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Space & Physics

The Beginning of All Things

UNPRECEDENTED VIEWS OF THE EARLY UNIVERSE SHED NEW LIGHT ON THE “COSMIC DAWN”

Plus:

THE DEBATE THAT WILL SHAPE THE NEXT DECADE OF ASTRONOMY AND PHYSICS

MYSTERY OF BETELGEUSE’S DIMMING SOLVED

CAN THE U.S. AND CHINA SPACE PROGRAMS COOPERATE?

WITH COVERAGE FROM nature

Liz Tormes

Beginnings and Endings

On July 12, NASA released a small set of images from its recently launched James Webb Space Telescope. The dazzling pictures are sure to jolt your imagination, if not give you a healthy bout of goosebumps (see “NASA Triumphantly Unveils Full Set of Webb’s First Images”). After decades of strife, a heart-pounding launch, and even getting hit by a micrometeoroid, the Webb telescope seems well on its way to transforming our understanding of the universe. As *Scientific American* space editor Lee Billings writes in this issue, the next great era of astronomy has begun.

It’s perhaps poetical, if a bit sad then, that this will be the final issue of our *Space & Physics* series. It’s been a joy bringing you the most important stories from *Scientific American* covering the incredible world of the cosmos, the quantum universe, and beyond. We editors are continually evaluating how to best deliver the crucial coverage on these topics, and as we move forward, these PDFs you have enjoyed will become part of *Scientific American*’s core digital subscription and will no longer be delivered as separate publications. Keep an eye on your in-box for more details, but I think you’ll be excited for what’s coming, and you can always find just as many fascinating articles on the topics that intrigue you most on our Web site and in our newsletters. Thank you for reading!

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On the Cover

The interacting galaxies of Stephan’s Quintet, as seen by the Webb telescope, approximately 290 million light-years away from Earth. Covering one fifth of the moon’s diameter, this mosaic is constructed from almost 1,000 separate images and reveals never-before-seen details of this galaxy group.

NASA, ESA, CSA and STScI

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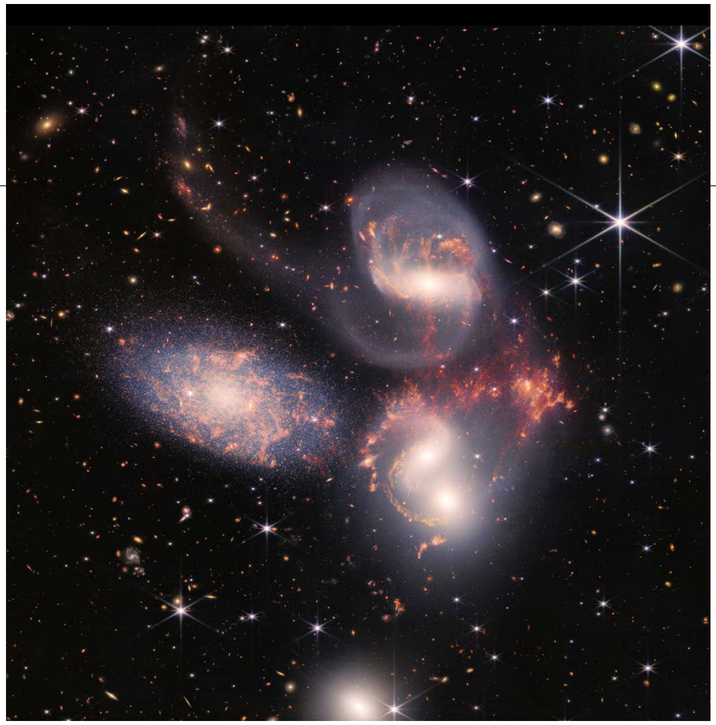
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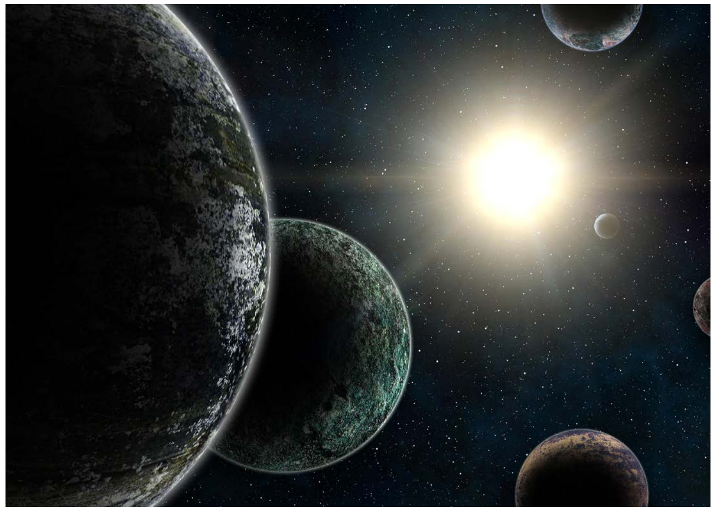
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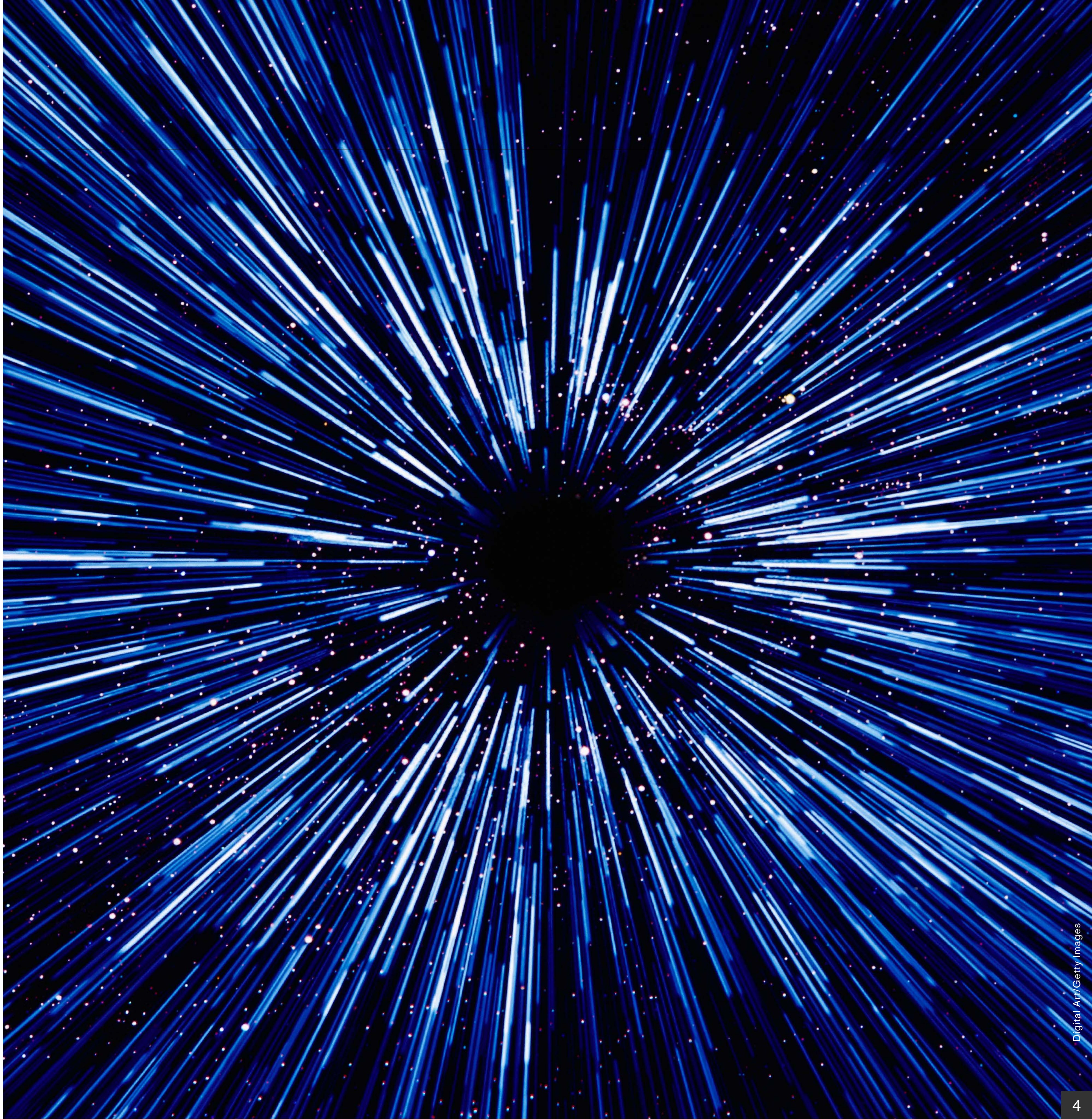
Physicists Find a Shortcut to Seeing an Elusive Quantum Glow

Once considered practically unseeable, a phenomenon called the Unruh effect might soon be revealed in laboratory experiments

Theoretical physics is full of weird and wonderful concepts: wormholes, quantum foam and multiverses, just to name a few. The problem is that while such things easily emerge from theorists' equations, they are practically impossible to create and test in a laboratory setting. But for one such "untestable" theory, an experimental setup might be just on the horizon.

Researchers at the Massachusetts Institute of Technology and the University of Waterloo in Ontario say they've found a way to test the Unruh effect, a bizarre phenomenon predicted to arise from objects moving through empty space. If scientists are able to observe the effect, the feat could confirm some



Digital Art/Getty Images

long-held assumptions about the physics of black holes. Their proposal was published in *Physical Review Letters* on April 21.

If you could observe the Unruh effect in person, it might look a bit like jumping to hyperspace in the *Millennium Falcon*—a sudden rush of light bathing your view of an otherwise black void. As an object accelerates in a vacuum, it becomes swaddled in a warm cloak of glowing particles. The faster the acceleration, the warmer the glow. "That's enormously strange" because a vacuum is supposed to be empty by definition, explains quantum physicist Vivishek Sudhir of M.I.T., one of the study's co-authors. "You know, where did this come from?"

Where it comes from has to do with the fact that so-called empty space is not exactly empty at all but rather suffused by overlapping energetic quantum fields. Fluctuations in these fields can give rise to photons, electrons, and other particles and can be sparked by an accelerating body. In essence, an object speeding through a field-soaked vacuum picks up a fraction of the fields' energy, which is subsequently reemitted as Unruh radiation.

The effect takes its name from the theoretical physicist Bill Unruh, who described his eponymous phenomenon in 1976. But two other researchers—mathematician Stephen Fulling and physicist Paul Davies—worked out the formula independently within three years of Unruh (in 1973 and 1975, respectively).

"I remember it vividly," says Davies, who is now a Regents Professor at Arizona State University. "I did the calculations sitting at my wife's dressing table because I didn't have a desk or an office."

A year later Davies met Unruh at a conference where Unruh was giving a lecture about his recent breakthrough. Davies was surprised to hear Unruh describe a very similar phenomenon to what had emerged from his own dressing-table calculations. "And so we got together in the bar afterward," Davies recalls. The two quickly struck up a collaboration that continued for several years.

Davies, Fulling and Unruh all approached their work from a purely theoretical standpoint; they never expected anyone to design a real-world experiment around it. As technology advances, however, ideas that were once relegated to the world of theory, such as gravitational waves and the Higgs boson, can come within reach of actual observation. And observing the Unruh effect, it turns out, could help cement another far-out physics concept.

"The reason people are working on the Unruh effect is not because they think that accelerated observers are so important," says Christoph Adami, a professor of physics, astronomy and molecular biology at Michigan State University, who was not involved in the research. "They are working on this because of the direct link to black hole physics."

Essentially the Unruh effect is the flip side of a far more famous physics phenomenon: Hawking radiation, named for physicist Stephen Hawking, who theorized that an almost imperceptible halo of light should leak from black holes as they slowly evaporate.

In the case of Hawking radiation, that warm fuzzy effect is basically a result of particles being pulled into a black hole by gravity. But for the Unruh effect, it's a matter of acceleration—which is, per Einstein's equivalence principle, gravity's mathematical equal.

Imagine you are standing in an elevator. With a jolt, the car rushes up to the next floor, and for a moment, you feel yourself pulled toward the floor. From your viewpoint, "that is essentially indistinguishable from Earth's gravity suddenly being turned up," Sudhir says.

The same holds true, he says, from a math perspective. "It's as simple as that: there is an equivalence between gravity and acceleration," Sudhir adds.

Despite its theoretical prominence, scientists have yet to observe the Unruh effect. (And for that matter, they haven't managed to see Hawking radiation either.) That's because the Unruh effect has long been considered extraordinarily difficult to test experimentally. Under most circumstances, researchers would need to subject an object to ludicrous accelerations—upward of 25 quintillion times the force of Earth's gravity—in order to produce a measurable emission. Alternatively, more accessible accelerations might be used—but in that case, the probability of generating a detectable effect would be so low that such an experiment would need to run continuously for billions of years. Sudhir and his co-authors believe that they have found a loophole, however.

By grabbing hold of a single

electron in a vacuum with a magnetic field, then accelerating it through a carefully configured bath of photons, the researchers realized that they could "stimulate" the particle, artificially bumping it up to a higher energy state. This added energy multiplies the effect of acceleration, which means that using the electron itself as a sensor, researchers could pick out Unruh radiation surrounding the particle without having to apply so many g-forces (or having to wait for eons).

Unfortunately, an energy-boosting photon bath also adds background "noise" by amplifying other quantum-field effects in the vacuum. "That's exactly what we don't want to happen," Sudhir says. But by carefully controlling the trajectory of the electron, the experimenters should be able to nullify this potential interference—a process that Sudhir likens to throwing an invisibility cloak over the particle.

And unlike the kit required for most other cutting-edge particle physics experiments, such as the giant superconducting magnets and sprawling beamlines of the Large Hadron Collider at CERN, the researchers say that their Unruh effect simulation could be set up in most university labs. "It doesn't have to be some huge experiment," says paper co-author Barbara Šoda, a physicist at the University of Waterloo. In fact, Sudhir and his Ph.D. students are currently designing a version they intend to actually build, which they hope to have running in the next few years.

Adami sees the new research as an elegant synthesis of several different disciplines, including classical physics, atomic physics and quantum-field theory. "I think this paper is correct," he says. But much like the Unruh effect itself, "to some extent, it's clear that this calculation has been done before."

For Davies, the potential to test the effect could open up exciting new doors for both theoretical and applied physics, further validating until now unobservable phenomena predicted by theorists while expanding the tool kit experimentalists can use to interrogate nature. "The thing about physics that makes it such a successful discipline is that experiment and theory very much go hand in hand," he says. "The two are in lockstep." Testing the Unruh effect promises to be a pinnacle achievement for both.

—Joanna Thompson

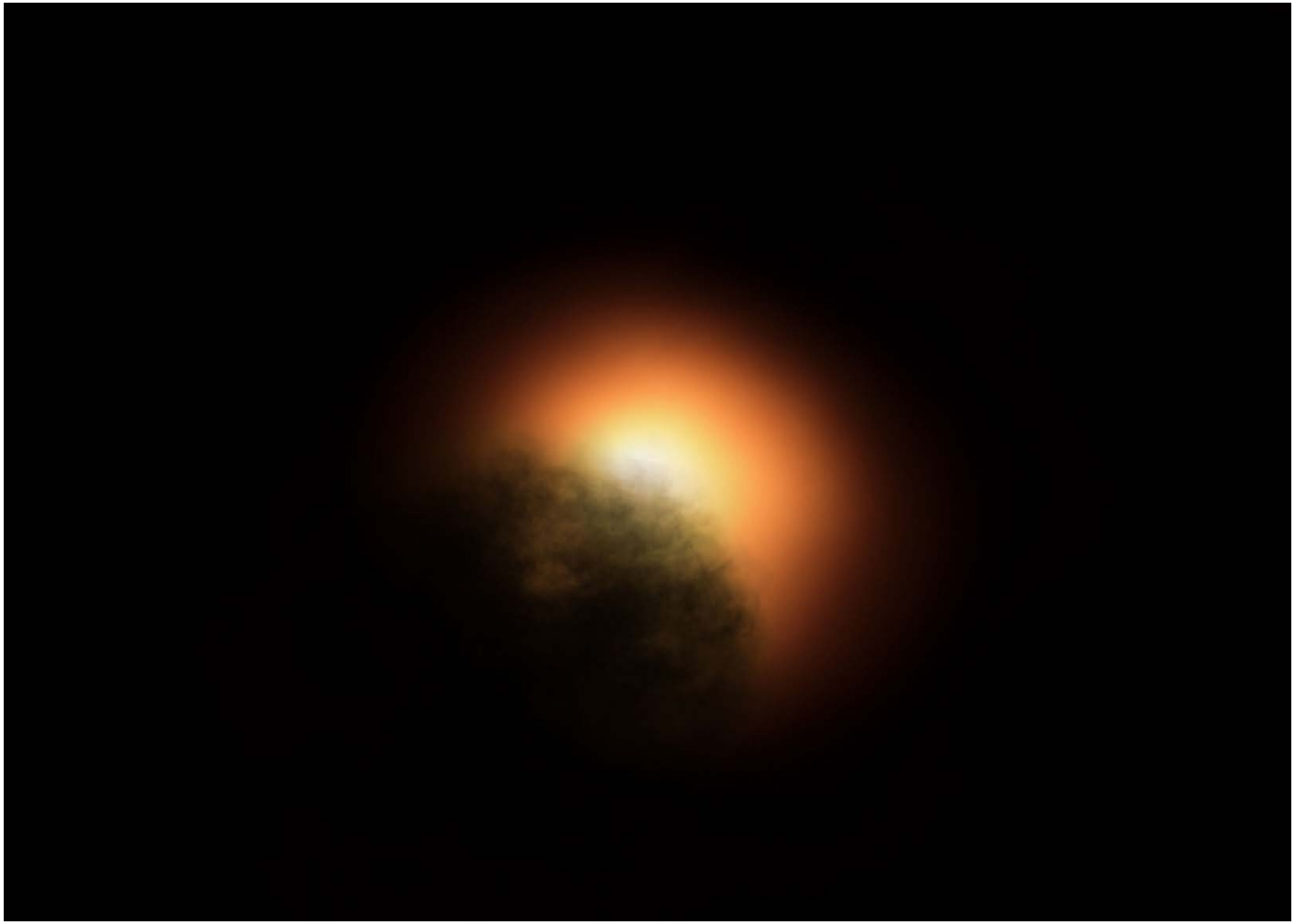
Betelgeuse "Great Dimming" Mystery Solved by Satellite Photobomb

Images from Japan's Himawari-8 spacecraft shed light on the red supergiant star's remarkable fading

In late 2019, mere months before the COVID-19 pandemic would engulf the globe, much of the world was instead concerned with a ruddy, fading point of light more than 500 light-years away. Betelgeuse, the red supergiant star easily recognizable as the right "shoulder" of the constellation Orion, had suddenly and mysteriously dimmed by more than a factor of two. Some astronomers speculated that it was on the verge of exploding as a supernova—an event otherwise predicted to occur within the next 100,000 years or so. By early February of 2020, however, the fading had stopped, and within weeks the star had returned to its regular brightness, which left researchers with lingering questions about this bizarre episode they called the "Great Dimming."

The answers emerged gradually from a host of observatories lavishing the star with attention. First, a team of researchers who had used the Hubble Space Telescope to observe Betelgeuse before, during and after the event reported that a massive ejection of hot material from the star's surface had created an obscuring cloud of dust that led to the apparent fading. Then a different team using data from the Weihai Observatory in China found that Betelgeuse's temperature had plummeted during the Great Dimming by at least 170 kelvins, and the researchers attributed the plunge not to a dust cloud but rather to a very large, relatively cool dark spot they concluded must have briefly formed on the star's surface.

Finally, yet another team used observations with the Very Large Telescope in Chile to conclude that both scenarios were correct. In this hybrid model, the emergence of a dark spot in the star's southern hemisphere had lowered surrounding temperatures and spat out a bubble of hot gas. An enormous, starlight-blocking dust cloud then formed from this escaping material as it cooled, creating the Great Dimming.



An artist's impression of Betelgeuse's dust cloud was generated using an image of the red supergiant taken with the SPHERE instrument on the European Southern Observatory's Very Large Telescope in late 2019.

ESO, ESA/Hubble, M. Kornmesser

Now an unconventional telescope—a camera on a weather satellite—has entered the mix with another novel suite of observations. After realizing that Betelgeuse appears in the field of view of Japan's Earth-observing satellite Himawari-8, three graduate students at the University of Tokyo decided to take a closer look at archival images captured by the satellite during the Great Dimming. Their results, published in *Nature Astronomy*, support the twofold hypothesis while also raising the exciting possibility that data from other meteorological satellites may be repurposed for a broad range of astronomical observations. The study of Himawari-8's images has even inspired the National Oceanic and Atmospheric Administration to explore whether one of its own satellites can replicate the findings.

"It's very clever what they've done," says Andrea Dupree, an astrophysicist at the Harvard-Smithsonian Institute for Astrophysics, who is familiar with the research. "And of course, I love the result." Dupree led the earlier study that used Hubble data to link the Great Dimming to Betelgeuse burping out a dust cloud—a conclusion that she notes was initially met with much debate.

Dupree is no stranger to using unconventional methods to make tricky observations. From April to August, Earth's orbit around the sun brings Betelgeuse so close in the sky to our star that the resulting glare scuttles observations from most telescopes on the ground or in low-Earth orbit. A telescope stationed elsewhere in the solar system or in certain special high orbits around Earth could still have an unimpeded view. Spurred by the Great Dimming, in early 2020 Dupree contacted officials at the NASA Goddard Space Flight Center to ask to use the agency's STEREO-A spacecraft, which orbits the sun rather than Earth, to get another look at Betelgeuse during the summer months. But despite her own creativity, Dupree says she would've never thought to use a meteorological satellite.

The idea to employ Himawari-8 data started with a Tweet. While scrolling Twitter, lead author Daisuke Taniguchi saw a post about Earth's moon photobombing some of Himawari-8's images. He wondered if the weather satellite could be used to observe Betelgeuse, too. There were several benefits that made the idea intriguing. "Ground-based telescopes inevitably suffer from Earth's atmosphere and cannot observe many parts of the infrared wavelength ranges," Taniguchi says. And while space-based telescopes do not have that barrier, the competition to obtain observation time on them is "very severe."

So Taniguchi got in touch with fellow graduate student and eventual study co-author Kazuya Yamazaki to see if they could circumvent the competition and make their own observations. At first, Yamazaki recalls, "I wasn't fully confident because [in Himawari-8's images], the stars are very dark, compared to the moon." But together with Taniguchi and a third graduate student, study co-author Shinsuke Uno, Yamazaki decided to try.

When it falls within Himawari-8's field of view, Betelgeuse is not actually that hard to see—it appears as a dot hovering right at the edge of Earth's disk. It also benefits from being bright at both optical and infrared wavelengths, boosting its chances of registering in meteorological satellite detectors, which are not designed for astronomical applications. But simply finding the star in satellite images is one thing—using the data to perform actual high-precision stellar measurements is another. Data wrangling, Yamazaki says, was the most arduous, time-consuming part of the study.

Inspired by the Himawari-8 result, Dupree has enlisted the aid of Jon Fulbright, a calibration scientist at the product quality team for NASA and NOAA's Geostationary Operational Environmental Satellite-R (GOES-R) series of weather-monitoring satellites, to see if those spacecraft could help replicate it. As of this writing, Fulbright is still trying to extract insights on Betelgeuse from the GOES-R data and is grappling with burdensome unit conversions and pixel resizing required for the task. The benefits of using such an unconventional data source, he says, may not always outweigh the drawbacks.

"I go back and forth on whether this is a one-time thing," Fulbright says. Just like the Japanese team, he and his colleagues suspect that for this novel approach to reach its full potential, better methods must be developed to bridge the gaps between meteorological and astronomical data sets. But those possible synergies with astronomy may only emerge if new generations of Earth-observing satellites are designed with them in mind. "Maybe," he says, "something like this will get people's ideas going."

—Allison Gasparini

Troubled U.S. Neutrino Project Faces Uncertain Future–and Fresh Opportunities

A new two-phase approach to building the Deep Underground Neutrino Experiment ignites controversy among particle physicists

Blasting and boring through a warren of tunnels in the abandoned Homestake Gold Mine in South Dakota, engineers are preparing for the installation of the Deep Underground Neutrino Experiment (DUNE), the U.S.'s latest, greatest major particle physics project. But things are not proceeding as planned: construction-related setbacks have delayed DUNE's full-scale debut from sometime later this decade to, at best, the mid-2030s. And as DUNE's schedule has slipped, so, too, has its competitiveness with other neutrino experiments, leading the U.S. Department of Energy (DOE) to announce last fall its controversial decision to split the megaproject into two phases.

That two-phase approach, particle physicists in the U.S. hope, will help this flagging flagship project to keep pace with rivals while also creating breathing room to reimagine the later stages of its design. “True success might not be exactly on the same path as we were thinking 10 years ago,” says Kate Scholberg, an experimentalist at Duke University.

Together with the Long-Baseline Neutrino Facility (LBNF), DUNE seeks to interrogate the most elusive particles in the Standard Model of particle physics, which many suspect are a portal to whatever theory comes next. But last year the megaproject’s price tag was reevaluated to more than $3 billion for the first phase alone—roughly double the original estimate for the entire endeavor.

Excavating 800,000 short tons of rock to make room for four hefty detection modules has proved more complicated than anticipated. “Incorrect assumptions or premature estimates” about the condition of the mine meant that infrastructure had to be refurbished before excavation could begin, says a spokesperson for DOE. The cost of installing detectors was also underestimated. As a result, switching on LBNF/DUNE has been set back by several years, and the project must be reaffirmed by Congress given the size of the budgetary overrun.

Homestake open pit gold mine in Lead, South Dakota.

Tom Grundy/Alamy Stock Photo

Now as particle physicists gather for Snowmass, a process with periodic meetings for thrashing out the coming decade’s research priorities in the U.S., some have raised the specter that LBNF/DUNE could come second, or even third, in scoring some of its motivating science objectives. “How do we change the way that we’re thinking about DUNE to do those goals and more, or do those even better?" asks Jonathan Asaadi, an experimentalist at the University of Texas Arlington. "The whole point of the Snowmass process is to have these very hard discussions and then build consensus."

FROM NEUTRINOS TO NEW PHYSICS

Neutrinos are, without question, the weirdest denizens of the vast and varied particle physics bestiary: They come in three types but somehow oscillate among these different forms as they travel. This is surprising, as neutrinos can only oscillate if they have mass—a property that conflicts with predictions from the otherwise highly successful Standard Model. Ever since the discovery of this shape-shifting behavior in 1998, physicists have struggled to pin down exactly how neutrinos oscillate, and three missing measurements of crucial parameters remain.

The first and most well-known parameter, charge-parity (CP) violation, dictates whether neutrinos and their antiparticle counterparts oscillate in the same way and could help explain why there is more matter than antimatter in the universe. The second determines which are the heaviest and which are the lightest types of neutrino. And the third is related to how likely it is for one type of neutrino to turn into another type. Physicists dreamed up LBNF/DUNE a decade ago, during an earlier Snowmass jamboree, as a way to measure all of this and more.

The motivations were much the same for Japan's competing neutrino experiment Hyper-K—an even bigger underground chamber that is filled with water instead of DUNE's liquid argon. Hyper-K aims to rigorously measure CP violation in the late 2020s, before LBNF/DUNE's now delayed neutrino beam would even turn on. Meanwhile combinations of several smaller neutrino experiments—namely, IceCube, JUNO and KM3NeT—are expected to weigh in on these and other long-standing neutrino puzzles over the coming decade. "DUNE runs a very serious risk of not measuring these parameters first," Asaadi says. "Historically, big projects in Japan have been able to stay to their schedule with much more fidelity than many big U.S. projects."

Yet Asaadi and many others emphasize that these experiments are collaborators as much as competitors. "We're all kind of rooting for each other and rooting against each other at the same time," says Mark Messier, an experimentalist who worked on Super-K (Hyper-K's predecessor) as a graduate student and now works on DUNE and other neutrino detectors.

For one, any discovery must be confirmed by another independent experiment to be taken seriously. "For the sake of the science, we don't really care about who gets the answer," says André Luiz de Gouvêa of Northwestern University. "But you don't want to have a big time difference between the projects.... One project can steal the thunder of another." And although high-minded physicists may accept the importance of validation instead of being first to a discovery, the concept of coming in "second place" is a harder sell for politicians who hold the purse strings.

Then again, the new phasing of LBNF/DUNE may be what ultimately keeps the project healthy and competitive. "You make sure that you're getting results rather than allowing everything to delay while you wait for the full scale," says Gabriel Orebi Gann of the University of California, Berkeley. "The only way that you guarantee losing the race is not even running it."

Yet this approach comes with a new risk: funding for the second phase is not assured. "People are being invited to think about phase two and what it's bringing to the table a little bit more carefully than before," de Gouvêa says. "You want to make sure you have a good story to tell, to convince yourself and everybody else that phase two is a worthwhile investment."

SUNK-COST FALLACY OR GOLDEN OPPORTUNITY?

As large-scale projects like LBNF/DUNE have ramped up over the past five years, Congress has increased the DOE's overall budget for high-energy physics by nearly 30 percent. Funding for core research at universities as well as for R&D on new accelerator and detector technologies, however, has declined. The new phasing of LBNF/DUNE aims to rebalance the budget, says a spokesperson for the DOE. "The community really has to be serious about what are the reasonable time lines and goals," Asaadi says, or the megaproject could “suck all the air out of the room.”

All of this is occurring during a turbulent period for the LBNF/DUNE’s host, Fermi National Accelerator Laboratory (Fermilab). Last fall Fermilab’s director Nigel Lockyer stood down for undisclosed reasons. Shortly thereafter Fermilab also received a rare “C” from the DOE in its Report Card for science and technology project management.

Despite the uncertainty, sticking to the original scope of LBNF/DUNE is to many still a no-brainer. “It’s hard to imagine a single neutrino oscillation experiment that is better,” says Peter Denton, a neutrino theorist at Brookhaven National Laboratory. Unlike other experiments, the neutrino beam would probe a wide range of energies, thus taking a fuller picture of how neutrinos are oscillating. Detectors filled with liquid argon can also track the paths of particles far more precisely than those containing water. “Liquid argon technology is difficult, but we get something for that difficulty,” Denton says. The hope is that this novel and ambitious setup will not only map out neutrino oscillations in high resolution but that signs of new particles and forces could show up, and physicists may at last grasp the baffling origin of neutrino mass.

For these reasons, in 2014, the particle physics community rallied behind novel liquid-argon detectors over tried-and-tested water detectors—and most neutrino physicists see no reason for that to change. “There is very strong support within the community for [LBNF/DUNE] to happen,” says Orebi Gann. Yet in internal documents seen by *Scientific American*, a current co-spokesperson for DUNE successfully ran for election earlier this year on the basis that “LBNF/DUNE is currently experiencing a poor acceptance in the [high-energy physics] community … seriously challenging the future of DUNE.”

Most everyone agrees that with billions of dollars already allocated to the megaproject—by the U.S. and international partners—there is no turning back. “The ‘sunk cost’ fallacy is always present when you’re this far down the road,” Asaadi says. Luminaries of the particle physics community are haunted by the cancellation of the Superconducting Super Collider, a multibillion-dollar particle accelerator, in the early 1990s. Congress pulled funding after the budget ballooned and dubious spending on costly parties and catered lunches was revealed. As a result, “particle physics moved to Europe,” says Francis Halzen, principal investigator of the IceCube neutrino experiment. “Hopefully everybody has learned that by killing a project, the money doesn’t return to you or even to science.”

Then again, unquestionably supporting a major project whose “world’s first” aspirations may no longer be achievable carries risks, too. “We are in a catch-22. Cancellation of DUNE would be a black eye to the credibility of high-energy physics,” an anonymous source and member of the DUNE collaboration told *Scientific American*. “We need to find a way out of this, and the way out isn’t obvious.”

ALL TOGETHER NOW

At Snowmass meetings, a balancing act is now underway to bring particle physicists resolutely together again around LBNF/DUNE, with some portraying the newly phased design as an opportunity to turn lemons into lemonade. As well as upgrading the neutrino beam and detector size, the second phase also leaves two of DUNE’s four modules undefined—and fresh ideas are welcome. “There’s a lot of excitement about that and a lot of creative ideas for the new detectors,” says Scholberg, who co-convenes the neutrino physics priority group for the latest Snowmass, which continues through this summer.

Theoretical insights in recent years have opened the door to new kinds of dark matter searches at LBNF/DUNE, while the to-be-determined detectors could also house a “neutrinoless double beta decay” experiment to look for evidence that neutrinos are their own antiparticle. Enhanced supernovae detectors and the pursuit of mysterious sterile neutrinos are also on the table for filling the two open detector slots. “If you enlarge that collaboration [to other areas of physics], that’s bringing in more people that can make this happen,” says Jocelyn Monroe, a dark matter experimentalist at Royal Holloway, University of London.

Others prefer to double down on DUNE’s world-best ambitions, giving priority to advances in detector designs and analysis techniques that would not normally be considered in a race to come first. "A lot of really good ideas tend to get pushed away because DUNE is 'on rails': it has to work, and it has to be done this way," Asaadi says. One novel proposal, called THEIA, combines a water-based detector, like Hyper-K, alongside a "scintillation" detector that is more akin to DUNE—to reap the benefits of both approaches.

Among physicists, there seems to be universal agreement on one thing: The stakes on turning DUNE's sunk-cost fallacy into an opportunity are high. "What we're really working on very hard right now is trying to establish all these connections with the rest of the Snowmass community," Scholberg says. Discussions will continue through the summer and then feed into decisions of the Particle Physics Project Prioritization Panel, a U.S. federal advisory group, which next year will decide whether DUNE/LBNF remains a flagship U.S. project. "We need to make sure that everybody is onboard," de Gouvêa says. "Uncertainty is bad for a very long-term project because people have to invest a large fraction of their time on it.... You don't want the effort to be in vain."

—*Thomas Lewton*

Canadian Telescope Delivers Deepest-Ever Radio View of Cosmic Web

Data from the CHIME radio observatory are a milestone in the quest to discover the hidden origins of universal structure

Peer into the sky through a powerful telescope and beyond the glare of the Milky Way, you can make out the faint glow of distant galaxies. These galaxies clump together in dense clusters joined by wispy filaments and separated by enormous voids hundreds of millions of light-years across. Since the 1980s scientists have observed millions of galaxies to map this "cosmic web" in ever greater detail in their quest to understand our universe's history.

But there is more to this large-scale structure than meets the eye. Hydrogen atoms naturally emit radio waves with a characteristic 21-centimeter wavelength, and because hydrogen gas clouds tend to gravitationally cluster around galaxies, patterns in this radio emission reflect matter's underlying cosmic distribution. In a recent preprint paper, radio astronomers working on the Canadian Hydrogen Intensity Mapping Experiment (CHIME) report their first detection of these telltale patterns.

The result is an important first step toward a full map of the cosmic web using hydrogen's radio emissions, although CHIME's measurements have yet to reach the precision of state-of-the-art infrared and optical surveys charting large-scale structure. "It's not the 'holy grail' result yet, but it's a milestone for CHIME and also for the field," says Tzu-Ching Chang, a research scientist at the NASA Jet Propulsion Laboratory, who was not involved in the work.

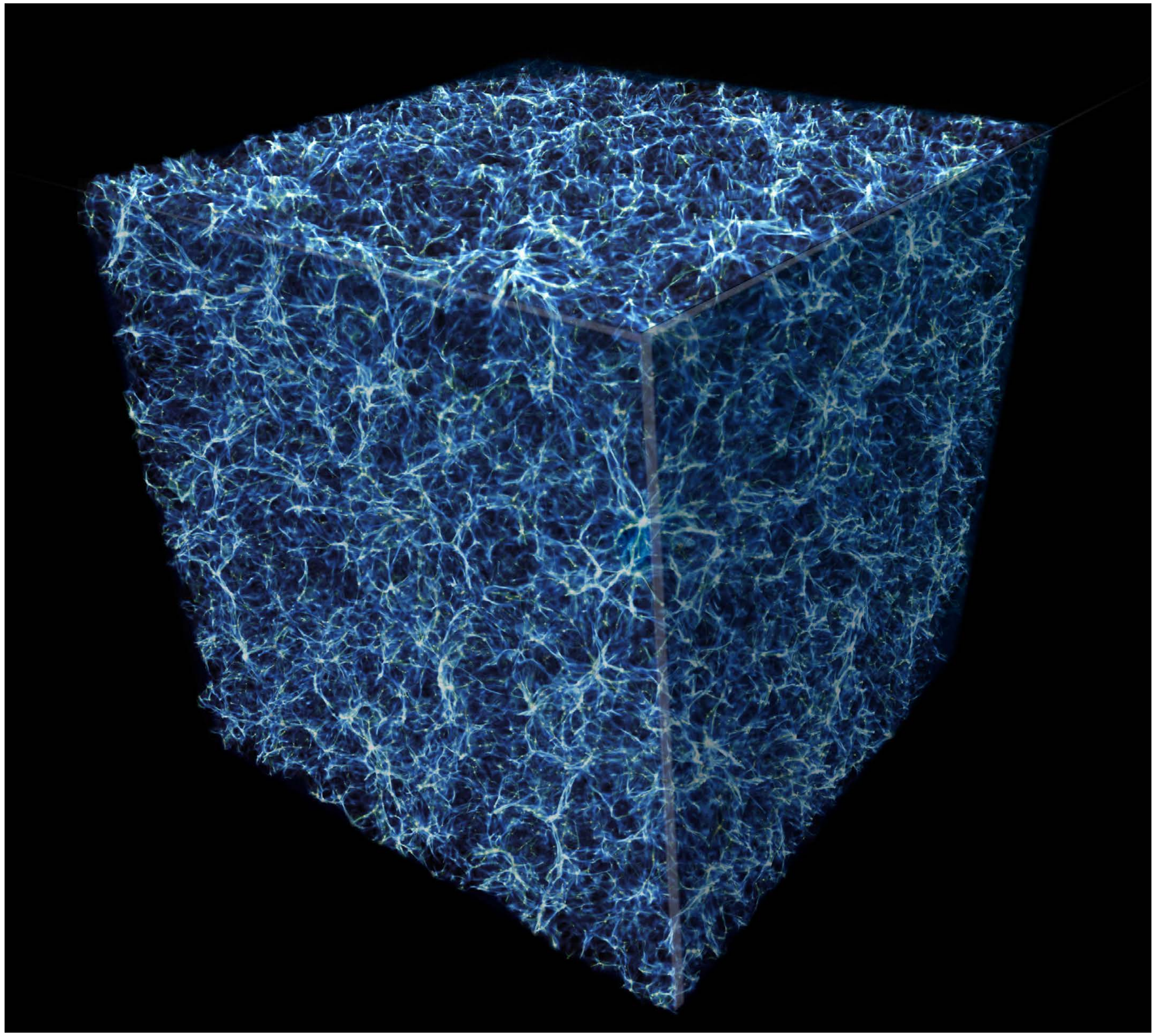
UNCHARTED SPACE

In the universe's "dark ages," the few hundred million years after protons and electrons first combined to form atoms following the big bang, no stars existed to illuminate all the hydrogen gas then suffusing space. That gas grew denser in some places and more rarefied in others as the tug of gravity competed with cosmic expansion, and the densest regions eventually gave birth to luminous stars, galaxies and galaxy clusters.

By the 1990s cosmologists thought they understood the broad strokes of this story. So they were shocked to discover in 1998 that cosmic expansion began mysteriously speeding up around five billion years ago, after more than eight billion years of contented coasting. Next to nothing is known about the "dark energy" responsible for this acceleration; one important open question is whether it is an immutable "cosmological constant" or rather a dynamic field with a strength that changes over time.

Maps of the cosmic web may point toward an answer. Light from more distant galaxies takes longer to reach us, and the expansion of the universe stretches the wavelength of this ancient light toward the red end of the visible spectrum: the more distant the galaxy, the larger the cosmic redshift. Precise redshift measurements, based on the unique spectral fingerprints of atoms that are abundant within galaxies, thus allow astronomers to construct three-dimensional maps of the cosmic web. These maps encode a wealth of information about the history of cosmic expansion and the evolution of large-scale structure.

The most recent completed galaxy survey, called the Extended Baryon Oscillation Spectroscopic Survey (eBOSS), catalogued the positions and redshifts of half a million galaxies and as many quasars—extremely bright regions at the cores of large galaxies powered by supermassive black holes. The eBOSS team then used this catalog to construct a map that covers about 15 percent of the sky and stretches back more than 11 billion years. And even more ambitious follow-up surveys are underway.



Visualization from a simulation of the "cosmic web," a network of filaments that are mostly made of dark matter. This web helps form galaxies, galaxy clusters and other immense structures.

NASA/ESA/E. Hallman (University of Colorado Boulder)

A NEW HOPE

Yet despite their successes, galaxy surveys have their limitations. Telescopes must first scan the sky to select galaxies to include in the survey, and subsequent measurements of individual galaxy redshifts tend to be time-consuming. State-of-the-art surveys also demand expensive spectrometers with thousands of moving parts.

Hydrogen intensity mapping, the strategy pursued by CHIME, could prove a cheaper and faster way to map the cosmos. 21-cm radio waves from distant gas clouds get redshifted just like visible light. But radio telescopes can measure how the intensity of radio emission varies across the sky at many different wavelengths at once, enabling astronomers to construct three-dimensional maps without separate redshift measurements. Dedicated intensity mapping telescopes are also inexpensive, "an order of magnitude cheaper than comparable spectroscopic instruments in optical or infrared," says Kavilan Moodley, a professor of astronomy at the University of KwaZulu-Natal in South Africa, who is not affiliated with CHIME.

Intensity mapping faces its own challenges. The main difficulty is that the cosmological signal is small, and the Milky Way itself is a strong radio emitter. "You're trying to look behind it at something which is 1,000 or 10,000 times fainter," Moodley says. Teasing out the imprint of the cosmic web requires precise telescope modeling and careful analysis.

CHIME is a row of four radio telescopes with no moving parts, each resembling a snowboarding half-pipe made of chicken wire. As Earth rotates, the telescopes sweep out a low-resolution map of the entire northern hemisphere. The resulting 3-D map is composed of "voxels" rather than "pixels," with each voxel roughly 30 million light-years on a side, 10 million light-years deep and typically filled with hundreds of galaxies. That coarse spatial resolution is a feature, not a bug: adding up the radio emission from all the hydrogen in each voxel allows astronomers to pick up faint signals they would not otherwise see. And because the effects of dark energy are most pronounced at very large distance scales, the structure within individual voxels is irrelevant for these studies.

In 2009 and 2010 Chang and other astronomers found the first traces of the cosmic web in hydrogen's 21-cm emission using radio telescopes in Australia and West Virginia. But these telescopes are 100-meter dishes that collect light from a small region of the sky, so they could not efficiently map the large areas necessary for a more complete view. These facilities are also in high demand, and only a fraction of their observations can be devoted to 21-cm observations.

The new CHIME results, derived from data collected in 2019, are the first from a radio telescope that was specifically designed to map the cosmic web. This allowed the CHIME researchers to better control systematic errors, and they did not have to compete with other astronomers for telescope time. The project's data go back as far as nine billion years, a billion years deeper into the past than previous radio measurements.

THE FIRST SIGNAL–BUT NOT THE LAST

After processing their data to remove foreground emission from the Milky Way and terrestrial sources, the researchers used a technique called "stacking" to study the correlations between CHIME's data and galaxy maps from the eBOSS survey. They saw an unmistakable signal: the regions of more intense radio emission overlapped with the positions of known galaxies and quasars. "When you have that first detection, it's enormously motivating," says Seth Siegel, a research scientist at McGill University and one of the leaders of the CHIME team's analysis. The result is an important milestone, he says, because it gives the CHIME researchers a baseline from which they can pursue further improvements.

The team is now working on using more recent CHIME data to construct a stand-alone map, without the aid of the eBOSS catalog. It then plans to search for correlations in the distribution of hydrogen gas on longer distance scales, for which teasing apart the signal from foreground emission becomes especially challenging. Such correlations are the vestiges of sound waves—called "baryon acoustic oscillations" by cosmologists—that rippled through the fiery primordial plasma that filled the early universe. The characteristic scale of these oscillations—roughly 500 million light-years in the present-day universe—has been measured precisely using other methods. Thus, baryon acoustic oscillations can serve as a sort of yardstick that the team can use to measure other distances in its maps in search of deviations from standard cosmology, such as changes in the strength of dark energy.

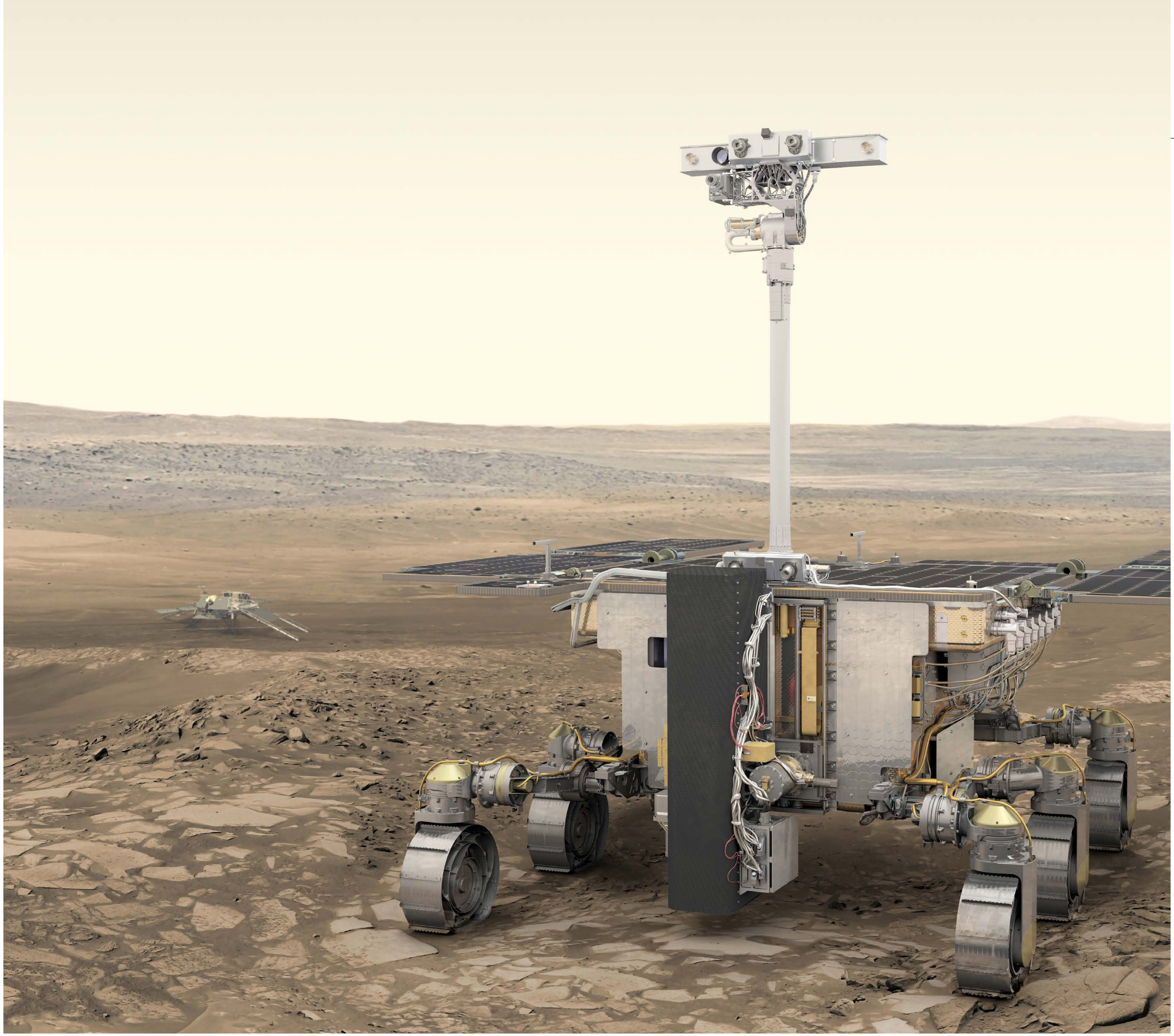
Richard Shaw, a research scientist at the University of British Columbia, who co-led the analysis with Siegel, emphasizes that this is just the beginning for CHIME. "We have bags of data in the can and more coming," he says.

—Ben Brubaker

Will NASA Save Europe's Beleaguered Mars Rover?

Russia's invasion of Ukraine ended hopes of launching the ExoMars rover in 2022. Now the mission may never lift off at all

Europe's long-awaited ExoMars rover—the first ever for the continent—seems to be cursed. Parachute problems scuppered its initially planned launch in 2018. Then the coronavirus pandemic prevented a launch in 2020. And now Russia's invasion of Ukraine has dashed chances for a liftoff in 2022. For members of the team hoping "the third time's the charm," this latest delay feels especially cruel. "It was impossible for me to speak about this mission for weeks without tears," says Valérie Ciarletti of the Laboratory for Atmospheres, Environments, Space Observations (LATMOS) in France, who leads the rover's subsurface radar instrument team. After more than 20 years of planning and development, the fully assembled



Artist's concept of the European Space Agency's ExoMars rover Rosalind Franklin on the surface of Mars.

ESA/ATG medialab

rover sits awaiting launch in a facility in Turin, Italy. Yet it appears increasingly likely that ExoMars will never lift off at all. European Space Agency (ESA) officials are now weighing whether to attempt a launch for a fourth time versus canceling the mission and moving on. The cursed rover may still be saved—but at what cost?

Named Rosalind Franklin after the famed English chemist who discovered the double helix structure of DNA, Europe's rover would be a significant step forward in the hunt for life on the Red Planet. Whereas NASA's Perseverance rover, currently exploring an ancient river delta inside Jezero Crater, relies on an elaborate grab-and-go Mars Sample Return program to deliver Martian material back to Earth for astrobiological analysis, the Franklin rover would perform a direct search without needing sample return. It would look deeper, too: using a drill, it would reach as much as two meters below the surface, where evidence of life is less likely to have been erased by blasts of cosmic radiation. (Neither Perseverance nor its near-twin the Curiosity rover is equipped to probe such depths.)

"The ExoMars rover has been built purely with astrobiology in mind," says Melissa McHugh of the University of Leicester in England, who is part of the science team for the rover's laser spectrometer instrument. "What's underneath the surface of Mars has huge biological implications."

If all had gone to plan earlier this year, the Franklin rover would have launched on a Russian Proton rocket in September before it was lowered to the surface by a Russian-powered landing platform called Kazachok in June 2023. But on March 17, 2022, following Russia's widely condemned invasion of Ukraine, ESA chose to cut ties with the nation on the mission, suspending the Franklin rover indefinitely. ESA officials expect to formally decide whether to proceed with the mission by the time of the agency's ministerial meeting in November 2022.

ROUTES TO THE RED PLANET

One possible route for the rover reaching the Martian surface runs through the U.S., via NASA-supplied components and capabilities to augment a new ESA-built lander replacing Kazachok. "Our teams are working with the teams in NASA about the technical steps that need to be done," said Josef Aschbacher, director general of ESA, in an interview with *SpaceNews* in April. In an e-mailed statement to *Scientific American*, NASA officials confirmed those exploratory efforts: "We have recently begun a joint assessment of options for the ExoMars mission," they wrote. "Once we know more, we will incorporate that information into our plans."

Alternatively (and improbably), the mission's route could still run through Russia. Jorge Vago, the rover's project scientist at ESA, says repartnering with Russia for a launch in 2024 would be "the most rapid and easiest way" to get to Mars, given that the rover and its landing platform are both already built. But "the way things are going with the war, it's very difficult to think this may be possible." Given the obstacles to such a partnership reemerging, Vago says the only real viable option is for ESA to build its own lander with NASA's assistance. "This takes time," he adds.

Time is not exactly on ESA's side, however. The Earth-to-Mars voyage is easiest when both planets are properly aligned, which occurs every 26 months. The laborious process of building and testing new hardware would take a 2024 launch off the table, Vago says, but a 2026 or 2028 liftoff could be a possibility. ESA could potentially repurpose the parts it contributed to the Kazachok lander, yet the Russian-built components—the landing legs, heat shield, descent engines, and more—would have to be developed from scratch. The engines pose a particular problem because no European manufacturers offer any that are capable of landing on Mars. Similarly, ESA lacks the plutonium required for a radioisotope heating unit to keep the rover warm—something the U.S. (or Russia) could provide. "So we are asking NASA if they could contribute those," Vago says. "These are the talks we're having right now."

ESA and NASA are already collaborating on the next steps for their joint Mars Sample Return program, with Europe assigned to develop the fetch rover to pick up the samples cached by Perseverance, as well as the spacecraft to bring those samples home. Vago says ESA might ask NASA to help out with ExoMars in return for ESA locking in its planned contributions to the sample-return effort.

The situation carries considerable irony: In the early 2000s Europe and the U.S. had tentative plans to work together on a life-seeking Mars mission, involving two rovers that would overlap in their science goals. But NASA pulled out of the endeavor in 2011, citing a lack of funding, before announcing the mission concept that would become the multibillion-dollar Perseverance rover later that year. The other European-led component became the Franklin rover, and ESA was forced to turn to Russia as a partner. The experience left a bitter taste for many in Europe. "We were perplexed," says Chris Lee, former chief space scientist at the U.K. Space Agency. "People were very annoyed."

OXIA PLANUM OR BUST

The Franklin rover would touch down in a region of Mars's northern hemisphere called Oxia Planum. This locale is home to another ancient river delta thought to date back 4.1 billion years—hundreds of millions of years older than the geologic features now being explored by Perseverance and Curiosity at their respective sites. If the rover is saved, it's unlikely ESA would consider sending it to a different location. "We want to go to the site we have," Vago says. "It's amazing. It would be the oldest location that had been visited by a Mars mission. It gives us a unique chance to look at the very earliest minerals that were produced on Mars."

The other uncomfortable possibility, however, is that ESA may cut its losses and choose to cancel the mission. Aside from developing a new landing system and purchasing a new rocket launch, storing the rover in perfectly clean conditions for six years would require a significant investment. Even now engineers must constantly flush the rover with argon to ensure it is kept in the pristine condition needed to minimize the chances of contamination from Earth-based microbes. Some experts wonder if those resources might be better spent elsewhere.

"Is it worth it?" Lee says. "Unless the NASA discussions with ESA are all about trying to bring ExoMars back in from the cold, I really don't see it going forward anymore." But David Southwood, former director of science and robotic exploration at ESA, says the agency should do all it can to get the rover to Mars. "That would be my highest priority on a wish list," he says.

What is certain is that the fate of this rover, troubled for so long, is likely to drag on for months. That leaves scientists working on the mission unsure of what their future holds. "If ExoMars is never going to be launched, this is a waste of our time and effort," Ciarletti says. "For almost 20 years we have been working on an instrument [for the rover]. It's absolutely disappointing." For now European scientists eager to see their first homegrown rover reach Mars can do little more than wait. *—Jonathan O'Callaghan*

NASA Triumphantly Unveils Full Set of Webb's First Images

Breathtaking pictures that include the deepest-ever infrared view of ancient galaxies offer a preview of the spectacular science in store for the most powerful space observatory in history

By Lee Billings

The Webb telescope's image of the galaxy cluster SMACS 0723 reveals thousands of galaxies, among them the faintest and most distant ever seen in infrared. This picture covers a patch of sky roughly equivalent to the size of a grain of sand held at arm's length.

NASA, ESA, CSA and STScI

Lee Billings is a senior editor for space and physics at *Scientific American*.

THE NEXT GREAT ERA OF ASTRONOMY TRULY BEGAN the morning of July 12. After nearly three decades of troubled development and $10 billion in spending, a pulse-pounding launch on Christmas Day in 2021 and a nail-biting half-year of delicate preparations in deep space, the James Webb Space Telescope has at last delivered a complete set of first full-color images. President Joe Biden himself offered a sneak preview from the White House, revealing what is destined to be the most iconic picture from the set.

"These images are going to remind the world that America can do big things and remind the American people—especially our children–that there's nothing beyond our capacity," President Biden said during the event. "We can see possibilities no one has ever seen before. We can go places no one has ever gone before."

Constructed by NASA, as well as Europe's and Canada's space agencies, Webb is controversially named for a former NASA administrator, and it is the most powerful off-world observatory yet built. But for a time the observatory was more of a cruel joke among astronomers: the technical demands of its development pushed the project so far over budget and behind schedule that many suspected it would never launch at all. Now it promises to revolutionize our understanding of the cosmos during a mission that could stretch into the 2040s. Each of the telescope's latest images has marshaled the might of at least one of Webb's four main instruments, as well as its giant 6.5-meter segmented primary mirror, composed of 18 coffee-table-sized hexagonal slabs of gold-plated beryllium that folded together like a piece of origami to fit within an Ariane 5 rocket. Perched 1.5 million kilometers from Earth and shaded by a multilayered sunshield as big as a tennis court, the telescope's kit is cooled close to the temperature of the vacuum of space. That deep freeze allows it to see—or rather feel—the infrared glow of far-flung galaxies, nearby planets and everything in between.

SPECIAL REPORT

The James Webb Space Telescope

- See the Oldest View of Our Known Universe, Just Revealed by the James Webb Space Telescope
- Webb's Record-Breaking First Image Shows Why We Build Telescopes
- Meet the Woman Who Makes the James Webb Space Telescope Work

Read the report

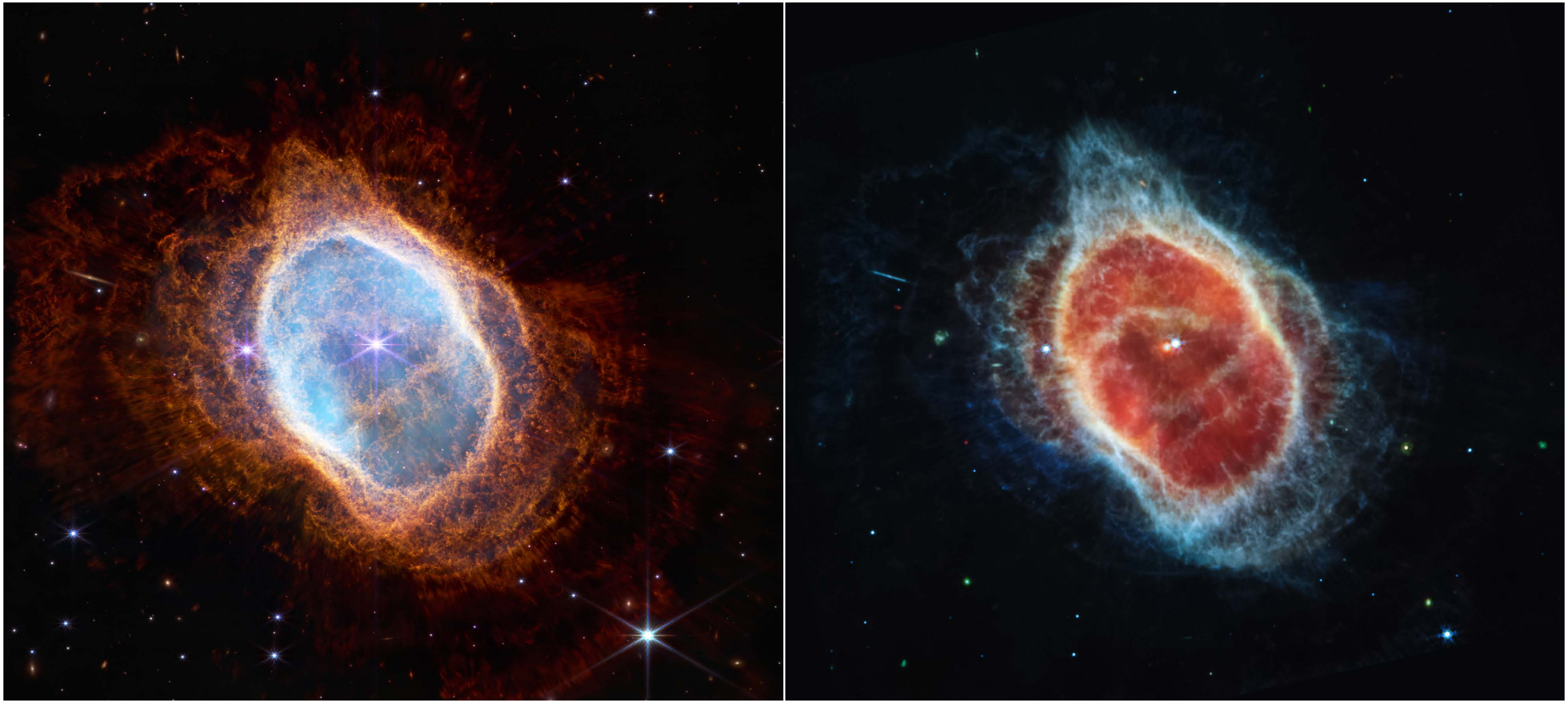
Even before the official images were released, earlier pictures taken to guide Webb's complex deep-space commissioning hinted at the observatory's stunning capabilities. Simple snapshots of a star obtained by the telescope's workhorse instrument, the Near Infrared Camera (NIRCam), also serendipitously included more than 1,000 "photobombing" background galaxies that would have been too faint to simply swim into view in any other observatory's optics. These and other preliminary tests, says NIRCam's principal investigator Marcia Rieke of the University of Arizona, have shown that "all of Webb's instruments are achieving even better sensitivities than we projected" and that the performance of its mirror is similarly exceeding expectations. With these new images, Rieke says, "we are now seeing that the science returns are probably going to be even greater than we had dared to hope."

ALL EYES ON WEBB

Designed to showcase the breadth and depth of Webb's cosmic vision while also serving as enrapturing eye candy, these first science images indeed do not disappoint. Among them are unprecedentedly detailed views of the Carina Nebula—a tumultuous stellar nursery about 7,600 light-years from Earth that is illuminated by the bright, brief lives of massive stars—as well as a portrait of the Southern Ring Nebula, a more than 2,000-light-year-distant dying sun expelling its element-enriched outer layers as turbulent shrouds of glowing gas. The cycle of celestial creation and destruction continues in other images from some 290 million light-years out that capture the interacting galaxies of Stephan's Quintet, which are sparking intense bouts of star formation within gigantic intergalactic shock waves as they slowly merge into a single larger galaxy.

But the full scope of Webb's audacious scientific ambit is best revealed through two other images—one striking and one subtle.

The subtle one is a spectrum—essentially just a squiggly series of peaks and valleys recording how various wavelengths of light shine through the upper atmosphere of WASP-96b, a scorched exoplanet with half the mass of Jupiter that orbits a star more than 1,000 light-years away once every 3.4 days. Such spectra are hardly images at all but can reveal an object's bulk composition, says Knicole Colón, Webb's deputy project scientist for exoplanet science at the NASA Goddard Space Flight Center. "Webb will provide the first relatively high-resolution infrared spectra of exoplanet atmospheres, opening a new



A side-by-side comparison shows the Webb telescope's remarkably detailed observations of the Southern Ring Nebula in near-infrared light (*left*) and mid-infrared light (*right*). Located more than 2,000 light-years from Earth, the nebula is composed of shells of gas and dust expelled from a dying star, which in each image can be seen near the nebula's core.

NASA, ESA, CSA and STScI

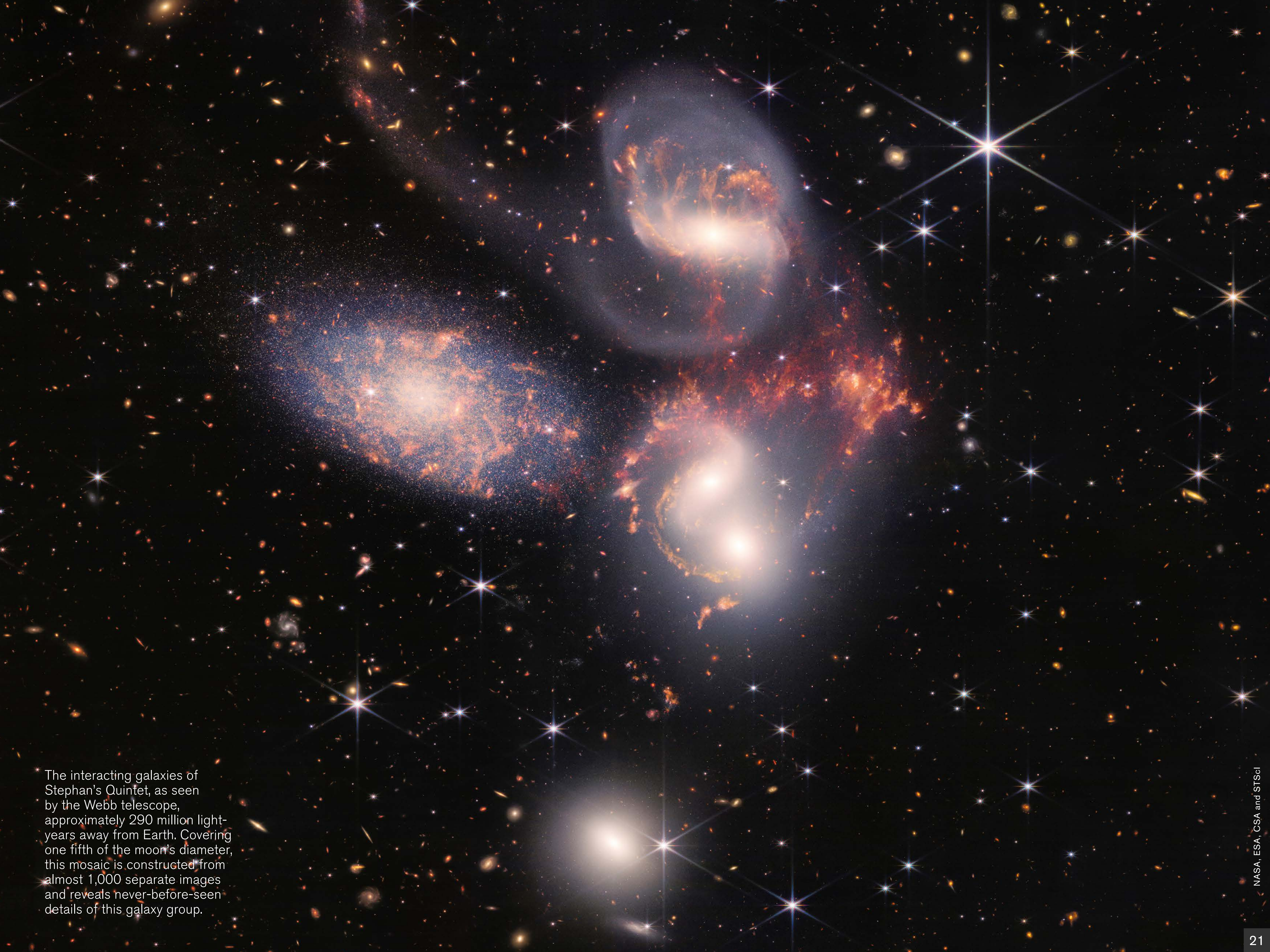
chapter in the era of exoplanet characterization," she adds.

A full 70 percent of the observatory's first year of planned observations involve taking spectra of some kind for targets all across the universe, according to Klaus Pontoppidan, Webb's project scientist at the Space Telescope Science Institute. Most of those measurements will chart the chemical evolution of galaxies across cosmic time and within star- and planet-forming disks scattered throughout the Milky Way. But some will instead record spectra for a handful of small, temperate worlds around nearby stars to sniff out the presence of atmospheric carbon dioxide, water vapor, methane and other compounds associated with habitability and life. Unlikely though it may be, one of Webb's hard-won spectra could in principle provide the first compelling evidence that we are not cosmically alone.

The most striking of the first images has little to do with the search for extraterrestrial life, yet is still so spectacular that it wooed the White House into a last-minute change of plans, allowing President Biden to share in the observatory's glory by presenting it to the world a day earlier than NASA originally intended. Captured by NIRCam, this image is Webb's "deep field" observation of SMACS 0723, a crowded region of the cosmos strewn with galaxies like so many jewels on black velvet. Most of those galactic jewels are more than four and a half billion light-years away, but they are a foreground distraction to the true treasure, which can be found in the dim, distorted shapes lurking in the darkness beyond. The entire galaxy-packed image spans a stretch of sky approximately the size of a sand grain held at arm's length.

CONTEMPLATING THE COSMIC DAWN

The collective bulk of SMACS 0723's clustered galaxies is so great that it warps the surrounding space, forming a bubblelike "gravitational lens" through which the fainter light of much more distant background galaxies—per-



The interacting galaxies of Stephan's Quintet, as seen by the Webb telescope, approximately 290 million light-years away from Earth. Covering one fifth of the moon's diameter, this mosaic is constructed from almost 1,000 separate images and reveals never-before-seen details of this galaxy group.

NASA, ESA, CSA and STScI

An image from the Webb telescope reveals hundreds of previously invisible newborn stars in the stellar nursery known as the Carina Nebula, a vast agglomeration of gas and dust some 7,600 light-years from Earth.

NASA, ESA, CSA and STScI

haps among the very first luminous objects in the cosmos—is warped and magnified into view. Such images make Webb less a telescope and more a time machine, for in creating them, it gathers light from eons ago, sent forth only a few epochal moments after the big bang, during the so-called cosmic dawn, when the first stars and galaxies are thought to have formed. The Hubble Space Telescope and other predecessor facilities have taken similar images but lacked the sensitivity to detect those most distant galaxies that Webb can see in droves. These objects not only appear intrinsically faint and minuscule in the sky but also lie so far back in the past that the subsequent expansion of the universe itself has stretched out, or "redshifted," the wavelengths of their emitted light into the infrared. They are the elusive quarry Webb was meant to hunt from the project's very inception in an obscure 1996 technical report that referred to it, after Hubble, as simply the Next Generation Space Telescope.

Knowing just how far back Webb has seen with the SMACS 0723 deep field, Rieke says, will require additional observations to measure redshifts for each gravitationally lensed galaxy. But what's already certain is that this is the deepest, clearest infrared image of the universe yet made—a fact not lost on those who helped create it. Cryptically referring to the image in a teaser press conference weeks before its release, Thomas Zurbuchen, associate administrator for NASA's Science Mission Directorate, stated that viewing Webb's first visualizations had almost moved him to tears.

It was Pontoppidan, tasked with downloading and then distributing Webb's raw data to the 30-person team that prepared its inaugural images, who was the very first to see the SMACS 0723 deep field. For a brief time, from his home office he gazed farther into the universe's luminous depths than any other earthling ever had. "I spent probably two full hours just staring at it," he recalls, "sitting in my basement, in front of my computer screen, feeling very alone in the world." The image elicited a similar hush when the rest of the team saw it during an in-person group meeting. "It was moving," Pontoppidan says. "All the people in that room were just quiet for a long time."

To see this image—to be, if even for a moment, lost in its ineffable galaxy-studded depths—is to appreciate just how far we have come. Webb is so technically daunting that, in the words of Keith Parrish, the telescope's observatory manager at Goddard, it "did not want to exist." Yet it did endure, surviving numerous near-death experiences on its decades-long path to the launchpad and then, against all odds, running a gauntlet of make-or-break deployments beyond Earth. Viewing its first dedicated deep-field image reveals a journey even more epic and tinged with what may best be called the divine: glimpsing those newborn galaxies ablaze with the light of the first stars, we see our earliest cosmic ancestors emerging from the void, holding the shape of all things to come—the Milky Way, the sun, Earth and us—latent in their ancient majesty. Fittingly, the more one knows about Webb's origins—and the more it reveals about ours—the more miraculous its existence and our own appear to be. For those attuned to perceive it, the great weight of this knowledge comes to rest within a wordless contemplative space, making the heart tremble as readily as any sermon or hymn.

"Astronomy has an inherent ability to make us think bigger—to think outside ourselves and consider our place in the universe," says Amber Straughn, Webb's deputy project scientist at Goddard. "Exploration and discovery tap into something deep inside all of us—they are key parts of what makes us human. This telescope is going to change how we understand the universe in ways we haven't even dreamed of."

THE ROAD AHEAD

The observatory's success, Pontoppidan whimsically muses, speaks against bleak, all-too-common assessments of our present moment on Earth being the darkest time line in some notional multiverse. "Webb's launch and early commissioning up through now can be seen as a split between two radically distinct worlds," he says. "There is a world where we put $10 billion into this complicated origami observatory, and it just collapsed in on itself in a huge fiasco. And then there is the world we're remarkably inhabiting now, where this thing actually worked! Where we go from here with Webb—with astronomy in general—is to a very different place."

And as most every astronomer will eagerly remind you, the telescope's transformative mission has scarcely even begun. "It's one thing to predict its power, but it's another to see what Webb can produce almost without even trying," Colón says. "These first images only scratch the surface of what Webb is capable of."

Hubble's deepest image of the universe, Pontoppidan notes, took 14 days of dedicated staring at the same spot on the sky. Webb's record-breaking deep-field image—along with all the others released today—collectively emerged from a total of just five days of observing time. "You know, we weren't trying to scoop anybody or make the forever-deepest field," he says. "Whatever we have done, other scientists using Webb will now do even better—and quickly."

That astounding pace, says Jane Rigby, the telescope's operations project scientist at Goddard, makes Webb "a Bugatti sports car that has been built in a horse-and-buggy world." "It's like the difference between traveling three versus 300 miles per hour," she says. "And now we're going to actually take this thing out on the racetrack. So how deep, how far can we go when we crank it up and push it hard? I'm as excited as anyone else about these first images, but my heart is with the thousands and thousands hours of competitively selected, peer-reviewed science we are about to undertake in Webb's first year of observations."

New Record-Breaking Simulation Sheds Light on “Cosmic Dawn”

THESAN–the largest, most detailed computer model of the universe’s first billion years yet made–is helping set expectations for observations from NASA’s James Webb Space Telescope

By Charles Q. Choi

Mark Garlick/Science Photo Library/Getty Images

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.

MUCH REMAINS A MYSTERY ABOUT THE FIRST BILLION YEARS OF THE universe's history, the epoch in which the cosmos emerged from its dark ages with the dawning of the earliest stars and galaxies. Now scientists have developed the largest, most detailed computer model of this period to date to help shed light on how the infant universe evolved. Named THESAN, after the Etruscan goddess of the dawn, this new project's predictions about the primordial past will soon be tested by data from NASA's recently launched James Webb Space Telescope (JWST) and other next-generation observatories.

In the immediate aftermath of the big bang, about 13.8 billion years ago, the universe was filled with a cosmic fog. The heat of creation was so great that electrons could not combine with protons and neutrons to form atoms, and space was instead suffused with a dense soup of plasma—electrically charged (or ionized) particles that scattered rather than transmitted light. This cosmic fog briefly lifted some 380,000 years later, during the so-called era of recombination, when the universe sufficiently cooled to allow atoms to freeze out from the plasma as clouds of optically transparent, electrically neutral hydrogen gas. Suddenly freed, light from the big bang's afterglow flashed throughout the universe, which then faded back to darkness because stars had yet to form.

Darkness reigned for the next few hundred million years until gravity began pulling matter together into stars and galaxies. Even then, the darkness only dissipated gradually, as intense ultraviolet radiation from the universe's first luminous objects reionized the surrounding neutral hydrogen, eventually burning away the gaseous gloom. This "epoch of reionization" lasted more than a half-billion years, but scientists know precious little about its details. What they do know with certainty is that its end marked the cosmic moment when light from across the electromagnetic spectrum—rather than the mere fraction that could pierce the veil of neutral hydrogen—started traveling freely through space. Simply put, this was when the universe at last became clear for study by curious astronomers seeking to learn how exactly the cosmic dawn occurred.

That is not to say that such studies are easy. To see light from such ancient times, researchers must use the largest, most sensitive telescopes available to look for objects that are as far away as possible. This is because the greater an object's distance, the more time its light took to reach Earth—and the more attenuated that light will be.

A COMPUTATIONAL COSMIC DAWN

Another way to gain insights on this bygone era is to simulate it on computers. The early stages of reionization are relatively simple to re-create because the universe was relatively dark and uniform then, explains Aaron Smith, an astrophysicist at the Massachusetts Institute of Technology. As primordial matter sorts itself into galaxies and stars, however, complex interactions between gravity, light, gas and dust become increasingly difficult to model. Smith is one of the three co-leads of the THESAN project, alongside Rahul Kannan of the Harvard-Smithsonian Center for Astrophysics and Enrico Garaldi of the Max Planck Institute for Astrophysics in Garching, Germany.

"Since modeling light is quite complicated and computationally expensive, there are only a few cosmological simulations that focus on exploring this epoch," Kannan says. "Each of these cosmological simulations have their own advantages and disadvantages."

THESAN is designed to simulate the early universe to an unprecedented extent. Some cosmological simulations, such as the Cosmic Dawn (CoDa) simulations and the Cosmic Reionization on Computers (CROC) project, have modeled large volumes at relatively low resolutions, while others, such as the Renaissance and SPHINX simulations, are more detailed but do not span great distances. In contrast, THESAN "combines high resolution with large simulated volumes," Kannan says.

"Usually there's a trade-off between studying in detail galaxy formation and cosmic reionization, but THESAN manages to do both," says astrophysicist John Wise of the

Georgia Institute of Technology, who did not work on THESAN.

THESAN's developers built it on the back of an older series of simulations called Illustris-TNG, which have been shown to accurately model many of the properties and populations of evolving galaxies. They next developed a new algorithm to model how the light from stars and galaxies interacted with and reionized their surrounding gas over the first billion years of the universe—details that previous simulations have not successfully incorporated at large scales. Finally, the THESAN team included a model of how cosmic dust in the early universe may have influenced the formation of galaxies.

"They've combined two state-of-the-art models and added a bit more—it looks really interesting," says Risa Wechsler, a cosmologist at Stanford University and director of the Kavli Institute for Particle Astrophysics and Cosmology, who did not take part on THESAN.

SCALING UP

THESAN can track the birth and evolution of hundreds of thousands of galaxies within a cubic volume spanning more than 300 million light-years across. Starting from circa 400,000 years after the big bang—before the first stars are thought to have emerged—the simulation extrapolates out through the first billion years of cosmic history. To do all that, THESAN runs on one of the largest supercomputers in the world, SuperMUC-NG, which has used nearly 60,000 computer processing cores to perform the simulation's calculations over an equivalent of 30 million CPU hours. (For perspective, that same computational feat would require 3,500 years of dedicated number crunching on a typical desktop computer.)

"One of the most exciting things about the THESAN simulations to me is the increased resolution," says astrophysicist Brian Welch of Johns Hopkins University, who did not work on THESAN. "They seem to be able to connect the small-scale structures within galaxies that create ionizing photons to the larger-scale intergalactic medium where those photons are driving the epoch of reionization. The simulations can then help determine how ionizing photons are escaping from galaxies and thus how those galaxies are driving reionization."

> **"Usually there's a trade-off between studying in detail galaxy formation and cosmic reionization, but THESAN manages to do both."**
>
> ***—John Wise***

Using the Hubble Space Telescope, Welch and his colleagues recently discovered the most distant single star detected yet, dubbed Earendel, which dates back to when the universe was just 900 million years old. Although THESAN cannot simulate individual stars such as Earendel "since that would require an inordinate amount of computational power," it can still shed light on the conditions in the galaxies in which Earendel and its compatriots were forming, he says.

The researchers say THESAN is already yielding predictions about the early universe. For example, it suggests the distance that light traveled increased near the end of reionization more dramatically than previously thought—by a factor of 10 over a few hundred million years—likely because dense pockets of gas that took longer to ionize were missed by previous lower-resolution simulations.

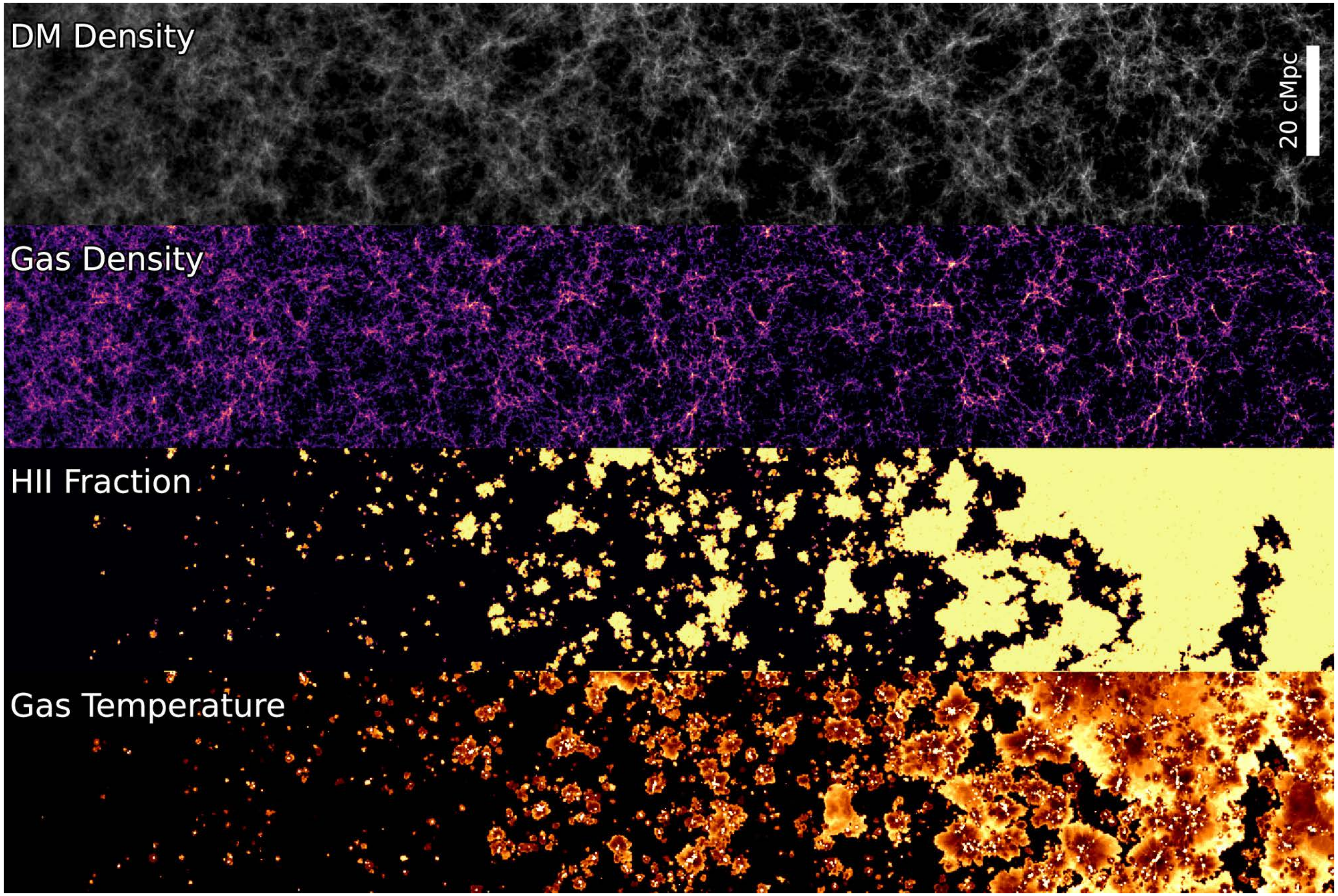
One drawback of THESAN, however, is that it uses a relatively simplistic model for the cold dense gas in galaxies, Kannan says. The THESAN team is currently working on a follow-on project dubbed THESAN-ZOOMS to replace this model "with a much more sophisticated one that takes into account many additional physical processes that impact the properties of this dense gas," he notes.

Another shortcoming of THESAN is that the volume it simulates is arguably too small to properly pinpoint key details on how the early universe evolved, such as the size and number of pockets of ionized transparent gas, Kannan says. The scientists are currently planning to scale up the simulation to a volume 64 times larger via a diverse set of optimization tweaks meant to improve its overall performance, he says.

EXPECTATIONS VERSUS REALITY

Whether any of these deficiencies actually make a meaningful difference for THESAN's predictions could soon be revealed by fresh observations from JWST, which is designed to see the first stars and galaxies. Will the stars and galaxies coalescing in THESAN's virtual cosmos mirror the populations of ancient objects as seen by JWST's optics? Researchers are eager to find out. Models of the faint galaxies in the early universe are very sensitive to uncertainties in phenomena such as star formation, "which remain highly debated," says Aaron Yung, a theoretical astrophysicist at NASA's Goddard Space Flight Center, who did not work on THESAN. Simulations that may successfully model known galaxies "can deliver diverging predictions in the faint populations. [JWST] will detect these galaxies for the first time and provide constraints on the physics that drives the formation of these galaxies."

By the end of this year, JWST will be able to collect enough data to test THESAN when it comes to many predictions of galaxy properties, Smith says. "We are already working with astronomers involved with JWST to interpret the data that will be available this year."



Evolution of simulated properties in the main THESAN run. Time progresses from left to right. The dark matter (*top panel*) collapses in the cosmic web structure, composed of clumps (haloes) connected by filaments. The gas (*second panel from top*) follows, collapsing to create galaxies. These produce ionizing photons that drive cosmic reionization (*third panel from top*), heating up the gas in the process (*bottom panel*).

Courtesy of THESAN Simulations (CC bY-NC-ND 3.0)

“My intuition tells me that JWST will match the statistics of the bright galaxies modeled in CoDa, CROC and THESAN,” says Wise, who helped develop the Renaissance simulations. “However, they don’t have sufficient resolution to model low-mass and small galaxies, where Renaissance and SPHINX will match better.” Astrophysicists, he reasons, will most likely use a combination of both types of simulations to interpret JWST observations of ancient galaxies.

No one expects THESAN or any other simulation of the epoch of reionization to get everything completely right. “Most, if not all, simulations done in this epoch are missing some physics—even though THESAN is quite high-resolution, it’s still low-resolution, compared to the physical processes actually happening,” Wechsler says. “Progress happens when data from observatories and insights from simulations work in concert. That interplay is what is exciting.”

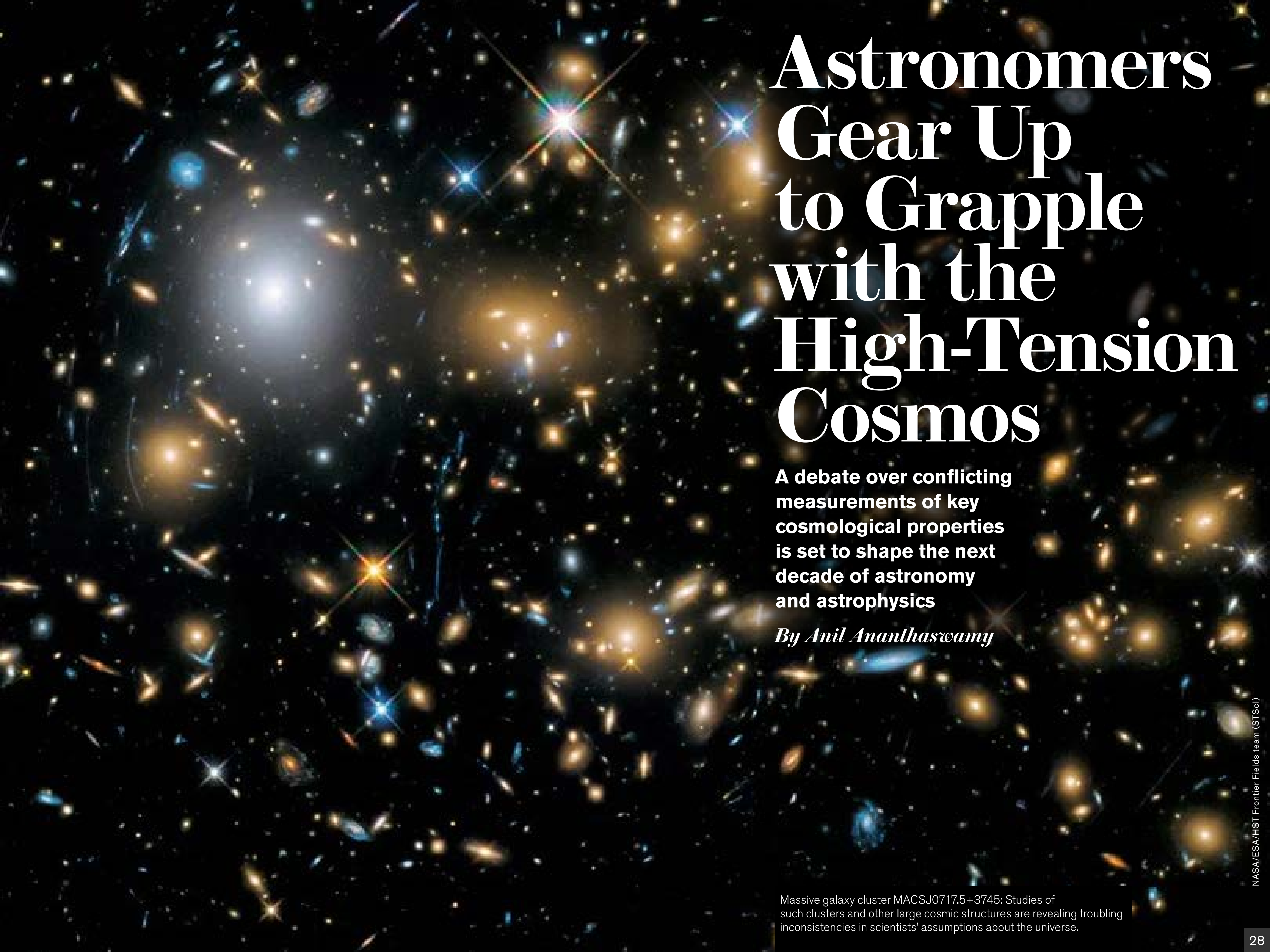
Ultimately “we will need more than JWST to confirm the complete picture of cosmic evolution in the early universe,” Garaldi says. “A variety of instruments covering a wide range of wavelengths are necessary to understand the various aspects of this epoch.” These include the Hydrogen Epoch of Reionization Array (HERA), the Square Kilometer Array (SKA), the Fred Young Submillimeter Telescope (FYST), the Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer (SPHEREx), and NASA’s next flagship astrophysical observatory, the Nancy Grace Roman Space Telescope. Ambitious computer models such as THESAN may ultimately help scientists make sense of the flood of data these projects will bring.

“THESAN aims to make predictions for as many of these observations as possible,” Smith notes. “Discrepancies with the data are often just as exciting because that tells us our models are lacking, forcing us to reconsider the underlying physics of these complex processes.”

Astronomers Gear Up to Grapple with the High-Tension Cosmos

A debate over conflicting measurements of key cosmological properties is set to shape the next decade of astronomy and astrophysics

By Anil Ananthaswamy



Massive galaxy cluster MACSJ0717.5+3745: Studies of such clusters and other large cosmic structures are revealing troubling inconsistencies in scientists' assumptions about the universe.

NASA/ESA/HST Frontier Fields team (STScI)

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

How fast is the universe expanding? How much does matter clump up in our cosmic neighborhood? Scientists use two methods to answer these questions. One involves observing the early cosmos and extrapolating to present times, and the other makes direct observations of the nearby universe. But there is a problem. The two methods consistently yield different answers. The simplest explanation for these discrepancies is merely that our measurements are somehow erroneous, but researchers are increasingly entertaining another, more breathtaking possibility: These twin tensions—between expectation and observation, between the early and late universe—may reflect some deep flaw in the Standard Model of cosmology, which encapsulates our knowledge and assumptions about the universe. Finding and fixing that flaw could transform our understanding of the cosmos.

One way or another, an answer seems certain to emerge over the coming decade, as new space and terrestrial telescopes give astronomers clearer cosmic views. "Pursuing these tensions is a great way to learn about the universe," says astrophysicist and Nobel laureate Adam Riess of Johns Hopkins University. "They give us the ability to focus our experiments on very specific tests rather than just making it a general fishing expedition."

These new telescopes, Riess anticipates, are about to usher in the third generation of precision cosmology. The first generation came in the 1990s and early 2000s with the Hubble Space Telescope and with NASA's WMAP satellite, which sharpened our measurements of the universe's oldest light, the cosmic microwave background (CMB). This first generation was also shaped by eight-meter-class telescopes in Chile and the twin 10-meter Keck behemoths in Hawaii.

Collectively, these observatories helped cosmologists formulate the Standard Model, which holds that the universe is a cocktail of 5 percent ordinary matter, 27 percent dark matter and 68 percent dark energy. The Standard Model can account with uncanny accuracy for most of what we observe about galaxies, galaxy clusters, and other large-scale structures and their evolution over cosmic time. Ironically, by its very success, the model highlights what we do not know: the exact nature of 95 percent of the universe.

Driven by even more precise measurements of the CMB from the European Space Agency's Planck satellite and various ground-based telescopes, the second generation of precision cosmology supported the Standard Model but also brought to light the tensions. The focus shifted to reducing so-called systematics: repeatable errors that creep in because of faults in the design of experiments or equipment.

The third generation is only now starting to take the stage with the successful launch and deep-space deployment of Hubble's successor, the James Webb Space Telescope (JWST). On Earth, radio telescope arrays such as the Simons Observatory in the Atacama Desert in Chile and the CMB-S4, a future assemblage of 21 dishes and half a million cryogenically cooled detectors that will be divided between sites in the Atacama and at the South Pole, should take CMB measurements with Planck-surpassing levels of precision.

The centerpieces of the third generation will be telescopes that stare at wide swaths of the sky. The first of these is likely to be the ESA's 1.2-meter Euclid space telescope, due for launch in 2023. Euclid will study the shapes and distributions of billions of galaxies with a gaze that spans about a third of the sky. Its observations will dovetail with those of NASA's Nancy Grace Roman Space Telescope, a 2.4-meter telescope with a field of view about 100 times bigger than Hubble's, which is slated for launch in 2025. Finally, when it begins operations in the mid-2020s, the ground-based Vera C. Rubin Observatory in Chile will map the entire overhead sky every few nights with its 8.4-meter mirror and a three-billion-pixel camera, the largest ever built for astronomy. "We're not going to be limited by noise and by systematics, because these are independent observatories," says astrophysicist Priyamvada Natarajan of Yale University. "Even if we have a systematic in our framework, we should [be able to] figure it out."

SCALING THE DISTANCE LADDER

Riess would like to see a resolution of the Hubble tension, which arises from differing estimates of the value of the Hubble constant, H_0—the rate at which the universe is expanding. Riess leads a project called Supernovae, H_0, for the Equation of State of Dark Energy (SH0ES). The goal is to measure H_0, starting with the first rung of the so-called cosmic distance ladder, a hierarchy of methods to gauge ever greater celestial expanses.

The first rung—the one concerning the nearest cosmic objects—relies on determining the distance to special stars called Cepheid variables, which pulsate in proportion to their intrinsic luminosity. The longer the pulsation, the brighter the Cepheid. This relation between variability and luminosity makes Cepheids benchmark "standard candles" for determining distances around the Milky Way and nearby galaxies. They also form the basis of the cosmic distance ladder's second rung, in which astronomers gauge distances to more remote galaxies by comparing Cepheid-derived estimates with those from another, more powerful set of standard candles called type Ia (pronounced "one A") supernovae, or SNe Ia.

Ascending further, astronomers locate SNe Ia in even more far-flung galaxies, using them to establish a relation between distance and a galaxy's redshift, a measure of how fast it is moving away from us. The result is an estimate of H_0.

In December, Riess says, "after a couple of years of taking a deep dive on the subject," the SH0ES team and the Pantheon+ team, which has compiled a large data set of type Ia supernovae, announced the results of nearly 70 different analyses of their combined data. The data included observations of Cepheid variables in 37 host galaxies that contained 42 type Ia supernovae, more than double the number of supernovae studied by SH0ES in 2016. Riess and his co-authors suspect this latest study represents the Hubble's last stand, the outer limits of that hallowed telescope's ability to help them climb higher up the cosmic scale. The set of supernovae now includes "all suitable SNe Ia—of which we are aware—observed between 1980 and 2021" in the nearby universe. In their analysis, H_0 comes out to be 73.04 ± 1.04 kilometers per second per megaparsec.

That number is way off the value obtained by an entirely different method that looks at the other end of cosmic history—the so-called epoch of recombination, when the universe became transparent to light, about 380,000 years after the big bang. The light from this epoch, now stretched to microwave wavelengths because of the universe's subsequent expansion, is detectable as the all-pervading cosmic microwave background. Tiny fluctuations in temperature and polarization of the CMB capture an important signal: the distance a sound wave travels from almost the beginning of the universe to the epoch of recombination.

This length is a useful metric for precision cosmology and can be used to estimate the value of H_0 by extrapolating to the present-day universe using the standard LCDM model. (L stands for lambda or dark energy, and CDM for cold dark matter; cold refers to the assumption that dark matter particles are relatively slow-moving.) Published a year ago, the latest analysis combined data from the Planck satellite and two ground-based instruments, the Atacama Cosmology Telescope and the South Pole Telescope, to arrive at an H_0 of 67.49 ± 0.53.

The discrepancy between the two estimates has a statistical significance of five sigma, meaning there is only about a one-in-a-million chance of its being a statistical fluke. "It's certainly at the level that people should take seriously," Riess says. "And they have."

HOW CLUMPY IS THE COSMOS?

The other tension that researchers are starting to take seriously concerns a cosmic parameter called S_8, which depends on the density of matter in the universe and the extent to which it is clumped up rather than evenly distributed. Estimates of S_8 also involve, on one end, measurements of the CMB and, on the other, measurements of the local universe. The CMB-derived value of S_8 in the early universe, extrapolated using LCDM, generates a present-day value of about 0.834.

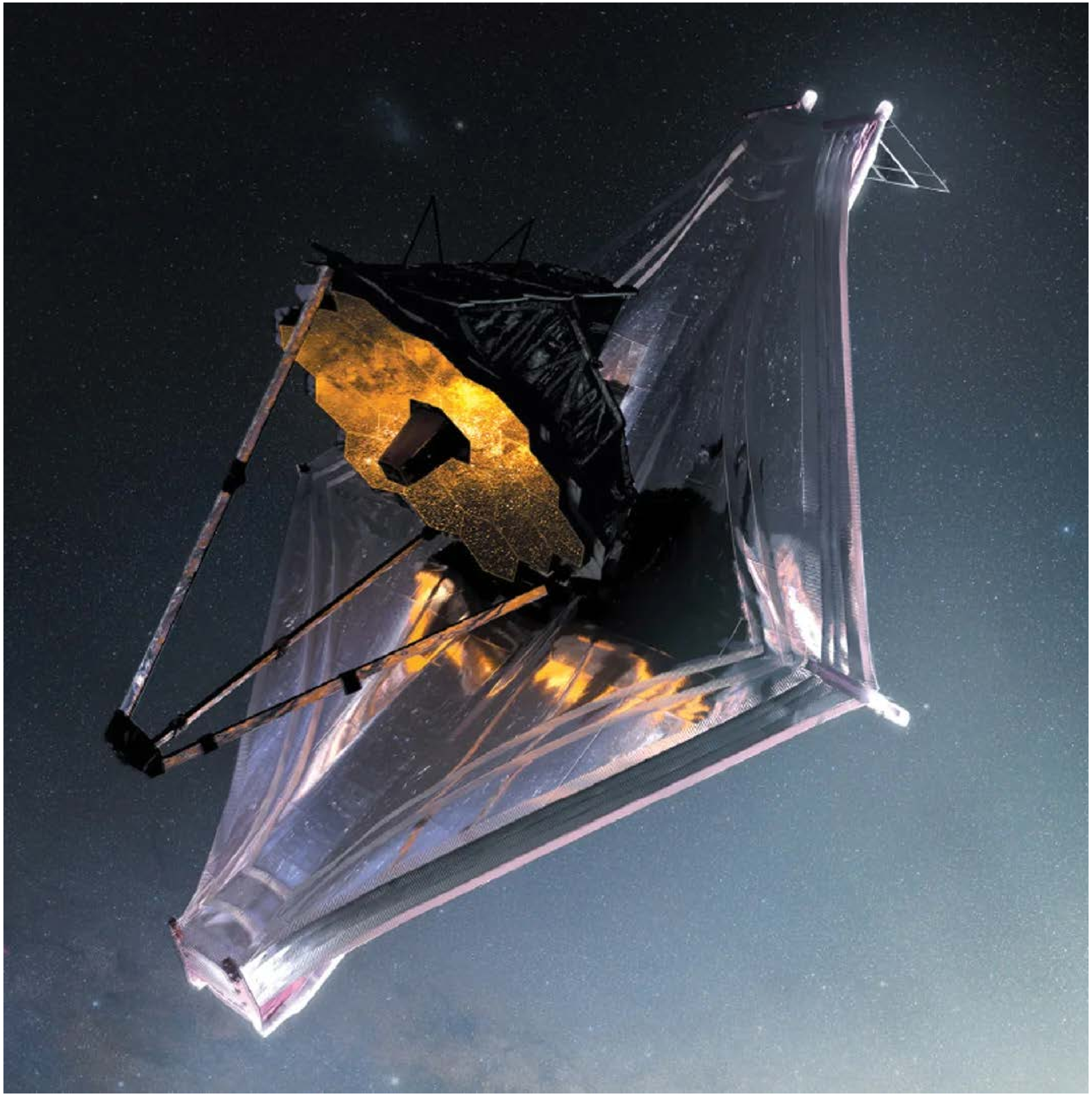
The local universe measurements of S_8 involve a host of different methods. Among the most stringent are so-called weak gravitational lensing observations, which measure how the average shape of millions of galaxies across large patches of the sky is distorted by the gravitational influence of intervening concentrations of dark and normal matter. Astronomers used the latest data from the Kilo-Degree Survey, which more than doubled its sky coverage from 350 to 777 square degrees of the sky (the full moon, by comparison, spans a mere half a degree) and estimated S_8 to be about 0.759. The tension between the early- and late-universe estimates of S_8 has grown from 2.5 sigma in 2019 to three sigma now (or a one-in-740 chance of being a fluke). "This tension isn't going away," says astronomer Hendrik Hildebrandt of Ruhr University Bochum in Germany. "It has hardened."

There is yet another way to arrive at the value of S_8: by counting the number of the most massive galaxy clusters in some volume of space. Astronomers can do that directly—for example, by using gravitational lensing. They can also count clusters by studying their imprint on the cosmic microwave background, thanks to something called the Sunyaev-Zeldovich effect. (This effect causes CMB photons to scatter off the hot electrons in clusters of galaxies, creating shadows in the CMB that are proportional to the mass of the cluster.)

A detailed 2019 study that used data from the South

Nocturnal view of the South Pole Telescope, one of several radio observatories mapping patterns in the cosmic microwave background.

Danvis Collection/Alamy Stock Photo



Pole Telescope estimated S_8 to be 0.749—again, way off from the CMB+LCDM-based estimates. These numbers could be reconciled if the estimates of the masses of these clusters were wrong by about 40 to 50 percent, Natarajan says, although she thinks such substantial revisions are unlikely. “We are not that badly off in the measurement game,” she says. “So that’s another kind of internal inconsistency, another anomaly pointing to something else.”

BREAKING THE TENSIONS

Given these tensions, it is no surprise that cosmologists are anxiously awaiting fresh data from the new generation of observatories. For instance, David Spergel of Princeton University is eager for astronomers to use JWST to study the brightest of the so-called red-giant-branch stars. These stars have a well-known luminosity and can be used as standard candles to measure galactic distances—an independent rung on the cosmic ladder, if you will. In 2019 Wendy Freedman of the University of Chicago and her colleagues used this technique to estimate H_0, finding that their value sits smack in the middle of the early- and late-universe estimates. “The error bars on the current tip of the red-giant-branch data are such that they’re consistent with both possibilities,” Spergel says. Astronomers are also planning to use JWST to recalibrate the Cepheids surveyed by Hubble, and separately the telescope will help create another new rung for the distance ladder by targeting Mira stars (which, like Cepheids, have a luminosity-periodicity relation useful for cosmic cartography).

Artist’s conception of the James Webb Space Telescope, which is poised to perform breakthrough studies of both the early and current universe.

NASA/GSFC/CIL/Adriana Manrique Gutierrez

Whereas JWST might resolve or strengthen the H_0 tension, the wide-field survey data from the Euclid, Roman and Rubin observatories could do the same for the S_8 tension by studying the clustering and clumping of matter. The sheer amount of data expected from this trio of telescopes will reduce S_8 error bars enormously. "The statistics are going to go through the roof," Natarajan says.

Meanwhile theoreticians are already having a field day with the twin tensions. "This is a playground for theorists," Riess says. "You throw in some actual observed tensions, and they are having more fun than we are."

The most recent theoretical idea to receive a great deal of interest is something called early dark energy (EDE). In the canonical LCDM model, dark energy only started dominating the universe relatively late in cosmic history, about five billion years ago. But, Spergel says, "we don't know why dark energy is the dominant component of the universe today. Because we don't know why it's important today, it could have also been important early on." That is partly the rationale for invoking dark energy's effects much earlier, before the epoch of recombination. Even if dark energy was just 10 percent of the universe's energy budget during those times, that would be enough to accelerate the early phases of cosmic expansion, causing recombination to occur sooner and shrinking the distance traversed by primordial sound waves. The net effect would be to ease the H_0 tension.

"What I find most interesting about these models is that they can be wrong," Spergel says. Cosmologists' EDE models make predictions about the resulting EDE-modulated patterns in the photons of the CMB. In February 2022 Silvia Galli, a member of the Planck collaboration at the Sorbonne University in Paris, and her colleagues published an analysis of observations from Planck and ground-based CMB telescopes, suggesting that they collectively favor EDE over LCDM by a statistical smidgen. Confirming or refuting this tentative result will require more and better data—which could come soon from upcoming observations by same ground-based CMB telescopes. But even if EDE models prove to be better fits and fix the H_0 tension, they do little to alleviate the tension from S_8.

Potential fixes for S_8 exhibit a similarly vexing lack of overlap with H_0. In March, Guillermo Franco Abellán of the University of Montpellier in France and his colleagues published a study in *Physical Review D* showing that the S_8 tension could be eased by the hypothetical decay of cold dark matter particles into one massive particle and one "warm" massless particle. This mechanism would lower the value of S_8 arising from CMB-based extrapolations, bringing it more in line with the late-universe measurements. Unfortunately, it does not solve the H_0 tension. "It seems like a robust pattern: whatever model you come up with that solves the H_0 tension makes the S_8 tension worse, and the other way around," Hildebrandt says. "There are a few models that at least don't make the other tension worse, but [they] also don't improve it a lot."

"WE ARE MISSING SOMETHING"

Once fresh data arrive, Spergel foresees a few possible scenarios. First, the new CMB data could turn out to be consistent with early dark energy, resolving the H_0 tension, and the upcoming survey telescope observations could separately ease the S_8 tension. That would be a win for early dark energy models—and would constitute a major shift in our understanding of the opening chapters of cosmic history. It's also possible that both H_0 and S_8 tensions resolve in favor of LCDM. This would be a win for the Standard Model and a possibly bittersweet victory for cosmologists hoping for paradigm-shifting breakthroughs. Of course, it might turn out that neither tension is resolved. "Outcome three would be both tensions become increasingly significant as the data improve—and early dark energy isn't the answer," Spergel says. Then, LCDM would presumably have to be reworked differently, although how is unclear.

Natarajan thinks that the tensions and discrepancies are probably telling us that LCDM is merely an "effective theory," a technical term meaning that it accurately explains a certain subset of the current compendium of cosmic observations. "Perhaps what's really happening is that there is an underlying, more complex theory," she says. "And that LCDM is this [effective] theory, which seems to have most of the key ingredients. For the level of observational probes we had previously, that effective theory was sufficient." But times change, and the data deluge from precision cosmology's third generation of powerful observatories may demand more creative and elaborate theories.

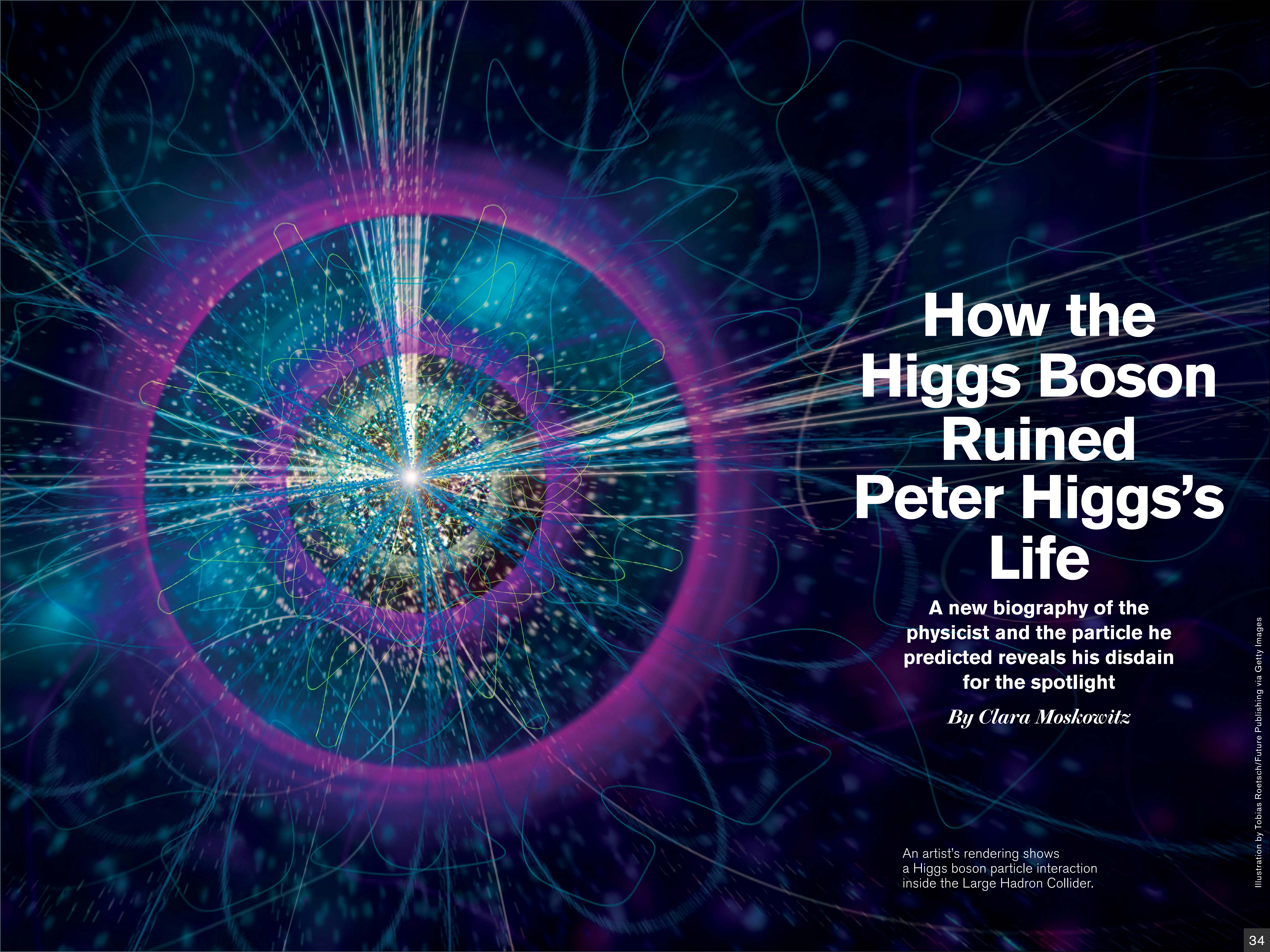
Theorists, of course, are happy to oblige. For instance, Spergel speculates that if early dark energy could interact with dark matter (in LCDM, dark energy and dark matter do not interact), this arrangement could suppress the fluctuations of matter in the early universe in ways that would resolve the S_8 tension while simultaneously taking care of the H_0 tension. "It makes the models more baroque," Spergel says, "but maybe that's what nature will demand."

As an observational astronomer, Hildebrandt is circumspect. "If there was a convincing model that beautifully solves these two tensions, we'd already have the next Standard Model," he says. "That we're instead still talking about these tensions and scratching our heads is just reflecting the fact that we don't have such a model yet." Riess agrees. "After all, this is a problem of using a model based on an understanding of physics and the universe that is about 95 percent incomplete, in terms of the nature of dark matter and dark energy," he says. "It wouldn't be crazy to think that we are missing something."

How the Higgs Boson Ruined Peter Higgs's Life

A new biography of the physicist and the particle he predicted reveals his disdain for the spotlight

By Clara Moskowitz



An artist's rendering shows a Higgs boson particle interaction inside the Large Hadron Collider.

Illustration by Tobias Roetsch/Future Publishing via Getty Images

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. Follow Moskowitz on Twitter @ClaraMoskowitz

TEN YEARS AGO SCIENTISTS ANNOUNCED one of the most momentous discoveries in physics: the Higgs boson. The particle, predicted 48 years earlier, was the missing piece in the Standard Model of particle physics. The machine built in part to find this particle, the 27-kilometer-long, circular Large Hadron Collider (LHC) at CERN near Geneva, had fulfilled its promise by showing signals of a new fundamental bit of nature that matched expectations for the Higgs.

The existence of this tiny object had first been proposed by physicist Peter Higgs in 1964. For years, the significance of the prediction was lost on most scientists, including Higgs himself. But gradually it became clear that the Higgs boson was not just an exotic sideshow in the particle circus but rather the main event. The particle and its associated Higgs field turned out to be responsible for giving all other particles mass and, in turn, creating the structure of galaxies, stars and planets that define our universe and enable our species. Physicists believed this story for many decades, but it wasn't proved until July 4, 2012, when researchers from two experiments at the LHC announced their discovery and confirmed the prediction Higgs made all those years ago.

Yet the finding, however scientifically thrilling, pushed a press-shy Peter Higgs into the public eye. When he shared the Nobel Prize in Physics the next year, Higgs left his home in Edinburgh and camped out at a pub across town on the day of the announcement so the prize committee wouldn't be able to reach him. Physicist Frank Close tells the story of Higgs and the physicist's big idea in his new book *Elusive: How Peter Higgs Solved the Mystery of Mass* (Basic Books, 2022). *Scientific American* spoke to Close about the particle, the quest to find it and the man who began it all.

[*An edited transcript of the interview follows.*]

Your book is called* Elusive. *Certainly the Higgs boson itself was elusive and took physicists decades and many billions of dollars to find. But Higgs the man emerges in your book as an elusive person as well.

One of the biggest shocks I had when I was interviewing him was when he said the discovery of the boson "ruined [his] life." I thought, "How can it ruin your life when you have done some beautiful mathematics, and then it turns out you had mysteriously touched on the pulse of nature, and everything you've believed in has been shown to be correct, and you've won a Nobel Prize? How can these things amount to ruin?" He said, "My relatively peaceful existence was ending. My style is to work in isolation and occasionally have a bright idea." He is a very retiring person who was being thrust into the limelight.

That, to my mind, is why Peter Higgs the person is still elusive to me even though I've known him for 40 years.

You quote Higgs as saying that this idea was "the only really original idea I've ever had." Do you think that's true?

Yes, but how many of us can say we've even had one really brilliant idea? There's no doubt that he had a really brilliant idea. In physics, the people who have done really big things tend to do many big things. Higgs is unique in this being once and once only. It's easy to dismiss it as luck, and clearly luck was part of it. But being in the right place at the right time, you have to recognize it. Higgs had spent two to three years really trying to understand a particular problem. And because he had done that hard work and was still trying to deepen his understanding of this very profound concept, when a paper turned up on his desk posing a related question, Higgs happened to have the answer because of the work he'd done. He sometimes says, "I'm primarily known for three weeks of my life." I say, "Yes, Peter, but you spent two years preparing for that moment."

The discovery of the Higgs boson came nearly 50 years after Higgs's prediction, and he said he never expected it to be found in his lifetime. What did it mean to him that the particle was finally detected?

He said to me that his first reaction was one of relief that it was indeed confirmed. At that moment he knew [the particle existed] after all, and he felt a profound sense of being moved that that was really the way it was in nature—and then panic that his life was going to change.

Why was Higgs's discovery so important?

Higgs's discovery was that mass is not something intrinsic to particles. It is a result of the whole cosmos. This comes about because there is some field of stuff out there that does this. And the strange, counterintuitive aspect of it is that if the vacuum [of space] was completely empty, it would be less stable than if you filled it with this mysterious stuff that we call the Higgs field. That's so counterintuitive that I wonder if that's why it took so long for this idea to emerge. And we now know it is true.

Most people have heard of the electromagnetic field. If you add energy to an electromagnetic field, you can excite it into photons. Similarly, there is this stuff we call the Higgs field. If we could apply enough energy to that, we could, in principle, excite it and produce Higgs bosons. The Higgs boson and the Higgs field are analogous to photons and the electromagnetic field.

Consider that striking a match produces millions of photons, but to produce one Higgs boson, we have to concentrate 125 billion electron volts into one spot, which is what they did at the LHC. That's the reason we've known about photons for 100 years and just recently found the Higgs boson.

It's been 10 years since the discovery of the Higgs boson, and some people have been decrying the lack of a similarly exciting finding at the LHC since then. Are you disappointed that there hasn't been another high-profile discovery after the Higgs?

This discovery was a seminal moment in human culture. It's a discovery that will rank alongside the discovery of the Rutherford atom and the nucleus. It's the discovery that we are immersed in this still mysterious essence, the Higgs field, which ultimately leads to structure in the universe. To expect other discoveries since then to meet this standard is to miss how profound this one was.

What is the outlook for the next 10 years at the LHC?

Finding the Higgs boson was like climbing up a mountain. When Higgs did his work, we didn't even know where the mountain range was or how tall it might be. The Standard Model of particle physics didn't even exist. There was a vague awareness that somewhere on this peak, there was a Higgs boson that would really be proof that this whole structure was there. As of the late 1990s, we had a sense of how high the mountain was. And then it wasn't until 2012 when we finally scaled that peak.

Now we're going down the other side of the mountain, across the plains, and they extend all the way out to the Planck scale [the minimum limit of the universe]. If we're correct, somewhere out there on the plains are other mountain ranges where particles of supersymmetry exist or dark matter particles exist. But we have no clear indication of how far across the plains you have to travel to see these new mountain ranges. That is the difference between where we are now and where we have been these past decades. We don't have any compelling way of telling how far we have to go. It's elusive. ■

Gary Doak/Alamy Stock Photo

Large Hadron Collider tunnel

Large Hadron Collider Seeks New Particles after Major Upgrade

Long-awaited boosts to the world's most powerful collider could spur breakthroughs in the hunt for physics beyond the Standard Model

By Daniel Garisto

Maximilien Brice/CERN

Daniel Garisto is a freelance science journalist covering advances in physics and other natural sciences. His writing has appeared in *Nature News*, *Science News*, *Undark*, and elsewhere.

IN THEIR FINAL MOMENTS, THE LAST PROTONS flew at nearly the speed of light. They completed the 27-kilometer loop underneath the Alpine countryside 11,245 times a second until they were released from their metal coil and slammed into a giant steel-coated graphite block. Since December 2018, other than a few tests here and there, the Large Hadron Collider (LHC) has been offline. But on April 22 the LHC fired up again and commenced its third run.

"The accelerator has been off for three years," says Freya Blekman, an experimental particle physicist at the Compact Muon Solenoid (CMS) detector at the LHC. "So there's people who have never been in the control room…, never have done shifts where data was taken. And for them, it's extremely exciting."

Located on the border between France and Switzerland, the LHC is the crown jewel of CERN, the European Organization for Nuclear Research near Geneva. By nearly every measure—funding, personnel, physical size—the LHC is the largest particle physics experiment in the world. In 2012 two LHC experiments, A Toroidal LHC ApparatuS (ATLAS) and CMS, discovered the Higgs boson and completed a five-decade search for the origins of elementary particle mass. Although researchers tout other results, such as the discovery of pentaquarks, these scientific results have sometimes been overshadowed by the sense that the LHC has failed for not discovering "new physics" beyond the Standard Model, the successful but incomplete account of elementary particles and forces that govern them.

Over the past few years, far from sitting idle, the powered down LHC has been a buzz of activity. Engineers have started to upgrade the collider's capabilities to improve its "luminosity," essentially a measure of how many particle collisions there are likely to be in a square centimeter per second. Meanwhile physicists have boosted their detectors to keep pace with an increased number of collisions resulting from the higher luminosity. Researchers have also developed new analyses to better sift through haystacks of data to find proverbial needles.

As Run 3 begins, particle physicists face a number of tantalizing anomalies, from the new, unexpectedly hefty measurements of the W boson mass to the long-standing muon g−2 discrepancy, but they lack firm evidence of new physics. "There aren't any obvious flashing lights," says Nishita Desai, a theorist at the Tata Institute of Fundamental Research in India. "It's not like 'this is where you will get a discovery.'"

While other avenues to discovering new physics exist, colliders remain vital. There is no better way to learn about fundamental particles than to smash them together and examine the wreckage. With prospects for another collider to supersede it still decades away, the LHC is perhaps particle physicists' best hope to discover what lies beyond the Standard Model.

SOMETHING OLD, SOMETHING NEW

By the turn of the millennium, particle physicists were putting the finishing touches on a theory of the universe's building blocks. Collider data showed that protons and neutrons are made of quarks strongly bound together by aptly named gluons. Fission and fusion occur when quarks exchange W bosons. The lightest pair of quarks, up and down, are followed by the heavier charm and strange quarks and then the even weightier bottom and top. Similarly, electrons have heavier cousins, muons and taus, which are identical to electrons but for their mass. Broadly, these particles were divided into fermions, which make up matter, and bosons, which carry forces.

This grand theory, perhaps unimaginatively dubbed the "Standard Model," left plenty of folks unsatisfied. For one, it was silent on gravity. The Standard Model also said nothing about dark matter or dark energy—two mysterious phenomena that account for more than 95 percent of mass in the universe. In particular, physicists itched to know where the particles of the Standard Model got their mass.

Theorists in the 1960s posited that particle mass arose from an imperceptible field permeating all of space: the more a particle interacts with this field, the greater its mass. Peter Higgs, a British theorist, suggested that the field would have an associated particle—the Higgs boson. Discovering it would confirm the mechanism that gave elementary particles their mass.

After a bumpy few first years, ATLAS and CMS announced on July 4, 2012, that they had discovered a "Higgs-like" particle of about 125 times the mass of a proton.

It was a historic accomplishment, the culmination of decades of work—not just from physicists but engineers, electricians, computer technicians, custodial staff, and more. Finding the Higgs was not a shock, however. “I think people would have been more shocked if you didn’t find anything,” Desai says.

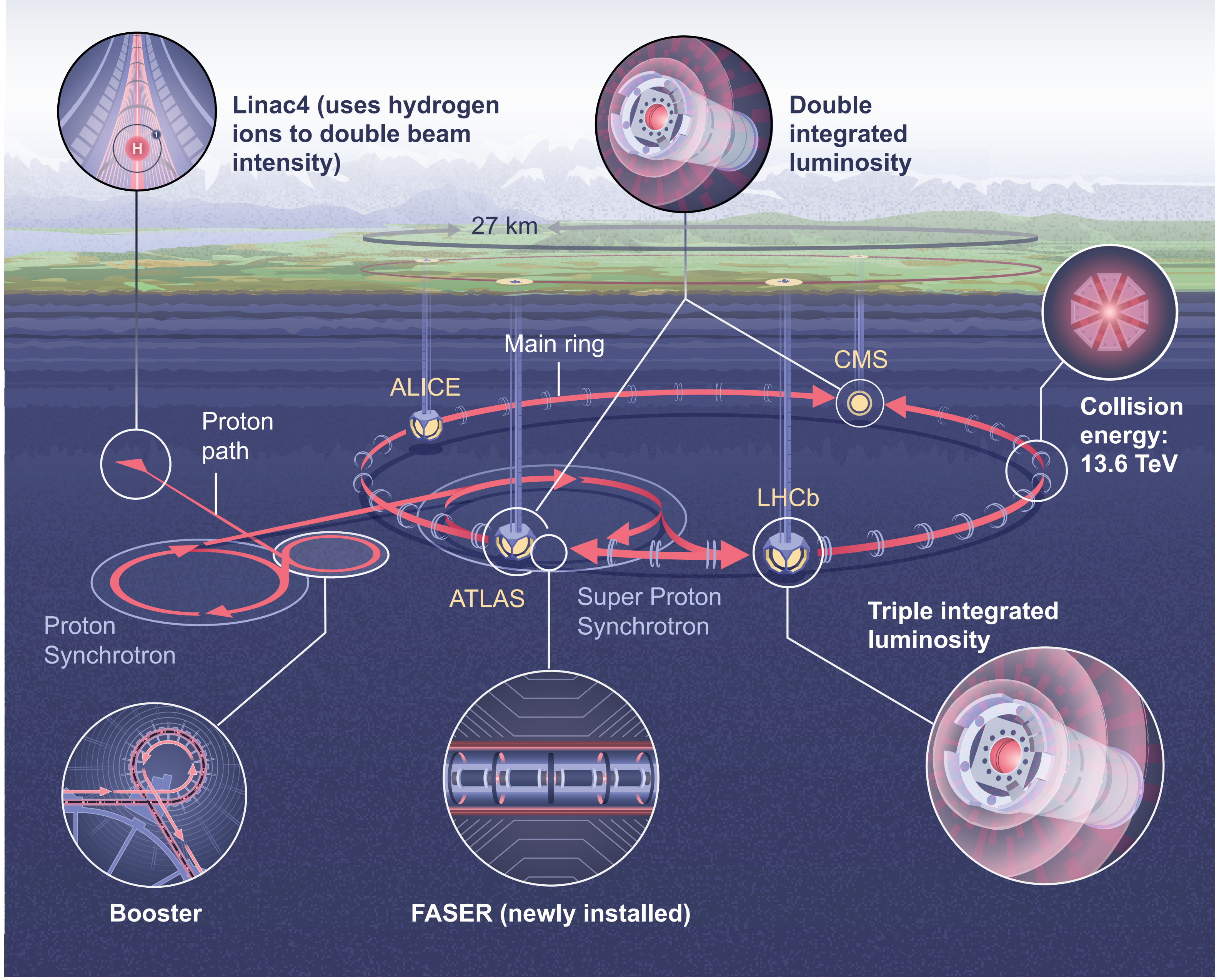
Between 2013 and 2015, LHC took its first long shutdown to repair and make small upgrades. Then, from 2015 to 2018, the LHC conducted its second run and smashed more particles at almost double its previous run’s energy. Hopes were still relatively high for new physics. When ATLAS and CMS reported hints of a new particle around 750 giga-electron-volts (GeV) in 2015, theorists leaped at the chance and published hundreds of papers on the anomaly. Many papers suggested it was a hint of supersymmetry (SUSY), a class of theories in which bosons have fermion counterparts, and vice versa—a new symmetry between matter and forces. Photons would be mirrored by photinos; quarks would be mirrored by squarks. These supersymmetric counterparts were thought to be hiding out of sight, at higher masses. Naming conventions aside, SUSY theories were attractive to physicists because the existence of supersymmetric particles could simultaneously explain the Higgs’s low mass and provide a candidate for dark matter. But as more information came in, the bump in the data turned out to be a statistical anomaly, not a new particle.

“There’s a certain generation of physicists who were told that, as soon as the accelerator turned on, they would see SUSY [and] find new physics.” Blekman says. “But there is no reason why it should be so easy.”

Discovery-hungry scientists have begun searching in other directions, such as long-lived particles (LLPs). When physicists look for new heavy particles, they assume a fleeting lifetime—the hefty 125 GeV Higgs boson lives for less than a billionth of a trillionth of a second. An LLP, however, could linger long enough to move out of the detector’s typical field of vision before decaying. During the third run, LHC detectors will use improved analyses to catch LLPs they might have missed before.

The Large Hadron Collider, Illuminated

An improved “booster” and a new proton beam source called Linac4 have given the upgraded Large Hadron Collider (LHC) at CERN denser, more luminous beams that will yield many more collisions over time. Enhancements to the resolution of the ATLAS, CMS and LHCb experiments at the LHC will help these detectors better handle the resulting flood of collision data. Improved magnets will allow proton collisions to occur at higher energies: 13.6 trillion electron volts (TeV) instead of 13 TeV. And a small new detector called FASER will seek out extremely low-mass particles leaking from ATLAS.



Graphic shows the Large Hadron Collider in its underground setting and highlights six major upgrades recently incorporated.

Nick Bockelman

The success of the Standard Model and failure to "break" it has led to accusations that particle physicists are facing a crisis, that they have been wandering in a desert for 40 years. For Desai, this narrative has it all backward. "In fact, I would say that particle physics is perhaps emerging from a crisis, which we did not realize we were in before, because everybody was working on the same thing," she says. "There are no easy answers, and I think most younger people are quite happy about that."

BUILT TOO VAST

Upgrading the largest machine in the world would be nothing short of a monumental effort, even if its critical infrastructure was not 100 meters underground.

After each multiyear run, the LHC's equipment requires refurbishing. José Miguel Jiménez, CERN's head of technology, who oversaw the second long shutdown, ticks off a rapid-fire list of areas that needed work: "technical infrastructure, cooling, ventilation, electrical distribution, electrical safety, elevators, cranes, all these fancy door access systems [and] fire detection."

Making repairs is difficult during routine operation because the LHC's critical components must be kept ultracold. About 130 metric tons of liquid helium—about the weight of a midsize blue whale—keep 36,000 metric tons of the collider under four kelvins. These components, which include magnets and bubble-shaped accelerating cavities, are chilled so that they can channel the immense electrical currents required for the entire facility's function without any resistance. It takes months to warm up the machine and months more to cool it back down, so even a small problem with cold portions of the machine can take a prohibitively long time to fix.

While the machine was warm, engineers completely replaced the source for the LHC's beams, Linac2—which had been in use since the 1970s—with Linac4; the name Linac3 was already used for a different accelerator. During Run 3, every particle that collides in the LHC will begin at Linac4 as an electrically charged soup of hydrogen ions—essentially protons with two electrons. Ions from this soup are sent out in "bunches" and accelerated to 160 mega-electron-volts (MeV), more than three times the energy of Linac2.

"By raising the injection energy, you can actually store higher intensities," explains Jorg Wenninger, head of LHC beam operation. Protons want to repel one another because they share the same charge. But at higher energies, protons generate a magnetic field that counters this repulsion, and more can fit into the same space. Using hydrogen ions and then removing the extra electrons further increases the beam density so that each bunch consists of roughly 120 billion protons squeezed into a diameter of about three microns.

This density is crucial because it determines how many collisions the detectors at the LHC will eventually see, says Bettina Mikulec, a senior physicist at CERN who led Linac4 operations. If the beam is not dense at the start, it will not be dense later.

From the injector, the beam enters the booster ring, which now accelerates the protons to 2 GeV, a 43 percent improvement from Linac2. Upon entering the main collider ring, protons encounter new aluminum beam pipes near the detectors. "The problem with stainless steel is that the cobalt inside the metal is getting radioactive by default," Jiménez says, "which is always quite problematic."

To avoid any interference, the beam requires a vacuum as devoid of air as possible. With pressures as low as one ten-trillionth of an atmosphere, the LHC's beamline has been called the emptiest place in the solar system. A proton can travel for hundreds of hours with essentially zero chance of hitting a molecule of air, according to Jiménez.

When it is running, the LHC—not just the magnets and beam but also computers and cryogenics and vacuum systems—consumes an astonishing amount of energy: about 800 gigawatt-hours per year, or about half that of the entire city of Geneva. "We are, in a certain way, the electrical utility for CERN," says Mario Parodi, head of electrical project management. CERN's electricity comes primarily from France, where about 80 percent of the grid relies on nuclear energy. Much of the power to smash nucleons, therefore, comes from splitting nuclei.

As COVID swept across the world, it shut down the shutdown—but only for a bit. CERN locked down on March 24, 2020, but some work resumed as early as May, according to Jiménez. Throughout the rest of the pandemic, teams had to be conscious of issues such as packing people into workspaces. Elevators act like bottlenecks, which made getting underground even more difficult and raised safety issues that were not exclusive to COVID—any kind of tunnel incident could leave workers stranded.

Thanks to careful planning by Jiménez and his team, the start of Run 3 was only delayed by a year.

EVERYTHING IS ILLUMINATED

Though they were not taking data, physicists at detector experiments were busy making repairs and upgrades of their own.

ATLAS is a gigantic tube-shaped machine that is 46 meters long, 25 meters high and about 7,000 metric tons—the weight of the Eiffel Tower's frame. Its counterpart, CMS, is a tightly bound detector half the size of ATLAS but twice its weight. CMS uses a solenoid, a ring-shaped magnet, to bend the path of charged particles such as muons.

Upgrades to the injector to create a denser beam mean that, for Run 3, both ATLAS and CMS will effectively double their luminosity over time. Denser beams mean more collisions, which mean more data, which mean a better chance of finding rare events that could be evidence for new physics.

Dealing with increased luminosity requires taking faster and better data, Blekman says. Both ATLAS and CMS have revamped their "triggers"—systems that use software and hardware to recognize particle events, such as a Higgs boson decaying to two photons. Sifting legible events from a mishmash early on is crucial for later analysis.

Some dismantling was required for these upgrades. CMS, despite its weight, is built from slices that rest on hovercraft-like air pads and can be pulled apart. But moving CMS apart and putting it back together can create micron-size displacements that affect the detector. To ensure things are where they should be, Blekman and her colleagues use the straight lines of cosmic rays passing through the device like a level.

A critical upgrade for ATLAS is the "new small wheels"—the wheels, it should be said, are 10 meters across, not exactly "small," and do not actually rotate. These thin chambers full of wires will capture the tracks of particles such as muons as they rocket outward from the collision point to the rest of the detector.

Upgrades could lead to the discovery of new particles, but ATLAS and CMS also have other responsibilities. "You have to remember that these experiments are more than just discovery machines. They are also measurement machines," Blekman says. A better understanding of the particles we know is important science in its own right, and precisely pinning down the parameters of the Standard Model may help future experiments break it.

Whereas ATLAS and CMS underwent moderate upgrades, the Large Hadron Collider beauty (LHCb) detector, which is use particles called beauty quarks, or b quarks, to search for rare decays will be completely changed. "We are going to start commissioning a completely new detector," says Patrick Koppenburg, an experimental particle physicist at LHCb. "We need a better resolution just so that we can tell [particles] apart."

LHCb will go from seeing one collision per proton bunch crossing to about six. If a detector's resolution is too low, it can turn "black"—every pixel is hit by a particle, rendering it useless. Koppenburg and his colleagues have installed much higher-resolution particle trackers that they hope will give LHCb the data to validate enticing anomalies it saw in Run 2.

The newest additions to the LHC are far smaller than their cohort—one new detector could fit snugly in a suitcase. The Forward Search Experiment (FASER) is designed to detect new featherweight particles, such as those connected to the dark sector, and FASERnu is designed to detect well-known particles: neutrinos.

Both detectors are situated in a snug tunnel separated from ATLAS by a few hundred meters of solid earth. Only feebly interacting particles such as neutrinos or as yet unknown dark sector particles can make the journey. Luckily, any lightweight particles from ATLAS collisions are highly focused. "Roughly speaking, about 90 percent of [the particles] actually pass through a piece of paper held 480 meters away," says Jonathan Feng, a physicist at the University of California, Irvine, and co-founder of FASER. "If we made it bigger, we wouldn't actually increase the event rate too much."

FASER is essentially a mostly empty tube full of trackers designed to detect a dark sector particle decaying. FASERnu uses the opposite strategy. "We want as dense of a material as possible to get the neutrinos to actually interact," Feng says. The detector is essentially made from camera film interleaved with 1,000 tungsten plates. Tungsten's high density—nearly twice that of lead—gives neutrinos more targets to scatter off. At the end of data taking, the tungsten-film sandwich is retrieved and analyzed. What it sacrifices in temporal resolution—it has none—it makes up for in spatial resolution, which will allow Feng and his colleagues to even identify the millimeter-long track from a tau neutrino decay.

For the newest experiments on the block, there is essentially no room for disappointment. "We have basically guaranteed interesting physics," Feng says about FASERnu. "And then we have speculative, revolutionary physics." If FASER actually sees a dark sector particle, even a small detector could usher in big new physics.

WATCHING, WAITING

As Run 3 starts, physicists have already pushed the beam to its new maximum energy of 6.8 tera-electron-volts (TeV), exceeding the previous energy record set by the LHC and making it the highest energy particle beam humans have ever created. "So far it is going very well," Wenninger says. Still, it will take time to straighten out any kinks. The first collisions, which will be at much lower energies, are expected to begin in about a month.

"We don't know what is working, what is not immediately working," Koppenburg says. To calibrate detectors like LHCb, the researchers will have to "[rediscover] the Standard Model particles one by one." Only once they have ascertained that photons look like photons, electrons look like electrons, and so on, can they have confidence in their results.

Even if everything works as planned, discoveries take time. A detector might spot hints of a new particle at the start of Run 3, but it could take years for scientists to comb through the massive trove of data and sort out all of the uncertainties before making any conclusions.

In the meantime, theorists will continue to puzzle over anomalies and dream up hypothetical particles that could be responsible for the discrepancies detectors have seen. Engineers are not disinterested parties, either. "We are watching very carefully what the experiments are doing," Jiménez says. "We can create the technology for future projects and future physics, but we can't discover anything. I mean, the discovery comes from the detector."

As for the detectors, the injectors, the magnets, the thousands of tons of ultracold collider? All of those come from the hard work done during the shutdown. ■

God, Dark Matter and Falling Cats:

A Conversation with 2022 Templeton Prize Winner Frank Wilczek

The physics Nobelist and author has not exactly found religion–but that doesn't mean he's stopped looking

By Zeeya Merali

Michael Clark

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

FRANK WILCZEK, A NOBEL PRIZE–WINNING theoretical physicist and author, has been announced as the recipient of the 2022 Templeton Prize, which is valued at more than $1.3 million. The annual award honors those "who harness the power of the sciences to explore the deepest questions of the universe and humankind's place and purpose within it," according to a press release from the John Templeton Foundation. Previous recipients include scientists such as Jane Goodall, Marcelo Gleiser and Martin Rees, as well as religious or political leaders such as Mother Theresa and Desmond Tutu.

Wilczek's Nobel-winning work traces back to the early 1970s, when he and two colleagues devised a theory describing the behavior of fundamental particles called quarks—a feat that proved crucial for establishing the Standard Model of particle physics. He has also proposed the existence of multiple new particles and entities. Some, such as "time crystals" and "anyons," have since been discovered and appear promising for developing better quantum computers. Another Wilczek prediction—the "axion"—remains unconfirmed but is a leading candidate for dark matter, the invisible substance thought to make up the majority of mass in the universe. He is also a prolific author, and in his recent books, he links his work as a physicist with his contemplations on the inherent beauty of reality, arguing that our universe embodies the most mathematically elegant structures.

Scientific American spoke with Wilczek about the interplay between science and spirituality, recent reports that the Standard Model may be "broken," and his latest research involving the hunt for hypothetical particles and the physics of falling cats.

[*An edited transcript of the interview follows.*]

Congratulations on receiving the Templeton Prize. What does this award represent for you?

My exploratory, science-based efforts to address questions that are often thought to be philosophical or religious are resonating. I'm very grateful for that, and I've started to think about what it all means.

One kind of "spiritual" awakening for me has been experiencing how a dialogue with nature is possible—in which nature "talks back" and sometimes surprises you and sometimes confirms what you imagined. Vague hopes and concepts that were originally scribbles on paper become experimental proposals and sometimes successful descriptions of the world.

You don't now identify with any particular religious tradition, but in your 2021 book* Fundamentals: Ten Keys to Reality, *you wrote, "In studying how the world works, we are studying how God works, and thereby learning what God is." What did you mean by that?

The use of the word "God" in common culture is very loose. People can mean entirely different things by it. For me, the unifying thread is thinking big: thinking about how the world works, what it is, how it came to be and what all that means for what we should do.

I chose to study this partly to fill the void that was left when I realized I could no longer accept the dogmas of the Catholic Church that had meant a lot to me as a teenager. Those dogmas include claims about how things happen that are particularly difficult to reconcile with science. But more important, the world is a bigger, older and more alien place than the tribalistic account in the Bible. There are some claims about ethics and attitudes about community that I do find valuable, but they cannot be taken as pronouncements from "on high." I think I have now gathered enough wisdom and life experience that I can revisit all this with real insight.

Can you give me some specific examples of how the wisdom you have now but didn't have earlier in your scientific career has influenced your outlook?

"Complementarity" says that you can't use a single picture to answer all meaningful questions. You may need very different descriptions, even descriptions that are mutually incomprehensible or superficially contradictory. This concept is absolutely necessary in understanding quantum mechanics, where, for instance, you can't make predictions about the position and the momentum of an electron simultaneously. When I first encountered [Niels] Bohr's ideas about taking complementarity beyond quantum mechanics, I was not impressed. I thought it was borderline bullshit. But I've come to realize that it is a much more general piece of wisdom that promotes tolerance and mind expansion. There's also the scientific attitude that openness and honesty allow people to flourish. It enhances the effectiveness of scientists to have a sort of loving relationship with what they are doing because the work can be frustrating and involves investing in learning some rather dry material. And then there is the lesson of beauty: when you allow yourself to use your imagination, the world repays with wonderful gifts.

You won a share of the Nobel Prize in Physics in 2004 for your work on understanding the strong force, which binds subatomic particles within the atomic nucleus. This work forms part of the backbone of the Standard Model. But the Standard Model is of course incomplete because it doesn't account for gravity or dark matter or the "dark energy" that seems to be powering the accelerating expansion of the universe. Many physicists, including yourself, consequently believe we will eventually find evidence that allows us to craft a successor to or extension of the Standard Model. In April physicists at the Fermi National Accelerator Laboratory in Batavia, Ill., announced that they had measured the mass of an elementary particle called the W boson to be significantly heavier than predicted by the Standard Model. Is this an exciting sign that the Standard Model's reign is approaching its end?
I am skeptical. This is an impressive piece of work, but it's an attempt to do a high-precision measurement of the mass of an unstable particle that decays very fast in exotic ways. And because the *W* boson has a finite lifetime, according to quantum mechanics, it has an uncertainty in mass. Just the fact that the measurement is so complicated raises an eyebrow. And then, even more serious, is that the result is not only discrepant with theoretical calculations but also with previous experimental measurements. If there were a compelling theoretical hypothesis suggesting that there should be this discrepancy with the *W* boson mass but no other discrepancy with all the other tests, that would be fantastic. But that's not the case. So, to me, the jury is still out.

One of your most recent successes was predicting the existence of a novel quantum state of matter that you dubbed a "time crystal" because its particles exhibit repetitive behavior—like a swinging pendulum—but without consuming energy. How did you come up with the idea?
Almost 10 years ago I was preparing to teach a course on symmetry, and I thought, "Let's think about crystal symmetry in more than just 3-D; let's think about crystals that are periodic in time." Basically, time crystals are self-organized clocks, ones that are not constructed but arise spontaneously because they want to be clocks. Now, if you have systems that spontaneously want to move, this sounds dangerously like a perpetual-motion machine, and that had scared physicists away. But I have been given several injections of confidence over my career, so I wasn't afraid and jumped in where angels fear to tread. I originally wanted to call it "spontaneous breaking of time-translation symmetry," but my wife, Betsy Devine, said, "What the heck?!" So they became time crystals.

Time crystals have now been created in the lab and in a quantum computer. How might they be useful?
The most promising application is to make new and better clocks that are more portable and robust. Making accurate clocks is an important frontier in physics; [they are] used in GPS, for example. It's also important to make clocks that are friendly to quantum mechanics because quantum computers will need compatible clocks.

You have a habit of coming up with catchy names. Back in the 1970s, you proposed a hypothetical new particle that you called the "axion"—inspired by a laundry detergent—because its existence would clean up a messy technical problem in the workings of particle physics. Since then, other physicists have suggested that axions, if they exist, have just the right properties to make up dark matter. How is the search for axions progressing?
Axions are superexciting. It was totally unexpected to me at the beginning that the theory was perfectly designed to explain the dark matter, but that possibility has been gaining ground. That's partly because searches for the other leading dark matter candidates, so-called WIMPs (weakly interacting massive particles), have turned up empty, so axions look better by comparison. And in the past few years there have been some truly promising ideas for detecting dark matter axions. I came up with one with Stockholm University researchers Alex Millar and Matt Lawson that uses a "metamaterial"—a material that has been engineered to process light in particular ways—as a sort of "antenna" for axions. The ALPHA collaboration has tested prototypes, and I'm optimistic, bordering on confident, that within five to 10 years, we will have definitive results.

And "axion" is now in the *Oxford English Dictionary.* When you're in the *OED,* you know you've arrived.

You also coined the name of another new particle, the "anyon." The Standard Model allows for two types of elementary particles: "fermions" (which include electrons) and "bosons" (such as photons of light). The anyon is a third category of

"quasiparticle" that emerges through the collective behavior of groups of electrons in certain quantum systems. You predicted this back in 1984, but it's only been confirmed in recent years. What's the latest news on anyons?
I thought it would take a few months to verify that you could have anyons, but it took almost 40 years. During that time, there have been literally thousands of papers about anyons, but very few were experimental. People also realized that anyons could be useful as ways of storing information—and that this could potentially be produced on an industrial scale—giving rise to the field of "topological quantum computing." There have now been prototype experiments in China and serious investment by Microsoft. In April, Microsoft announced that they have made the kind of anyon we need to get the quantum-computing applications off the ground in a serious way. So all these thousands of papers of theory are finally making contact with practical reality and even technology.

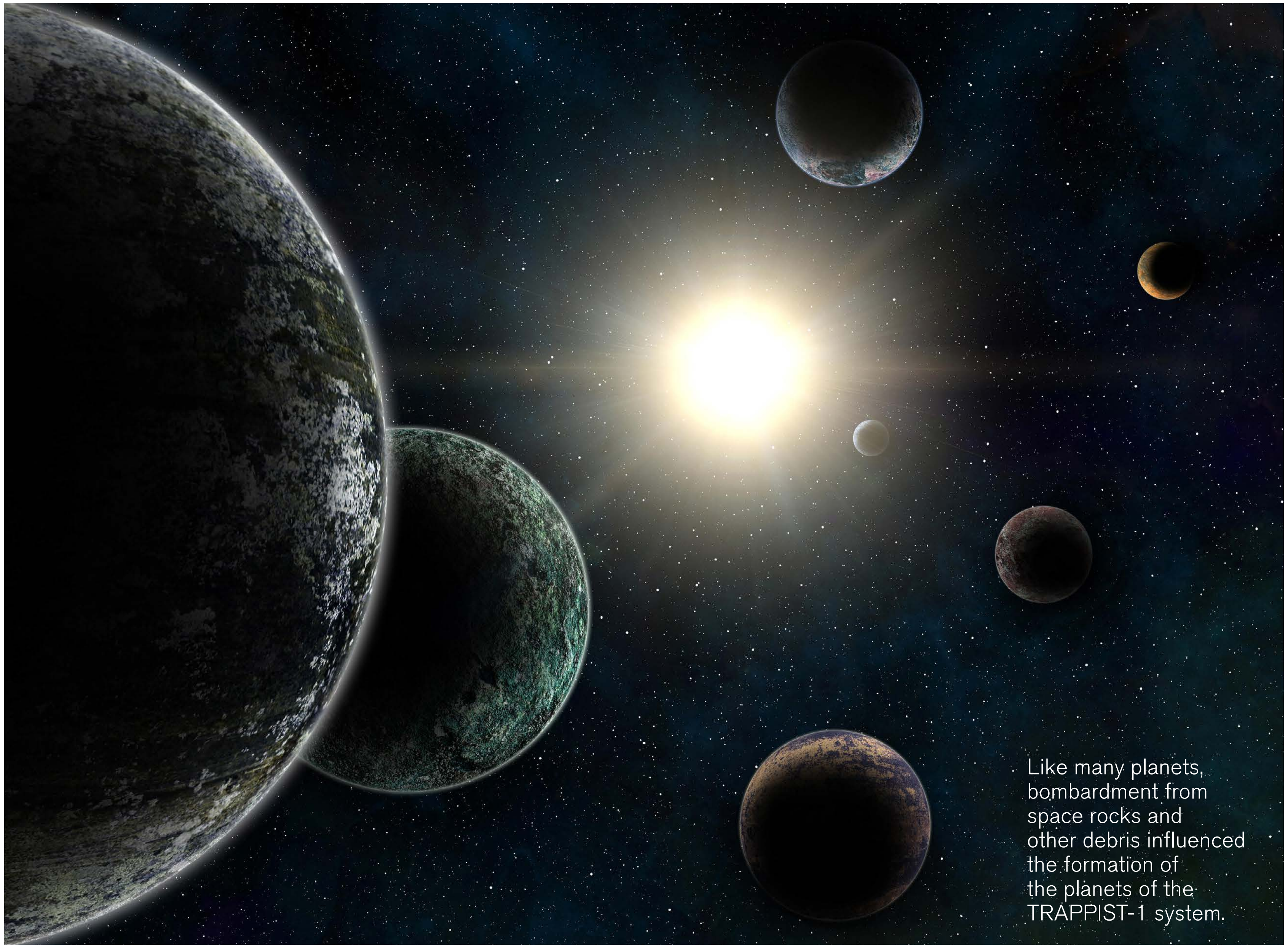
You clearly have a knack for coming up with groundbreaking concepts in physics. Do you have any other revolutionary ideas brewing?
Yes, but I don't want to jinx them by casually mentioning them here! I'll tell you something amusing I am working on, though: there's an abstract mathematical idea called "gauge symmetry" that underpins particle physics. It's a powerful tool, but it's a mystery as to why it is there. An interesting observation is that gauge symmetry also arises in the description of the mechanics of bodies that are squishy and can propel themselves. Amazingly, gauge symmetry appears when you try and work out how a cat that falls out of tree can manage to land on its feet or how divers avoid belly flops. I realized this with [physicist] Al Shapere 30 years ago, but in recent work I have been generalizing it in several directions. It's a lot of fun—and it might turn out to be profound.

And finally, what are your long-term hopes for the future of society?
Looking at big history reinforces cosmic optimism. I like to say that God is a "work in progress." Day to day, you can have backsliding—pandemics, wars—but if you look at the overall trends, they are extraordinarily positive. Things could go wrong, with nuclear war or ecological catastrophe, but if we are careful as a species, we can have a really glorious future. I view it as part of my mission in the remainder of my life to try and point people toward futures that are worthy of our opportunities and not to get derailed.

Sean Raymond is an American astrophysicist working at the Bordeaux Astrophysical Laboratory in France. He also writes a blog at the interface of science and fiction (planetplanet.net) and recently published a book of astronomy poems.

Cosmic Collisions Yield Clues about Exoplanet Formation

Low levels of bombardment reveal that the TRAPPIST-1 system probably grew quickly



Like many planets, bombardment from space rocks and other debris influenced the formation of the planets of the TRAPPIST-1 system.

Dimitar Todorov/Alamy Stock Photo

Some of the best movies are origin stories. When we know where a superhero is coming from, then we can understand why they do what they do. The same goes for planets: knowing how they formed is key to understanding their internal structure, geology and climates. We know a lot about how Earth formed from decades of analyzing meteorites and lunar rocks. We think the final phases of Earth's growth involved titanic collisions, the last of which spun out a disk of vaporized rock that coalesced into the moon.

But what about the thousands of planets we've found around other stars—did they form like Earth? Answering this question may seem hopeless because we'll never have rocks from those planets to analyze. But there may be another way, and this way is important because it gives us the rare opportunity to compare our planet's origins story with those of rocky exoplanets.

In a recent study published in *Nature Astronomy,* we used the orbital architecture of a system of exoplanets to figure out how planets might form, using the TRAPPIST-1 system as an example. This system is iconic among exoplanets: it contains seven known planets, each close to Earth's size and three of which receive a similar amount of energy from their tiny red star as Earth does from the sun.

For the purpose of our analysis, a key feature of

TRAPPIST-1 is orbital resonance. After a specific number of orbits, each pair of neighboring planets realigns. For example, among the outer pair of planets, called g and h, orbital alignment repeats every three orbits of planet g and two orbits of planet h; this is a 3:2 resonance. Each adjacent pair is in a similar resonance. Together all seven planets participate in this orbital dance, forming a resonant chain.

In paintball, each time a person is hit, the impact leaves behind a blob of paint, so you can tell at a glance how often any player gets shot. Likewise, the surfaces of planets and moons retain the signs of impacts; when an object from space crashes down, it explodes and leaves behind a crater. You can see the biggest craters on the moon by eye; Tycho is one of the most dramatic.

We wanted to figure out how much space junk—meaning, leftover asteroids and comets—could have bombarded the TRAPPIST-1 planets. A key piece of our study was to calculate exactly how fragile the system's orbital resonances are. It turns out the resonances are extremely easy to break. When an asteroid or comet collides with a planet or even just passes close by, the planet's orbit shifts a little. Add up a few of these shifts, and the orbits of neighboring planets are spread apart enough far enough to lose their resonance. From that point onward, they can never realign again.

Using orbital simulations, we determined how much space junk would have collided with each TRAPPIST-1 planet if the system's resonances had been lost. Of course, TRAPPIST-1's resonances were not lost; they have survived for billions of years since the planets formed, and we observe them today. TRAPPIST-1 is like a paintball player wearing an outfit that's still almost perfectly clean. Our simulations show us the "worst-case scenario"; the maximum amount of material that could have impacted any of the TRAPPIST-1 planets since they formed is tiny (in cosmic terms), less than 1 percent of Earth's mass. Any more than that would have permanently disrupted the resonances we see today.

We know a lot about how Earth formed from decades of analyzing meteorites and lunar rocks.

Because there were so few impacts, the TRAPPIST-1 planets must have grown much faster than Earth. Resonances like TRAPPIST-1's form by orbital migration, as the growing planets' orbits slowly shrink by interacting with the gaseous planet-forming disk. Once the disk is gone, resonances can break, but they cannot re-form. So the TRAPPIST-1 system must have been fully formed within the lifetime of its star's disk—just a few million years. There was at most a gentle bombardment over the ensuing billions of years.

In contrast, analysis of Earth and moon rocks indicates that the planet-sized collision that formed the moon took place about 100 million years after the start of solar system formation. The TRAPPIST-1 planets may well have experienced such giant collisions, but only very early in their histories, before the resonant chain was set in stone. We don't fully understand how these different formation pathways affect the internal evolution, geology and climate of the TRAPPIST-1 planets as compared with Earth, but it's an active area of study. For instance, it's possible that their rapid growth would greatly increase the amount of water that could be stored within rocks in the planets' interior but decrease the amount that could remain as surface oceans.

Our study borders the controversy-ridden waters of what objects should be called "planets." Following the International Astronomical Union's definition, the factor that was used to demote Pluto to the status of "dwarf planet" was that it has not cleared the neighborhood around its orbit of space junk. Rather Pluto orbits within the Kuiper belt of ice-rich cometlike objects. Our simulations show that no substantial population of space junk can remain in the TRAPPIST-1 system. Each of these seven objects therefore deserves to be called a planet.

For now we can apply our new technique only to the handful of other systems, the resonant chains with nearly clean paintball jerseys. Yet these are some of the most interesting systems that we know both from an orbital point of view and because one theory proposes that almost all planetary systems spend some time as a resonant chain (although very few resonant chains survive). Understanding the bombardment histories of planets in these systems is a first step toward telling the origins stories of other worlds.

OPINION

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Space Won’t Be Safe until the U.S. and China Can Cooperate

The two countries must put aside their mistrust to establish rules for the peaceful use of outer space

The ever growing swarm of debris orbiting Earth poses dire risks to spacecraft.

ESA/ID&Sense/ONiRiXEL, (CC BY-SA 3.0 IGO)

China is undeniably one of the world’s top players in space these days, with successful missions to the moon and Mars and a solar probe due to be launched soon. Its rise has spurred competition with the U.S.; “Watch the Chinese,” NASA administrator Bill Nelson recently warned. Given the strategic value the two nations have placed on their space programs and the political tension that already exists between the countries, the contest over achievements in space is likely to intensify.

Despite the tension, the U.S. and China must figure out a way to cooperate on some, if not all, issues in the use of space. The most critical area is the safety of space infrastructure, where a lack of communication could be damaging and possibly even deadly. This need was highlighted by the recent saga of a near miss between two of Elon Musk’s Starlink satellites and China’s in-progress crewed space station. Although the Starlink spacecraft are privately owned, the U.S. government is internationally responsible for their space activities under the 1967 Outer Space Treaty.

Yet, there are serious barriers to a tête-à-tête—including the fact that some kinds of cooperation are illegal. The Wolf Amendment prohibits NASA from using government funds to engage with the Chinese government and China-affiliated organizations. Still, this legislation does not block all cooperative possibilities, such as exchanging orbit information about human-made space objects through agencies such as the North American Aerospace Defense Command. In the case of the Starlink satellites, U.S. representatives said they had determined that the spacecraft posed no risk to the Chinese space station. China, however, disagreed, and adjusted the station’s orbit to be safe. Cases like this could be better handled in the future through direct communication.

Both nations will continue to rely on space infrastructure for civil, commercial and national security purposes. The U.S. has 2,944 satellites, more than half of the total number of operating satellites in the world. This means that it has the most to lose from satellite collisions and risks posed by space debris. China also has a large collection, along with plans to send significant numbers of satellites to low-Earth orbit in the next few years. The risks are growing from what the U.N. calls “congested, contested and competitive” space, and it suits both countries’ interests to undertake constructive dialogues on how to keep orbital passages safe.

But the path ahead may not be smooth. The U.S. has accused China of worsening the issue, notably during a 2007 Chinese antisatellite test that created more than 150,000 pieces of space debris. Because everything in orbit is moving so fast, a collision between a small bit of debris and a spacecraft could prove catastrophic. Yet, one year later, the U.S. shot down its own satellite, although this event created fewer and shorter-lived pieces of debris, because the intercept occurred at lower altitude so the pieces burned up more quickly in Earth’s atmosphere.

Despite the acrimony, the two sides appear to agree on some important legal rules applicable to space. For instance, in a recent white paper, China professes to use outer space “for peaceful purposes.” Although this claim is open to interpretation, similar language is also widely used in U.S. space policy documents and even the Space Force’s 2020 doctrine. The fact that there is some ambiguity to the term may be a good starting point for the two countries to embark on a dialogue about whether antisatellite testing, for instance, is a peaceful activity. Although defensive in nature and not an act of war, it can pose threats to others by creating more space debris.

China appears keen to be involved in the international rulemaking process for space under the framework of the United Nations, according to statements in the white paper. Realistically, China can achieve this goal only through open and constructive engagement with other stakeholder nations. Promisingly, in February, when asked about the danger posed by the Starlink satellites to the Chinese space station, a Chinese spokesperson expressed willingness to establish a long-term communication mechanism with the U.S. to protect the safety of its astronauts and space station.

But the continuing finger-pointing could hold both countries back. For instance, the U.S. and China have exchanged diplomatic fire over a U.S. unilateral commitment to stop all antisatellite missile testing. Although the move could seriously reduce the future creation of space debris, the U.S. only did so while blaming Russia and China for their previous tests. Not surprisingly, in response China demanded that the U.S. “fully reflect upon its negative moves in the field of outer space.”

To make real progress, the two countries should adopt a “think big, start small” approach. Because there is a lack of mutual trust between the two sides at this stage, it would be unrealistic to expect an agreement on space safety issues as a whole. By tackling smaller problems, such as rules about communicating when a crewed space station is at risk of collision, the two sides may more easily find common interests and are more likely to work in a cooperative manner. Thus, they can establish mutual trust in this process and, over time, expand their cooperation to other spheres in space.

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