argues eloquently that philosophy is more damaging than helpful for physics—it is often a straitjacket that physicists have to free themselves from. Stephen Hawking famously wrote in *The Grand Design* that "philosophy is dead" because the big questions that used to be discussed by philosophers are now in the hands of physicists.[2] Neil deGrasse Tyson publicly stated that "we learn about the expanding universe,… we learn about quantum physics, each of which falls so far out of what you can deduce from your armchair that the entire community of philosophers … was rendered essentially obsolete."[3] I disagree. Philosophy has always had an essential role in the development of science, physics in particular, and is very likely to continue to do so.

This is a long-standing debate. An early delightful chapter of the debate was played out in Athens during its classical period. At the time, the golden youth of the city were educated in famous schools. Two stood out: the school of Isocrates's and the Academy, founded by a certain Plato. The rivalry between the two was not just about quality: their approach to education was different. Isocrates's offered a high-level practical education, teaching young people the skills and knowledge directly required to become politicians, lawyers, judges, architects, and so on. The Academy focused on discussing general questions about foundations: What is justice? What would be the best laws? What is beauty? What is matter made of? And Plato had invented a good name for this way of posing problems: "philosophy."

Isocrates's criticisms of Plato's approach to education and knowledge were direct and remarkably like the claim by those contemporary scientists who argue that philosophy has no role in science: "Those who do philosophy, who determine the proofs and the arguments … and are accustomed to enquiring, but take part in none of their practical functions,… even if they happen to be capable of handling something, they automatically do it worse, whereas those who have no knowledge of the arguments [of philosophy], if they are trained [in concrete sciences] and have correct opinions, are altogether superior for all practical purposes. Hence for sciences, philosophy is entirely useless."[4]

As it happened, a brilliant student in Plato's school wrote a short work in response to Isocrates' criticisms: the *Protrepticus*, a text that became famous in antiquity. The bright young fellow who authored the pamphlet later left Athens but eventually returned to open his own school and had quite a career. His name was Aristotle. Two millennia of development of the sciences and philosophy have vindicated and, if anything, strengthened Aristotle's defense of philosophy against Isocrates' accusations of futility. His arguments are still relevant, and we can take inspiration from them to reply to the current claims that philosophy is useless to physics.

Quantum mechanics springs from Heisenberg's intuition, grounded in the strongly positivist philosophical atmosphere in which he found himself: one gets knowledge by restricting oneself to what is observable.

The first of Aristotle's arguments is the fact that general theory supports and happens to be useful for the development of practice. Today, after a couple of millennia during which both philosophy and science have developed considerably, historical evidence regarding the influence of philosophy on science is overwhelming.

Here are a few examples of this influence, from astronomy and physics. Ancient astronomy—that is, everything we know about Earth being round, its size, the size of the moon and the sun, the distances to the moon and the sun, the motion of the planets in the sky, and the basis from which modern astronomy and modern physics have emerged—is a direct descendant of philosophy. The questions that motivated these developments were posed in the Academy and the Lyceum, motivated by theoretical rather than practical concerns. Centuries later Galileo and Newton took great steps ahead, but they relied heavily on what had come before.[5] They extended previous knowledge, reinterpreting, reframing and building on it. Galileo's work would have been inconceivable without Aristotelian physics. Newton was explicit about his debt to ancient philosophers, Democritus in particular, for ideas that arose originally from philosophical motivations, such as the notions of empty space, atomism and natural rectilinear motion. His crucial discussion about the nature of space and time built on his discussions with (and against) Descartes.

In the 20th century both major advances in physics were strongly influenced by philosophy. Quantum mechanics springs from Heisenberg's intuition, grounded in the strongly positivist philosophical atmosphere in which he found himself: one gets knowledge by restricting oneself to what is observable. The abstract of Heisenberg's 1925 milestone paper on quantum theory is explicit about this: "The aim of this work is to set the basis for a theory of quantum mechanics based exclusively on relations between quantities that are in principle observable."[6] The same distinctly philosophical attitude nourished Einstein's discovery of special relativity: by restricting to what is observable, we recognize that the notion of simultaneity is misleading. Einstein recognized very explicitly his debt to the philosophical writings of Mach and Poincaré. The philosophical influences on the conception of general relativity were even stronger. Once again, he was explicit in recognizing his debt to the philosophical arguments in Leibniz, Berkeley and Mach. Einstein claimed that even Schopenhauer had had a pervasive influence on him. Schopenhauer's ideas on time and representation are perhaps not so hard to recognize in Einstein's ideas leading to general relativity.[7] Can it really be a coincidence that, in his younger days, the greatest physicist of the 20th century should have had such a clear focus on philosophy,[8] reading Kant's *Three Critiques* when he was 15?

Why this influence? Because philosophy provides methods leading to novel perspectives and critical thinking. Philosophers have tools and skills that physics needs yet are not part of the physics training: conceptual analysis, attention to ambiguity, accuracy of expression and the ability to detect gaps in standard arguments, to devise radically new perspectives, to spot conceptual weak points and to seek out alternative conceptual explanations. Nobody puts this better than Einstein himself: "A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is—in my opinion—the mark of distinction between a mere artisan or specialist and a real seeker after truth."[9] It is sometimes said that scientists do not do anything unless they first get permission from philosophy. If we read what the greatest scientists had to say about the usefulness of philosophy, physicists such as Heisenberg, Schrödinger, Bohr and Einstein, we find opposite opinions to those of Hawking and Weinberg.

Here is a second argument from Aristotle: those who deny the utility of philosophy are doing philosophy. The point is less trivial than it may sound at first. Weinberg and Hawking have obtained important scientific results. In doing this, they were doing science. In writing things like "philosophy is useless to physics" or "philosophy is dead," they were not doing physics. They were reflecting on the best way to develop science. The issue is the methodology of science: a central concern in the philosophy of science is to ask how science is done and how it could be done to be more effective. Good scientists reflect on their own methodology, and it is appropriate that Weinberg and Hawking have done so too. But how? They express a certain idea about the methodology of science. Is this the eternal truth about how science has always worked and should work? Is it the best understanding of science we have at present?

It is neither. In fact, it is not difficult to trace the origins of their ideas. They arise from the background of logical positivism, corrected by Popper and Kuhn. The current dominant methodological ideology in theoretical physics relies on their notions of falsifiability and scientific revolution, which are popular among theoretical physicists; they are often referred to and are used to orient research and evaluate scientific work.

Hence, in declaring the uselessness of philosophy, Weinberg, Hawking and other "antiphilosophical" scientists are in fact paying homage to the philosophers of science they have read or whose ideas they have absorbed from their environment. The imprint is unmistakable. When viewed as an ensemble of pseudo-statements—words that resemble statements but have no proper meaning—of the kind recurrent, for instance, in the way Tyson mocks philosophy, these criticisms are easily traced to the Vienna Circle's anti-metaphysical stance.[10] Behind these anathemas against "philosophy," one can almost hear the Vienna Circle's slogan of "no metaphysics!" Thus, when Weinberg and Hawking state that philosophy is useless, they are actually stating their adhesion to a particular philosophy of science.

In principle there's nothing wrong with that, but the problem is that it is not a very good philosophy of science. On the one hand, Newton, Maxwell, Boltzmann, Darwin, Lavoisier and so many other major scientists worked within a different methodological perspective and did pretty good science as well. On the other hand, philosophy of science has advanced since Carnap, Popper and Kuhn, recognizing that the way science effectively works is richer and more subtle than the way it was portrayed in the analysis of these thinkers. Weinberg and Hawking's error is to mistake a particular, historically circumscribed, limited understanding of science for the eternal logic of science itself.

The weakness of their position is the lack of awareness of its frail historical contingency. They present science as a discipline with an obvious and uncontroversial methodology, as if this had been the same from Bacon to the detection of gravitational waves or as if it was completely obvious what we should be doing and how we should be doing it when we do science.

Reality is different. Science has repeatedly redefined its own understanding of itself, along with its goals, its methods and its tools. This flexibility has played a major part in its success. Let us consider a few examples from physics and astronomy. In light of Hipparchus's and Ptolemy's extraordinarily successful predictive theories, the goal of astronomy was to find the right combination of circles to describe the motion of the heavenly bodies around Earth. Contrary to expectations, it turned out that Earth was itself one of the heavenly bodies. After Copernicus, the goal appeared to be to find the right combination of moving spheres that would reproduce the motion of the planets around the sun. Contrary to expectations, it turned out that abstract elliptical trajectories were better than spheres. After Newton, it seemed clear that the aim of physics was to find the forces acting on bodies. Contrary to this, it turned out that the world could be better described by dynamic fields rather than bodies. After Faraday and Maxwell, it was clear that physics had to find laws of motion in space, as time passes. Contrary to assumptions, it turned out that space and time are themselves dynamic. After Einstein, it became clear that physics must search for only the deterministic laws of nature. But it turned out that we can at best give probabilistic laws. And so on.

Here are some sliding definitions for what scientists have thought science to be: deduction of general laws from observed phenomena, finding out the ultimate constituents of nature, accounting for regularities in empirical observations, finding provisional conceptual schemes for making sense of the world. (The last one is the one I like.) Science is not a project with a methodology written in stone or a fixed conceptual structure. It is our ever evolving endeavor to better understand the world. In the course of its development, it has repeatedly violated its own rules and its own stated methodological assumptions.

> **"A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is—in my opinion—the mark of distinction between a mere artisan or specialist and a real seeker after truth."**
>
> ***—Albert Einstein***

A common current description of what scientists do is collecting data and making sense of them in the form of theories. As time goes by, new data are acquired and theories evolve. In this picture, scientists are depicted as rational beings who play this game using their intelligence, a specific language and a well-established cultural and conceptual structure. The problem with this picture is that conceptual structures evolve as well. Science is not simply an increasing body of empirical information and a sequence of changing theories. It is also the evolution of our own conceptual structure. It is the continuous search for the best conceptual structure for grasping the world at a given level of knowledge. The modification of the conceptual structure needs to be achieved from within our own thinking rather as a sailor must rebuild his own boat while sailing, to use the beautiful simile of Otto Neurath of Austria so often quoted by American philosopher Willard Quine.[11]

This intertwining of learning and conceptual change and this evolution of methodology and objectives have developed historically in a constant dialogue between practical science and philosophical reflection. The views of scientists, whether they like it or not, are impregnated by philosophy.

And here we come back to Aristotle: philosophy provides guidance about how research must be done. Not because philosophy can offer a final word about the right methodology of science (contrary to the philosophical stance of Weinberg and Hawking), but because the scientists who deny the role of philosophy in the advancement of science are those who think they have already found the final methodology—they have already exhausted and answered all methodological questions. They are consequently less open to the conceptual flexibility needed to go ahead. They are the ones trapped in the ideology of their time.

One reason for the relative sterility of theoretical physics over the past few decades may well be precisely that the wrong philosophy of science is held dear today by many physicists. Popper and Kuhn, popular among theoretical physicists, have shed light on important aspects of the way good science works, but their picture of science is incomplete, and I suspect that, taken prescriptively and uncritically, their insights have ended up misleading research.

Kuhn's emphasis on discontinuity and incommensurability has misled many theoretical and experimental physicists into not valuing the formidable cumulative aspects of scientific knowledge. Popper's emphasis on falsifiability, originally a demarcation criterion, has been flatly misinterpreted as an evaluation criterion. The combination of the two has given rise to disastrous methodological confusion: the idea that past knowledge is irrelevant when searching for new theories; that all unproved ideas are equally interesting and all unmeasured effects are equally likely to occur; and that the work of a theoretician consists in pulling arbitrary possibilities out of the blue and developing them because anything that has not yet been falsified might in fact be right.

This is the current "Why not?" ideology: any new idea deserves to be studied just because it has not yet been falsified; any idea is equally probable because a step further ahead on the knowledge trail there may be a Kuhnian discontinuity that was not predictable on the basis of past knowledge; any experiment is equally interesting, provided it tests something as yet untested.

I think that this methodological philosophy has given rise to much useless theoretical work in physics and many useless experimental investments. Arbitrary jumps in the unbounded space of possibilities have never been an effective way to do science. The reason is twofold: first, there are too many possibilities, and the probability of stumbling on a good one by pure chance is negligible; more important, nature always surprises us, and we, limited critters, are far less creative and imaginative than we may think. When we proudly consider ourselves to be "speculating widely," we are mostly playing out rearrangements of old tunes: true novelty that works is not something we can just find by guesswork.

The radical conceptual shifts and the most unconventional ideas that have actually worked have indeed been always historically motivated, almost forced, either by the overwhelming weight of new data or by a well-informed analysis of the internal contradictions within existing, successful theories. Science works through continuity, not discontinuity.

Examples of the first case—novelty forced by data—are Kepler's ellipses and quantum theory. Kepler did not just "come out with the idea" of ellipses: nature had to splash ellipses on his face before he could see them. He was using ellipses as an approximation for the epicyclic motion of Mars and was astonished to find that the approximation worked better than his model.[12] Similarly, atomic physicists of the early 20th century struggled long and hard against the idea of discontinuities in the basic laws, doing everything they could to avoid accepting the clear message from spectroscopy, that is, that there was actually discontinuity in the very heart of mechanics. In both instances, the important new idea was forced by data.

Examples of the second case—radical novelty from old theories—are the heliocentric system and general relativity. Neither Copernicus nor Einstein relied significantly on new data. But neither did their ideas come out of the blue. They both started from an insightful analysis of successful well-established theories: Ptolemaic astronomy, Newtonian gravity and special relativity. The contradictions and unexplained coincidences they found in these would open the way to a new conceptualization.

It is not fishing out unfalsified theories and testing them that brings results. Rather it is a sophisticated use of induction, building on a vast and ever-growing accumulation of empirical and theoretical knowledge, that provides the hints we need to move ahead. Einstein's relativity was not a new idea: it was Einstein's realization of the extensive validity of Galilean relativity. There was no discontinuity: in fact, it was continuity at its best. It was Einstein's insightful conservatism in the face of those who were too ready to discard the relativity of velocity, just because of Maxwell's equations. I think this lesson is missed by much contemporary theoretical physics, where plenty of research directions are too quick to discard what we have already found out about nature.

Three major empirical results have marked recent fundamental physics: gravitational waves, the Higgs and the absence of supersymmetry at the Large Hadron Collider. All three are confirmations of old physics and disconfirmations of widespread speculation. In all three cases, nature is telling us: do not speculate so freely. So let's look more closely at these examples.

The detection of gravitational waves, rewarded by the last Nobel Prize in fundamental physics, has been a radical confirmation of century-old general relativity. The nearly simultaneous detection in August 2017 of gravitational and electromagnetic signals from the merging of two neutron stars by the LIGO and Virgo detectors has improved our knowledge of the ratio between the speeds of propagation of gravity and electromagnetism by something like 14 orders of magnitude in a single stroke.[13] One consequence of this momentous increase in our empirical knowledge has been to rule out a great many theories put forward as alternatives to general relativity, ideas that have been studied by a large community of theoreticians over the past decades, confirming instead the century-old general relativity as the best theory of gravity available at present.

The well-publicized detection of the Higgs particle at CERN has confirmed the Standard Model as the best current theory for high-energy physics, against scores of later alternatives that have long been receiving much attention.

But CERN's emphasis on the discovery of the Higgs when the Large Hadron Collider became operational has also served to hide the true surprise: the absence of supersymmetric particles where a generation of theoretical physicists had been expecting to find them. Despite rivers of ink and flights of fancy, the minimal supersymmetric model suddenly finds itself in difficulty. So once again, nature has seriously rebuffed the free speculations of a large community of theoretical physicists who ended up firmly believing them. Nature's repeated snub of the current methodology in theoretical physics should encourage a certain humility, rather than arrogance, in our philosophical attitude.

Part of the problem is precisely that the dominant ideas of Popper and Kuhn (perhaps not even fully digested) have misled current theoretical investigations. Physicists have been too casual in dismissing the insights of successful established theories. Misled by Kuhn's insistence on incommensurability across scientific revolutions, they fail to build on what we already know, which is how science has always moved forward. A good example of this is the disregard for general relativity's background independence in many attempts to incorporate gravity into the rest of fundamental physics.

Einstein's "relativity" was not a new idea: it was Einstein's realization of the extensive validity of Galilean relativity. There was no discontinuity: in fact, it was continuity at its best.

Similarly, the emphasis on falsifiability has made physicists blind to a fundamental aspect of scientific knowledge: the fact that credibility has degrees and that reliability can be extremely high, even when it falls short of absolute certainty. This has a doubly negative effect: considering the insights of successful theories as irrelevant for progress in science (because "they could be falsified tomorrow") and failing to see that a given investigation may have little plausibility even if it has not yet been falsified.

The scientific enterprise is founded on degrees of credibility, which are constantly updated on the basis of new data or new theoretical developments. Recent attention to Bayesian accounts of confirmation in science is common in the philosophy of science but largely ignored in the theoretical physics community, with negative effects, in my opinion.[14]

What I intend here is not a criticism of Popper and Kuhn, whose writings are articulate and obviously insightful. What I am pointing out is that a simpleminded version of their outlooks has been taken casually by many physicists as the ultimate word on the methodology of science.

Far from being immune from philosophy, current physics is deeply affected by philosophy. But the lack of philosophical awareness needed to recognize this influence, and the refusal to listen to philosophers who try to make amends for it, is a source of weakness for physics.

Here is one last argument from Aristotle: more in need of philosophy are the sciences where perplexities are greater.

Today fundamental physics is in a phase of deep conceptual change because of the success of general relativity and quantum mechanics and the open "crisis" (in the sense of Kuhn, I would rather say "opportunity") generated by the lack of an accepted quantum theory of gravity. This is why some scientists, including myself, working as I do on quantum gravity, are more acutely aware of the importance of philosophy for physics. Here is a list of topics currently discussed in theoretical physics: What is space? What is time? What is the "present"? Is the world deterministic? Do we need to take the observer into account to describe nature? Is physics better formulated in terms of a "reality" or in terms of "what we observe," or is there a third option? What is the quantum wave function? What exactly does "emergence" mean? Does a theory of the totality of the universe make sense? Does it make sense to think that physical laws themselves might evolve? It is clear to me that input from past and current philosophical thinking cannot be disregarded in addressing these topics.

In loop quantum gravity, my own technical area, Newtonian space and time are reinterpreted as a manifestation of something which is granular, probabilistic and fluctuating in a quantum sense. Space, time, particles and fields get fused into a single entity: a quantum field that does not live in space or time. The variables of this field acquire definiteness only in interactions between subsystems. The fundamental equations of the theory have no explicit space or time variables. Geometry appears only in approximations. Objects exist within approximations. Realism is tempered by a strong dose of relationalism. I think we physicists need to discuss with philosophers because I think we need help in making sense of all this.

To be fair, some manifestations of antiphilosophical attitudes in scientific circles are also a reaction to antiscientific attitudes in some areas of philosophy and other humanities. In the post-Heideggerian atmosphere that dominates some philosophy departments, ignorance of science is something to exhibit with pride. Just as the best science listens keenly to philosophy, so the best philosophy listens keenly to science. This has certainly been so in the past: from Aristotle and Plato to Descartes, Hume, Kant, Husserl and Lewis, the best philosophy has always been closely tuned in to science. No great philosopher of the past would ever have thought for a moment of not taking seriously the knowledge of the world offered by the science of their times.

Science is an integral and essential part of our culture. It is far from being capable of answering all the questions we ask, yet it is an extremely powerful tool. Our general knowledge is the result of the contributions from vastly different domains, from science to philosophy, all the way to literature and the arts, and our capacity to integrate them.

Those philosophers who discount science—and there are many of them—do a serious disservice to intelligence and civilization. When they claim that entire fields of knowledge are impermeable to science and that they are the ones who know better, they remind me of two little old men on a park bench: "Aaah," says one, his voice shaking, "all these scientists who claim they can study consciousness or the beginning of the universe." "Ohhh," says the other, "how absurd! Of course, they can't understand these things. We do!"

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Celestial Movement

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

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Astronomical Events
October—November 2018

October	Event
2	Moon: last quarter
	Moon reaches northernmost declination (+20.7°)
5	Venus stationary
	Moon at perigee (366,392 km), apparent diameter 32´ 36˝
9	New moon
11	Evening sky: moon near Jupiter
14	Evening sky: moon near Saturn
15	Moon reaches southernmost declination (–22.0°)
16	Moon: first quarter
17	Moon at apogee (404,227 km), apparent diameter 29´ 35˝
	Evening sky: moon near Mars
22	Morning sky: maximum of Orionid meteor shower
24	Uranus in opposition
	Moon: full moon
26	Venus in inferior conjunction
31	Moon: last quarter
	Moon at perigee (370,204 km), apparent diameter 32´ 16˝

October—November 2018: Visibility of planets

Two of the brightest planets can be seen in the evening sky: Saturn and Mars. Jupiter's visibility is coming to an end as the planet moves closer to the wun. Venus switches from the evening to the morning sky, where it appears as a bright object in November.

Venus is in inferior conjunction on October 26. The planet reappears in the morning sky in east-southeast direction around November 3, about 30 minutes before sunrise. Its morning visibility then strongly improves, and you might notice the daily motion of Venus relative to the star Spica, the brightest star in the constellation Virgo. Again, binoculars are recommended, because Spica is five magnitudes fainter than Venus.

Mars is moving eastward through the constellation Capricornus and enters Aquarius on November 11. The red planet becomes visible at dusk, when it is well above the southern horizon. Its brightness gradually decreases during October and November. The waxing moon is near Mars in the evening sky on October 17 and November 15.

Saturn is about halfway between Jupiter and Mars in the evening sky in the constellation Sagittarius, close to the Milky Way's center. If you want to observe Saturn's famous rings in a telescope now is the time—for the remainder of the year Saturn will move too close to the sun for observation.

Astronomical Events
October—November 2018

November	Event
2	Morning sky: moon near Regulus
6	Mercury greatest elongation east (23°)
7	Moon: new moon
11	Evening sky: moon near Saturn
12	Occultation of dwarf planet Pluto by the moon
	Moon reaches southernmost declination (−22.2°)
14	Venus stationary
	Moon at apogee (404,339 km), apparent diameter 29′ 32″
15	Moon: first quarter
	Evening sky: moon near Mars
17	Mercury stationary
	Minor planet Juno at opposition
18	Maximum of Leonid meteor shower
23	Moon: full moon
25	Neptune stationary
26	Jupiter in conjunction with sun
	Moon reaches northernmost declination (+21.1°)
	Moon at perigee (366,620 km), apparent diameter 32′ 35″
27	Mercury in inferior conjunction
29	Morning sky: moon near Regulus
30	Moon: last quarter

October—November 2018: Visibility of planets

Two of the brightest planets can be seen in the evening sky: Saturn and Mars. Jupiter's visibility is coming to an end as the planet moves closer to the sun. Venus switches from the evening to the morning sky, where it appears as a bright object in November.

Mercury remains hidden in the sun's bright glare during October. The innermost planet achieves its greatest eastern elongation on November 6. Around this date, Mercury might be spotted in the southwest direction with the help of binoculars about 40 minutes after sunset, when the evening sky is still bright. The planet is only 3° above the horizon at this time and it will set 20 minutes later. But make sure not to confuse Mercury with the somewhat brighter Jupiter, which is nearly at the same altitude, but 8° further to the west. The best chance to see Mercury is on the evening of November 9, about 45 minutes after sunset: in the southwest sky Mercury is 9° vertically beneath the 2.3-day-old waxing moon. On November 27, Mercury is in inferior conjunction, between the Earth and the sun.

Jupiter can only be seen in the evening sky, close to the horizon after suset. From early November it becomes too close to the sun for observation. The gas planet is in conjunction with the sun on November 26.

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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.

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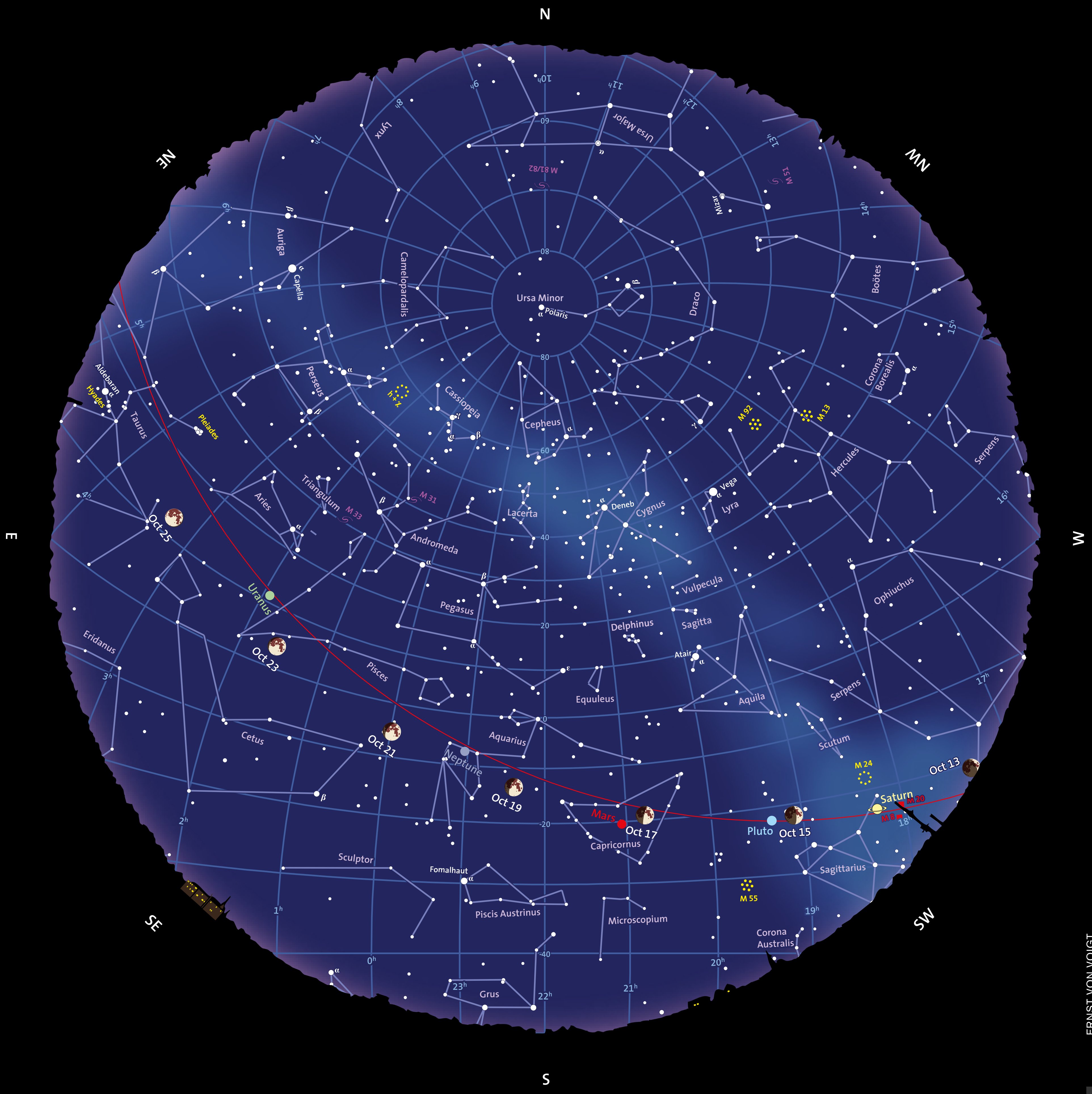
−1 0 1 2 3 4 5
Apparent magnitudes

⁘ Open cluster
⁙ Globular cluster
௹ Galaxy
■ Nebula



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SKY REPORT

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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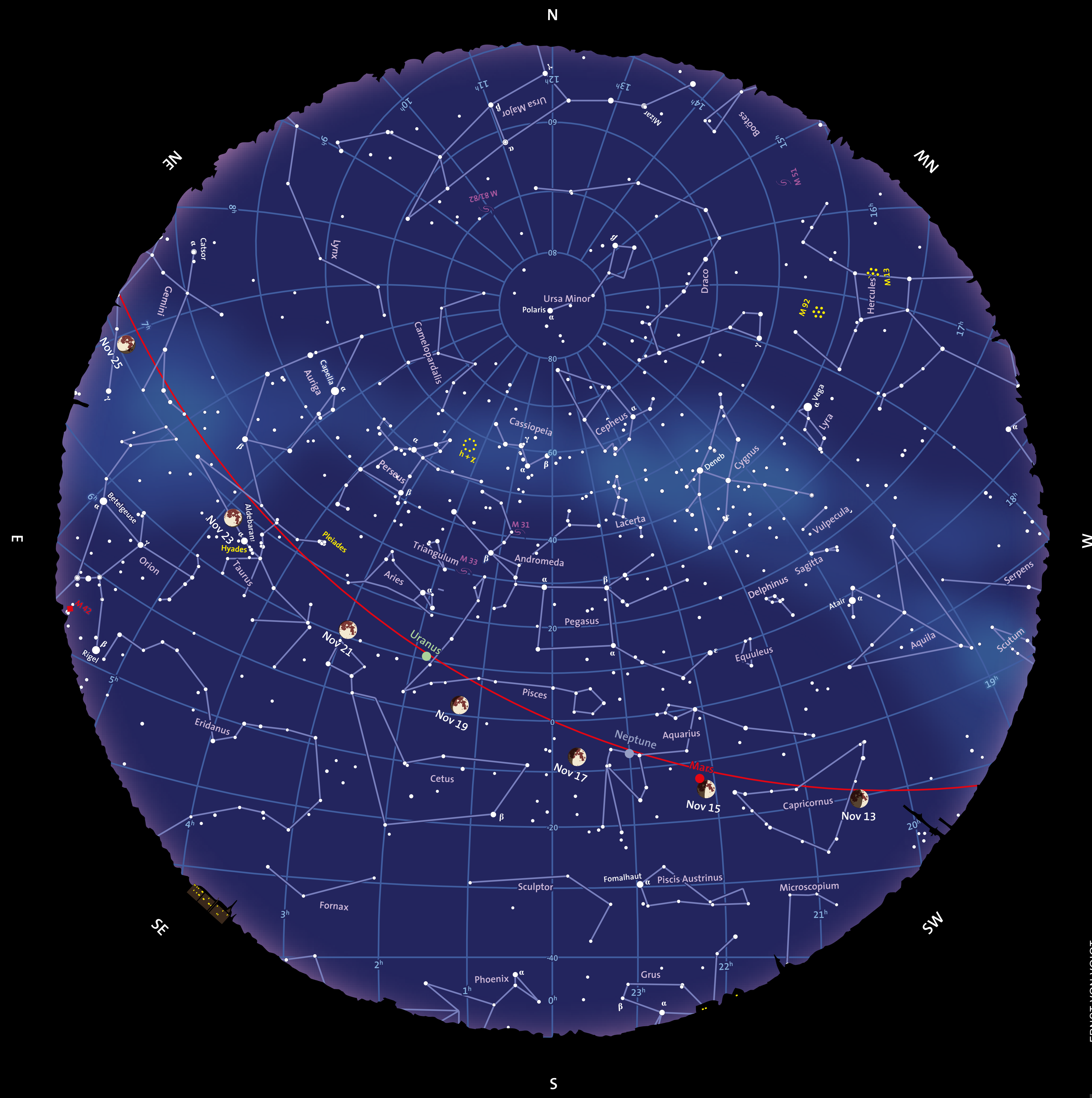
●	●	●	•	•	·	·
−1	0	1	2	3	4	5

Apparent magnitudes

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



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