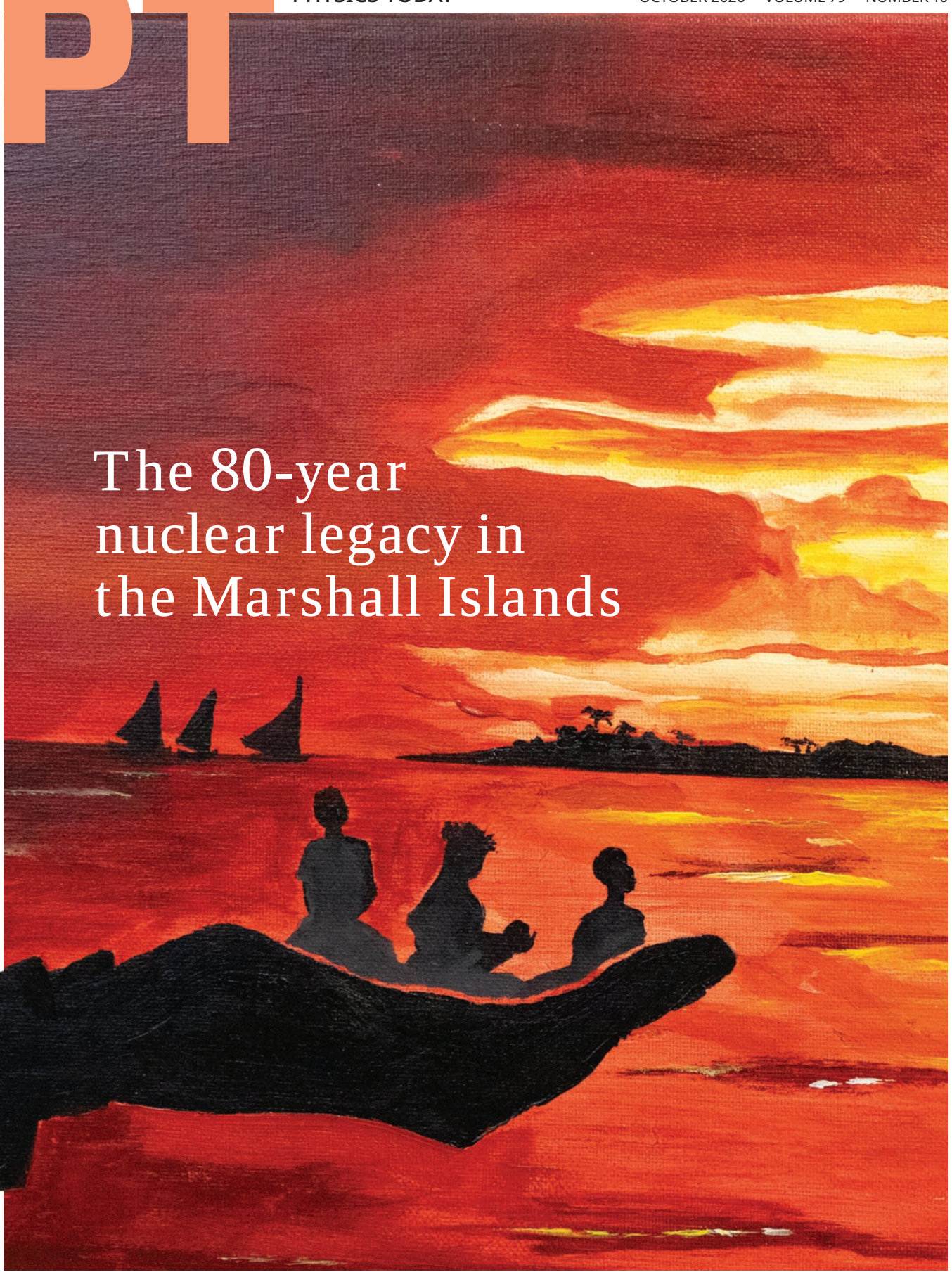
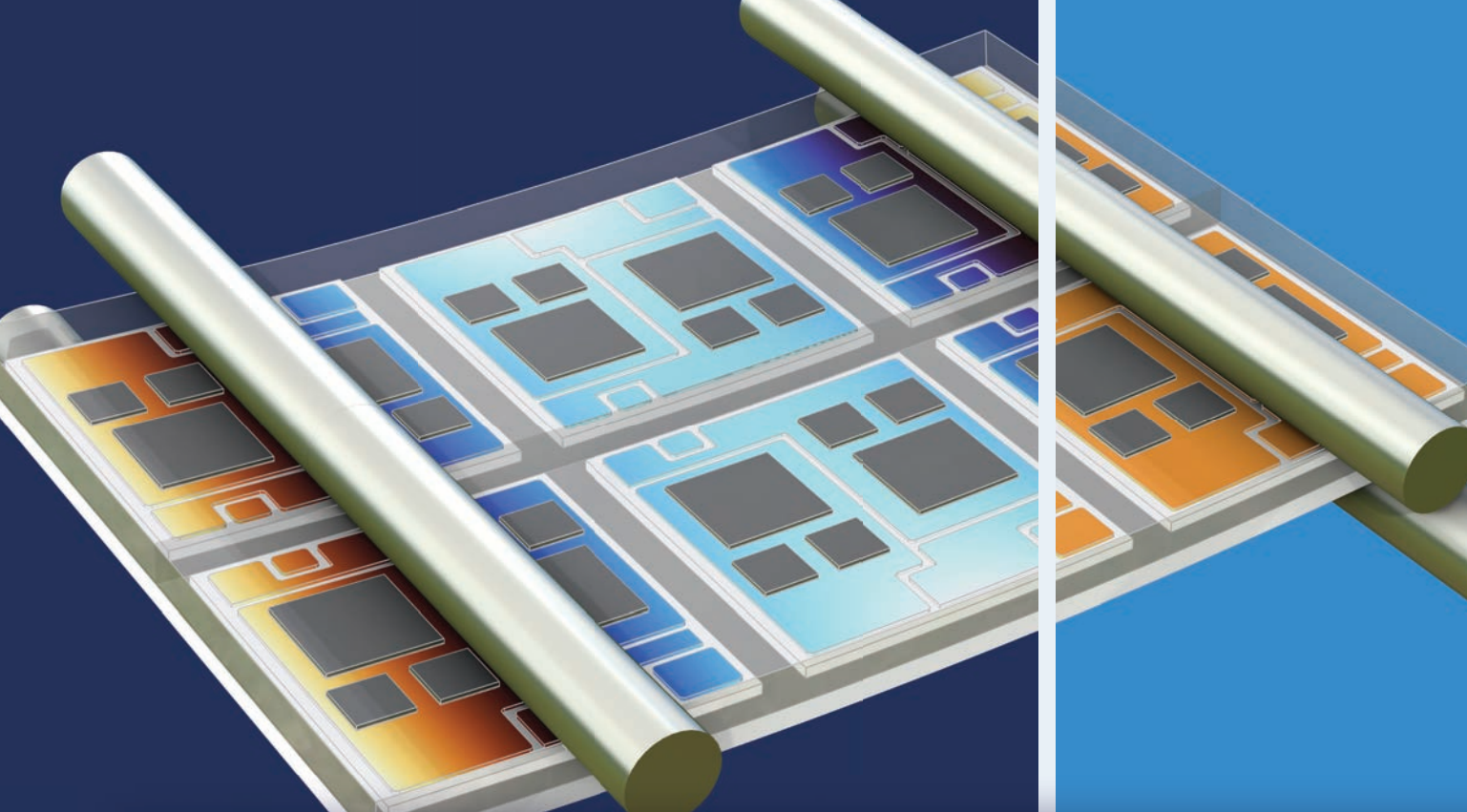




The 80-year nuclear legacy in the Marshall Islands



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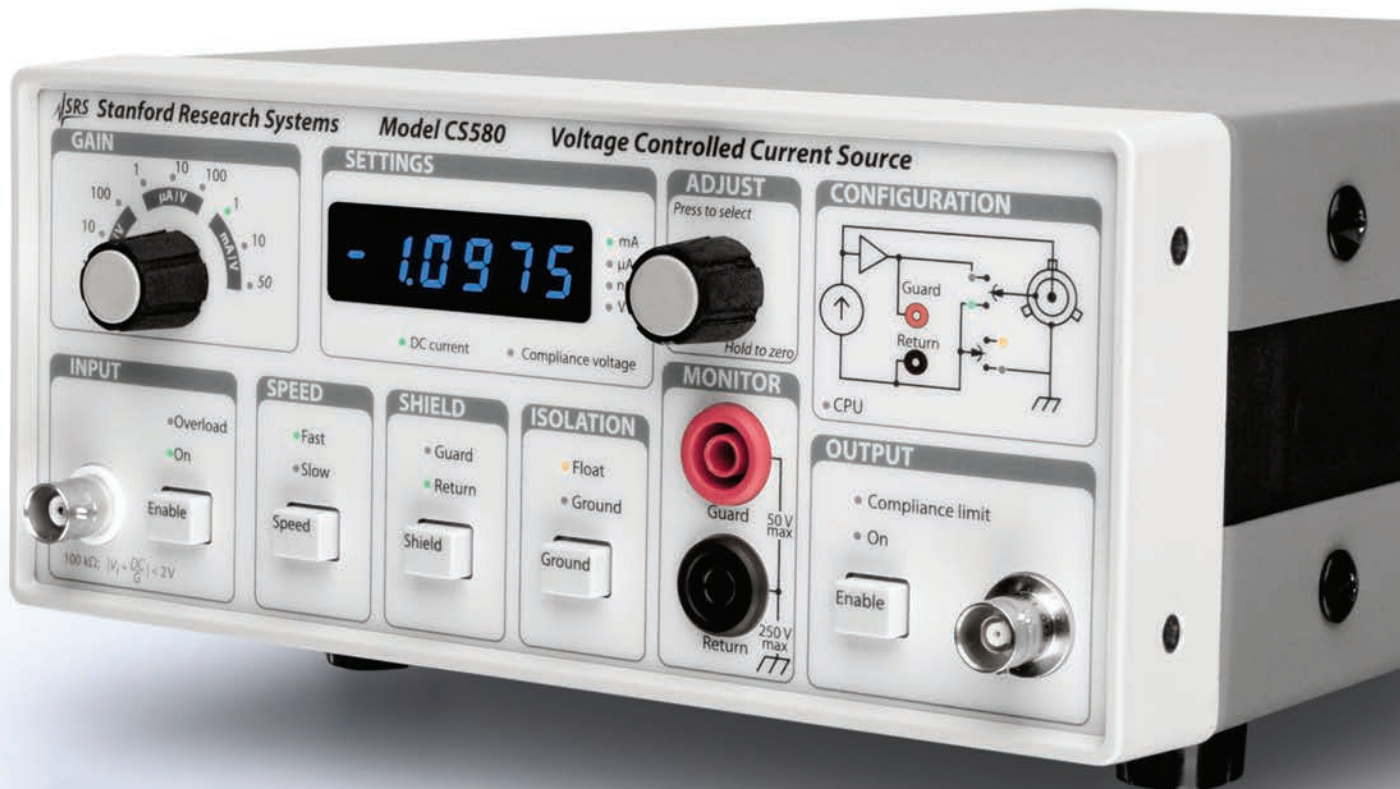
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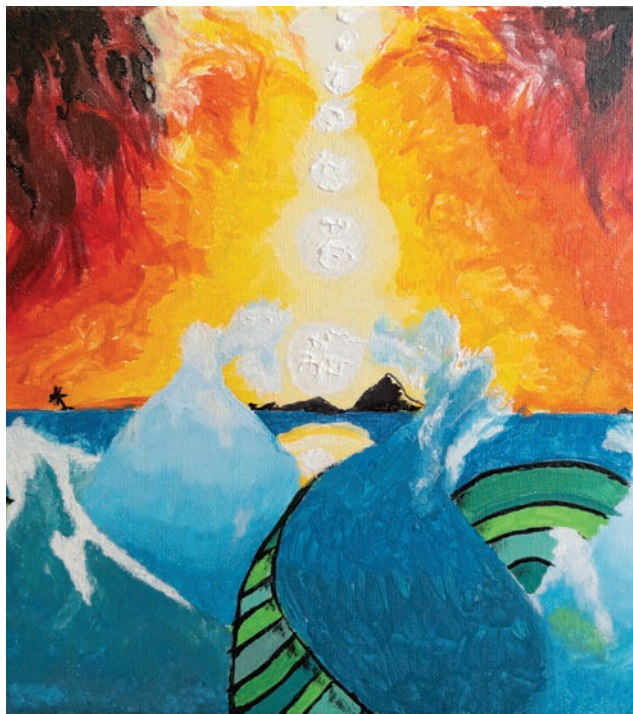
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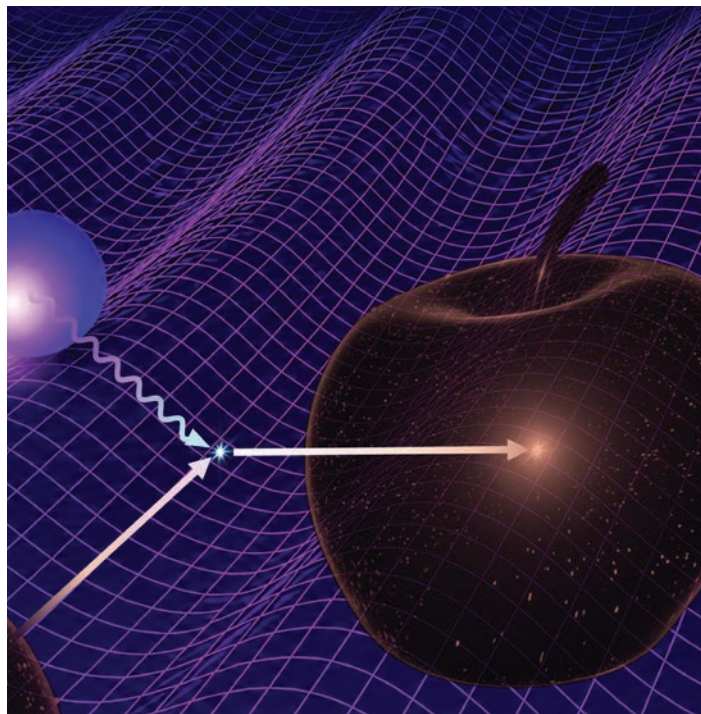
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M. X. Mitchell

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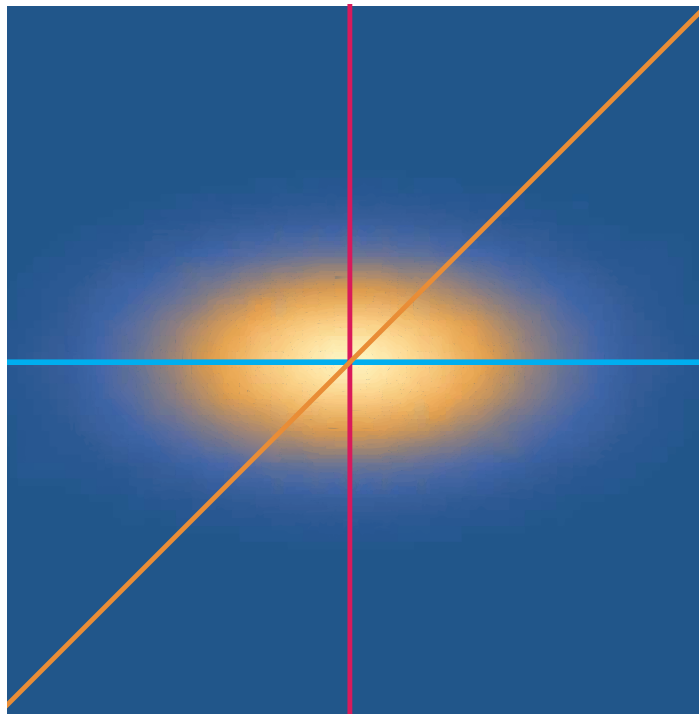
Igor Pikovski

Detecting quantum particles of gravity was long considered hopeless. A new perspective, which takes advantage of quantum technologies, suggests that an experimental realization may be closer than previously thought.

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QUICK STUDY**How and why to measure a quantum state****Michael G. Raymer**

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**ON THE COVER**

The cover is a detail from a 2022 painting, ...*for the good of mankind* (see inset at left), by Marshallese artist Marino Morris. It depicts a nuclear detonation above Bikini Atoll as Marshall Islanders look on, cradled in what Morris describes as "God's hands." The painting's title references the phrase used by US Commodore Ben Wyatt when he announced to the atoll inhabitants in February 1946 that they had to leave because of the impending explosion. To read about the lingering impact of the US detonations there on the Islanders, turn to the article by M. X. Mitchell on **page 30**. (Image courtesy of Marino Morris and the Marshallese Educational Initiative; adapted by Masie Chong.)

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TO READ ABOUT THE REOPENING OF NIST'S NEUTRON SOURCE, TURN TO PAGE 21

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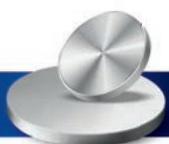


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A shaken lattice of ultracold atoms can simulate extreme quantum chaos

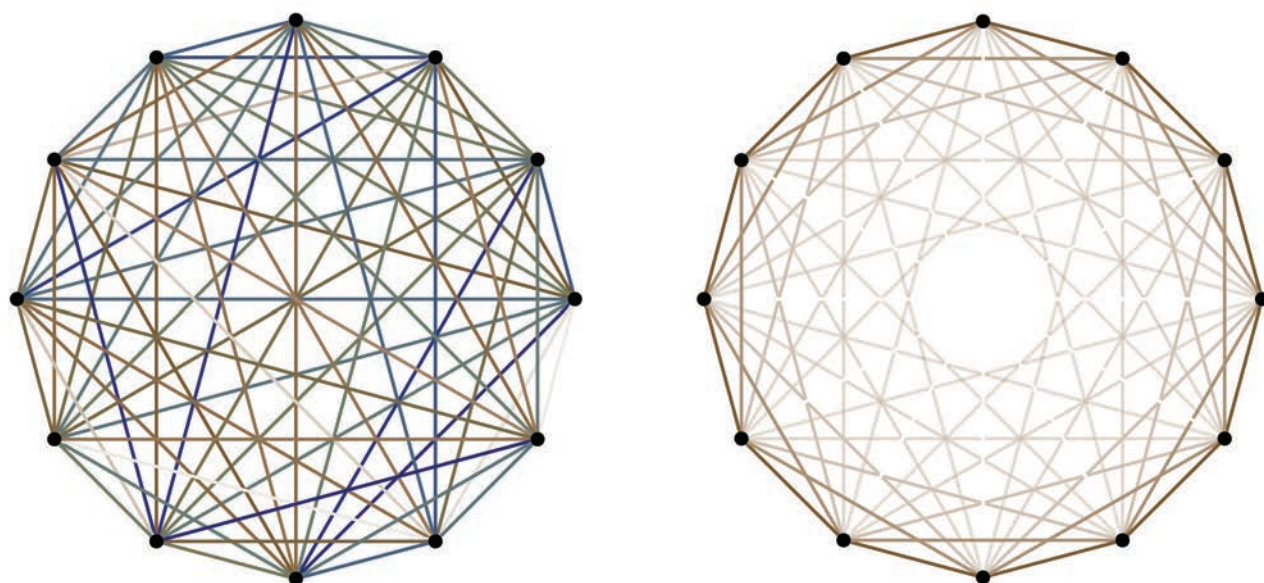
Although atoms in an optical lattice typically have only local interactions, periodically shaking them can effectively induce random long-range couplings.

By Sarah Wells

To understand the quantum chaos of many-body systems, researchers in recent years have turned to the Sachdev-Ye-Kitaev (SYK) model. Named after theorists Subir Sachdev, Jinwu Ye, and Alexei Kitaev, the model can be used to study diverse research areas, such as how information is destroyed inside a black hole and the behavior of high-temperature superconductors just above the superconducting transition. But realizing it with a practical experimental setup is challenging. Charles Creffield (Complutense University of Madrid),

Nathan Goldman (Université Libre de Bruxelles and Collège de France), and colleagues have now offered one solution to that problem: They demonstrate that key characteristics of the SYK model can be simulated by shaking ultracold atoms in a 1D optical lattice.¹ Although the work was conducted using computer simulations, the researchers say it can be realized experimentally using existing cold-atom technologies.

Proposed in the early 1990s and refined in 2015, the SYK model has captured the attention of researchers



▲ In the Sachdev-Ye-Kitaev (SYK) model of extreme many-body quantum-chaos (**left**), each particle couples randomly to all the others. Charles Creffield and colleagues have shown how periodically shaking an optical lattice (**right**) can generate quasi-random long-range couplings. Although the interactions are weaker (indicated by the lower-opacity lines) for particles that are farther apart, the resulting behavior captures many important features of the SYK model. (Image adapted from ref. 1.)

because of how it describes collective behavior between particles that interact with all the other particles in the system with random coupling strengths. The interactions result in an excitation spectrum that is extremely dense at low energies and can be solved directly. Those characteristics make the SYK model an attractive tool for studying extreme many-body quantum chaos systems that exhibit fast rates of information scrambling via rapidly decaying correlations between particles.

The researchers found they could trigger the same type of collective behavior between particles by shaking ultracold atoms in an optical lattice roughly 1000 times per second. Atoms in an optical lattice can typically hop between adjacent lattice sites and repel each other when on the same site. But shaking the lattice suppresses the hopping of individual atoms, and they instead interact—with nearly random coupling amplitudes—with all the others in the lattice. Through numerical simulations, the team found that periodically shaking the lattice re-created key characteristics of the SYK model, including fast information scrambling. The lattice model, however, could not re-create the truly random interparticle interactions that are in the idealized SYK model, Creffield says. Instead, as illustrated in the figure, the shaking generates quasi-random

interactions that are weaker for particles farther apart on the lattice.

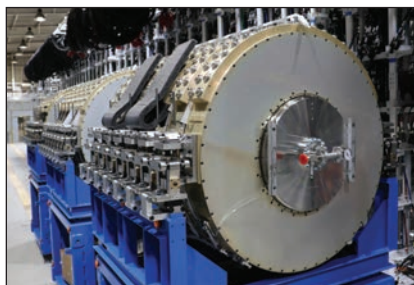
Goldman says that in practice, shaking could be created by moving a mirror back and forth to modulate the position of a laser used in creating the lattice. Although such a kinetic approach should work for both fermions and bosons, the researchers focused on bosons—the boson SYK model has been less explored than the fermion model. The boson implementation may be more accessible for future experimental work because the particles are relatively easy to cool down.

Among the next priorities for the team are extending the approach to higher-dimension lattices and investigating the equivalent fermion model. Although lattice-shaking experiments are possible with existing technology, researchers will need to develop methods to extract data from the experiments to validate their accuracy as SYK analogues. Such advances could provide a practical path to better understanding quantum chaos in a variety of astrophysical and condensed-matter contexts.

PT

Reference

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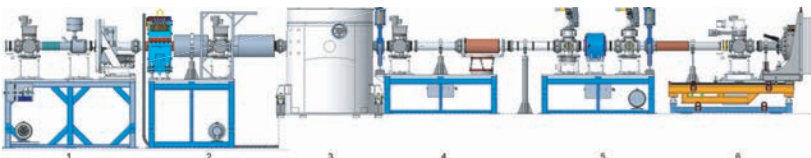
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Geomagnetic storms could get worse than we thought

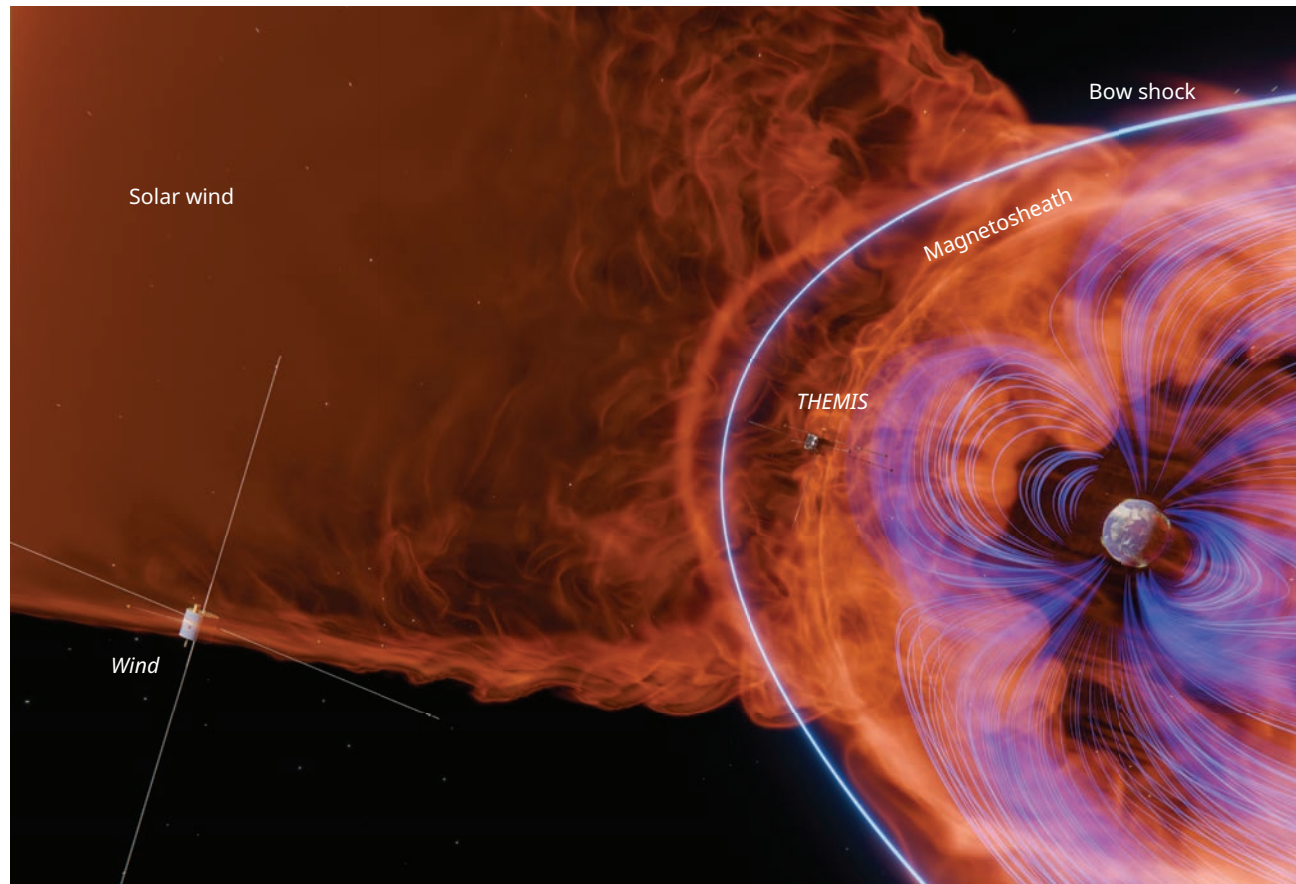
What had appeared to be an upper limit to the strength of the events is an artifact of measurement uncertainty and statistical bias. Those lessons could be relevant for data analyses in other disciplines.

By **Laura Fattaruso**

Unusually bright auroras were seen across the globe in late August and early September 1859—the light displays extended all the way to the tropics. Telegraph wires across Europe and North America failed and, in some cases, caught fire. The events were caused by the largest recorded geomagnetic storm, triggered by a coronal mass ejection colliding with Earth's magnetic field. Such a storm today could cause power grid failure, disruptions to GPS and global communication, and increased radiation exposure. The National Research Council has estimated that the damage could exceed a trillion dollars and take a decade to repair.

Though we've known that an 1859-scale event could happen again, some comfort could be found in evidence that suggested that the amount of energy that solar wind could transfer to Earth's ionosphere has an upper limit, which corresponds to a limit on the intensity of geomagnetic storms. When the strength of solar wind is relatively low, Earth's geomagnetic

▼ **Figure 1.** Solar wind intensity is measured by the *Wind* spacecraft roughly 1.5 million km upstream from where solar wind hits Earth's magnetosphere. Measurements collected closer to Earth by spacecraft such as *THEMIS* (*Time History of Events and Macroscale Interactions during Substorms*) were used in a recent study to evaluate the uncertainty of the solar wind intensity measurements from *Wind*. (Figure courtesy of Nithin Sivadas, NASA's Goddard Space Flight Center.)



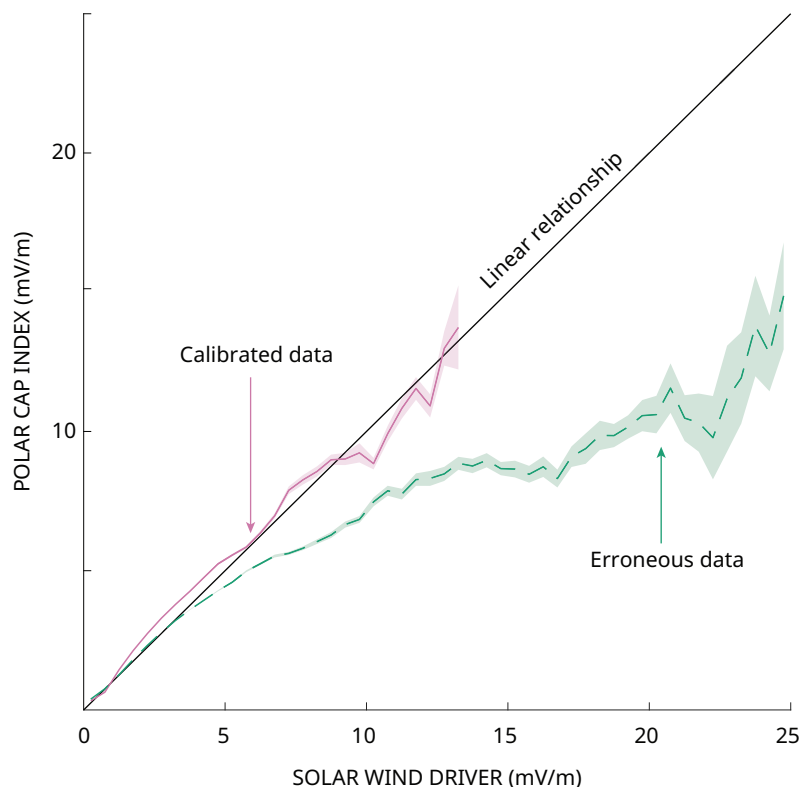


Figure 2. An analysis of uncertainty in solar wind data reveals that an apparent upper limit to the polar cap index, a measure of geomagnetic activity, was a statistical illusion. Calibrated data show that solar wind and geomagnetic activity have a linear relationship and that, under extreme conditions, geomagnetic storms could be roughly twice as intense as previously thought. (Figure adapted from ref. 1.)

response is linear. It seemed, though, that at higher solar wind intensities, the geomagnetic response would reach a saturation limit, and the resulting geomagnetic storm would be weaker than predicted by a linear relationship. Researchers have put forth nearly a dozen ideas for physical mechanisms that could explain the saturation effect, but they've not reached a consensus.

Now research by Nithin Sivadas of NASA's Goddard Space Flight Center and colleagues shows that uncertainty in the measurements of solar wind has created the illusion of an upper limit.¹ The errors stem largely from the position of the solar wind intensity measurements, which, as shown in figure 1, are collected by NASA's *Wind* spacecraft about 230 Earth radii upstream from where the solar wind interacts with the ionosphere.

Unknown bias

The illusion of the saturation effect, the researchers found, was caused by regression to the mean—a phenomenon in which measurement of an extreme value is likely to be followed by a near-average value. A common example is seen in pain treatment. One explanation for the placebo effect is that after reporting extreme pain, patients are statistically more likely to have a closer-to-average amount of pain the next time it is measured. “Usually, people think random error is harmless because we can average it off. You take enough readings, and all the overestimates and underestimates

cancel each other out,” says Sivadas. “But this is not always the case.”

The *Wind* spacecraft, launched in 1994, sits at a point where the gravitational forces of Earth and the Sun are balanced. That position in space enables continuous data collection from a point roughly stationary relative to Earth, whereas data collection by satellites closer to Earth is affected by their orbits around the planet. But the distance between the measurement and interaction points creates substantial uncertainty about the intensity of the solar wind that is actually reaching the ionosphere. Between the position of the *Wind* measurements and Earth's ionosphere, interaction with Earth's magnetosphere causes solar wind to slow and form a bow shock. Though that doesn't lower the strength of the wind's electric field—the primary relevant factor for geomagnetic storms—variability in the solar wind's propagation time, turbulence, and orientation all contribute to the uncertainty.

Sivadas and colleagues used solar wind data collected closer to Earth, by spacecraft such as *THEMIS* (*Time History of Events and Macroscale Interactions during Substorms*, launched in 2007), to estimate the uncertainty and create an error model. They found that the highest intensities measured by *Wind* were not representative of the intensity of solar wind that interacts with the ionosphere; because of regression to the mean, the true values were lower. After correcting the data, they found a linear relationship between solar wind strength and the polar cap index,

a measure of geomagnetic activity, as shown in figure 2. The implication is that if the solar wind that reaches the ionosphere is as intense as some of the high measurements from *Wind*, then the resulting geomagnetic storms could be nearly twice as intense as researchers had previously thought.

Wider implications

In addition to data from *THEMIS*, the researchers used measurements from other near-Earth satellites, including ones from the Double Star, Cluster II, and Magnetospheric Multiscale missions. To account for the variable positions of orbiting satellites, they used machine learning to classify the positions of data points relative to the magnetosphere, which significantly increased the number of measurements available for the analysis.

“It’s nice that we have such long-term datasets,” says Sarah Vines, a lead scientist in the space science division at the Southwest Research Institute in San Antonio, Texas. “Now we’ve got multiple measurement points spread around, so we can actually look at the consistency between those.” She says that more work

is needed to unpack the complex interactions between solar wind and the magnetosphere and that the many physical models aimed at explaining the saturation effect may still contain relevant physics.

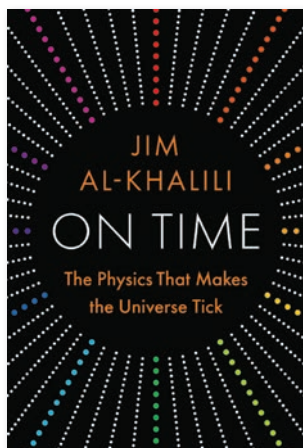
The study demonstrates that unrecognized regression to the mean can be easily misinterpreted as nonlinear physics, Sivadas says. And he says it is especially important to consider when studying climate change, earthquakes, and other topics where extreme events are of interest. He notes that AI analyses could be especially susceptible.

Solar wind activity has been high over the past few years; the 11-year solar cycle reached its peak near the end of 2024. In 2022, SpaceX’s Starlink lost 38 of 49 satellites during a launch because of a geomagnetic storm that increased atmospheric drag and caused the satellites to fall out of orbit—just one example of the many types of hazards posed by the storms. **PT**

Reference

1. N. Sivadas et al., “Regression to the mean can explain saturation of geomagnetic storms,” *Nature* **655**, 1143 (2026).

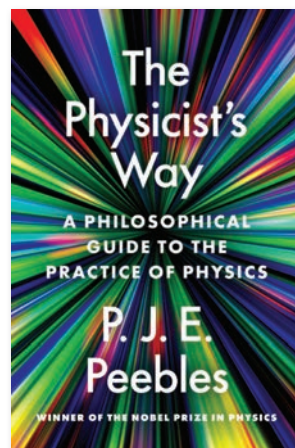
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Kilometer-scale oceanic warm fronts can rapidly alter the atmosphere

Data from a multi-instrument observation campaign shed light on fine-scale, fast-changing air-sea interactions that have implications for scientists' understanding of larger-scale climate dynamics.

By **Laura Fattaruso**



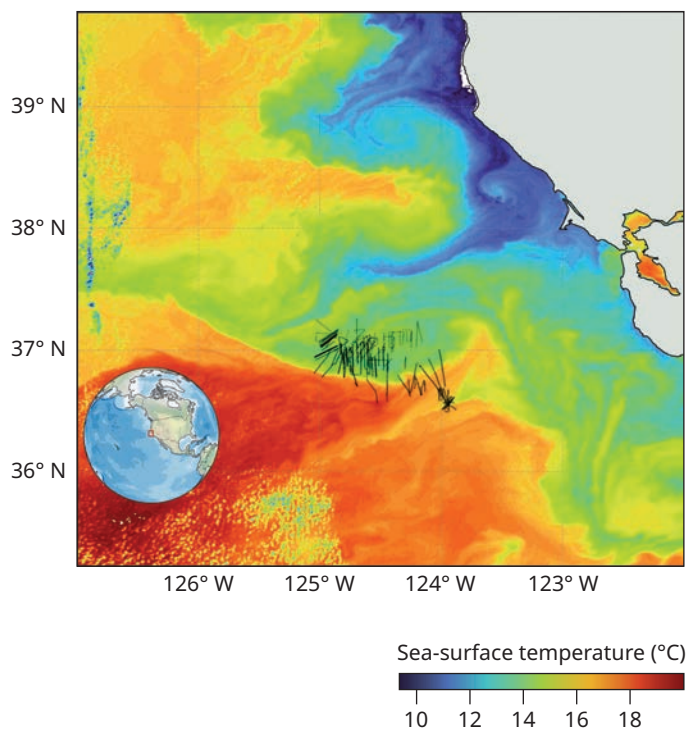
Three aircraft, a fleet of autonomous vehicles on and beneath the ocean surface, and a ship, shown in figure 1, set out off the California coast in October 2022 to collect nearly a month's worth of ocean and atmospheric data. It was the second of three legs of NASA's Sub-Mesoscale Ocean Dynamics Experiment, which aimed to quantify the effect of kilometer-scale air-sea exchanges on climate and biological processes.¹

A new analysis of the 2022 data by PhD student Igor Uchoa and his adviser Jacob Wenegrat, at the University of Maryland in College Park, and their colleagues shows that warm sea-surface temperature fronts in the ocean can quickly transfer energy to the air and cause turbu-

▲ **Figure 1.** NASA's Sub-Mesoscale Ocean Dynamics Experiment used aircraft, ships, and a fleet of autonomous vehicles to collect comprehensive data on kilometer-scale, fast-moving features in the ocean and atmosphere. The research vessel *Bold Horizon*, shown here, was used to take measurements during the experiment's October 2022 research expedition. (Photo courtesy of Nick Statom, Air-Sea Interaction Laboratory, Scripps Institution of Oceanography, UCSD.)

lent mixing of the lower atmosphere.² Similar kilometer-scale temperature variability is found across global oceans, and the resulting air-sea energy fluxes can affect larger-scale climate processes.

Previously, high-resolution physics-based models of air-sea interactions had suggested that kilometer-scale



◀ **Figure 2.** The highly variable sea-surface temperatures off the coast of Northern California lead to sharp fronts, eddies, and filaments like the ones shown here. Black lines depict 63 transects along which detailed temperature and velocity measurements were collected from the ocean and atmosphere during NASA's Sub-Mesoscale Ocean Dynamics Experiment. (Figure adapted from ref. 2.)

(also known as submesoscale) temperature gradients in the ocean could generate the effects observed by the research team. Large-scale winds that blow down the West Coast of the US push warm surface water offshore, and deep, cool water rises to replace it. That produces sharp temperature fronts and mixing features like eddies and filaments, shown in figure 2. Those sharp gradients of cold and warm water then in turn exchange energy with the air and alter kilometer-scale wind patterns. “Winds are basically decelerated over cold parts of the front and accelerated by warm parts of the front,” says Uchoa.

Until now, there were no real-world observations that could confirm what had been seen in high-resolution models. The small scale of such features and the speed at which they move make them challenging to observe. Orbiting satellites, for example, don’t collect repeat measurements quickly enough.

During the study, researchers collected ocean temperature profiles that extended 40 m deep along 63 transects, shown in figure 2. Other observations came from the airborne DopplerScatt instrument, which records simultaneous measurements of wind and ocean currents. Uchoa and colleagues used those measurements and others to analyze how temperature changes in the water altered wind patterns and atmospheric mixing. They found that in addition to altering wind speed, small-scale temperature gradients in the ocean induce vertical circulation in the atmosphere. And the rate at which variable ocean temperatures drive

changes in wind speed is similar to the rate observed at larger scales, but with the changes occurring along sharper boundaries.

“I was surprised that we saw such a strong signal,” says Wenegrat. “At these very small length scales, there’s a lot of atmospheric physics that you might expect to sort of smear out or broaden the response.”

Though global climate models do not resolve features at the kilometer scale, better real-world constraints on localized energy exchange processes can be used to improve how such models account for energy fluxes at air–sea interfaces. “Submesoscale processes are unlikely to be a primary control on global climate sensitivity,” says Paul Palmer, a climate scientist at the University of Edinburgh in the UK. “But they may have outsized importance because they occur at critical interfaces where the ocean, atmosphere, biogeochemistry, and larger-scale circulation interact and exchange energy, momentum, heat, and carbon.”

PT

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2. I. Uchoa et al., “Observed rapid adjustment of the atmospheric boundary layer to submesoscale sea surface temperature fronts,” *Proc. Natl. Acad. Sci. USA* **123**, e2605662123 (2026).

Earthquake detectors measure hurricane turbulence

Seismic and acoustic data can be used to understand atmospheric energy exchanges occurring just above the surface.

By Sarah Wells

As a hurricane makes landfall, it shakes the ground beneath it. The shaking has historically been treated as background noise in seismic monitoring. Now, by analyzing both seismic waves and sound waves from a 2012 storm at frequencies below the threshold of human hearing, researchers have shown how instruments designed to measure earthquakes can be used to better understand the turbulence inside hurricanes.¹ Similar analyses could help improve hurricane simulations and storm prediction.

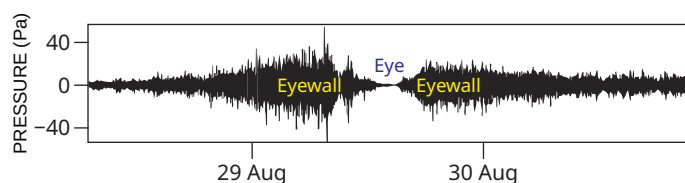
Turbulence data from inside the hurricane boundary layer, the atmosphere's lowermost region (the researchers specify its height as roughly 1–2 km) that exchanges energy, momentum, and moisture with the surface, can provide evidence as to how a storm converts kinetic energy to heat, which can influence storm intensity. Those data are often sparse, however, as the usual methods of flying aircraft directly into storms or using portable weather

towers are dangerous and require manual deployment, respectively.

Qing Ji, then at Stanford University, and colleagues turned to seismic and infrasound monitoring stations from the NSF-funded USArray Transportable Array network, which in 2012 included about 400 stations spaced 70 km apart across the contiguous US. The team looked at data captured in August 2012 by stations located under Hurricane Isaac. The hurricane, shown in figure 1, made landfall in Louisiana as a Category 1 storm and resulted in severe flooding and more than \$2 billion in damage across several states.

▼ **Figure 1.** Hurricane Isaac on 28 August 2012 shortly before making landfall in Louisiana as a Category 1 storm. Once on land, the storm passed over seismoacoustic monitoring stations, which captured seismic and infrasound data. Researchers recently analyzed those 2012 data and demonstrated how infrasound signals can be used to study hurricane turbulence. (Image by Jeff Schmaltz, NASA, LANCE/EOSDIS Rapid Response.)





◀ **Figure 2.** A seismoacoustic monitoring station in Louisiana captured infrasound pressure measurements on 28–30 August 2012 as Hurricane Isaac approached, passed close to the station, and departed. The data gave researchers insights into the turbulence in the lowest layers of the storm. (Figure adapted from ref. 1.)

The stations' microphones recorded infrasound signals of atmospheric pressure fluctuations, which were caused by the transport of atmospheric eddies in the HBL by the storm's high-speed winds. The stations' seismometers also logged weak ground shaking, which was caused by the pressure fluctuations displacing the ground at the sensor location and by distant hurricane-stirred ocean waves that pounded the seafloor. The pressure data, plotted in figure 2, show that the fluctuations increased as the most intense part of the storm, the eyewall, passed by but fell steeply when the calm eye passed over.

Using the frequency patterns found in the pressure measurements, the team calculated the turbulent dissipation rate, which describes how energy is exchanged between eddies of different length scales within the HBL. The result was comparable to those

measured by portable weather towers and by simulations. The team also determined that the origin of the turbulence was well within the HBL, about 100–200 m above the monitoring stations.

The work demonstrates the potential use of seismoacoustic monitoring stations to provide continuous, accessible measurements of events beyond earthquakes. Next steps include seeing if seismoacoustic sensors can measure less powerful storms. The team is also investigating how stations can be used to detect atmospheric inertia-gravity waves, which are key drivers of global wind patterns.

PT

Reference

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The *Roman Space Telescope* isn't the only US observatory built from spy tech

The newest spacecraft from NASA started as a spy telescope. It's just one example of the intelligence world offering resources to astronomers.

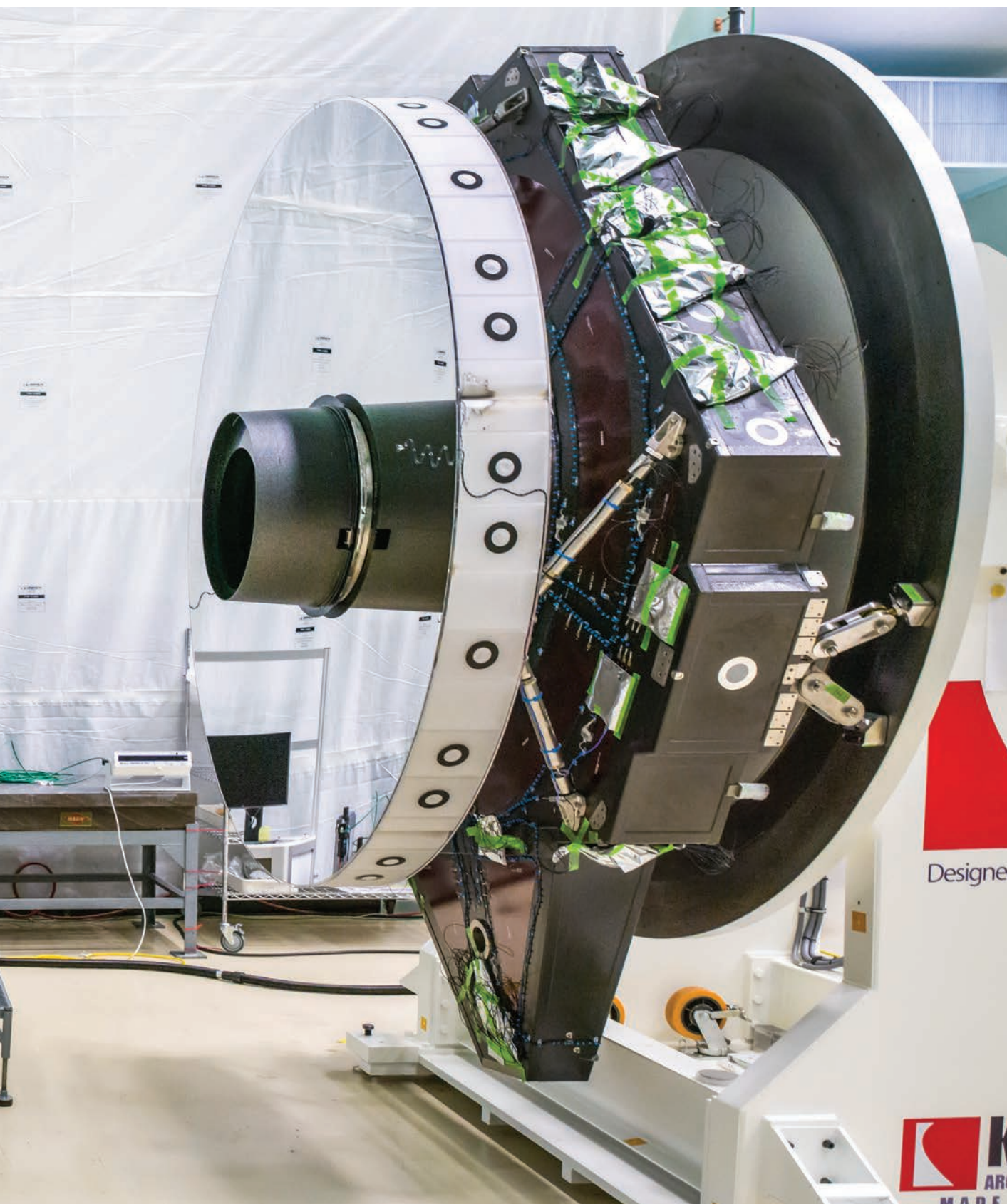
By **Jenessa Duncombe**

It sounds like a quirky fact or colorful footnote: NASA's latest space telescope came from the bones of an unused reconnaissance satellite. The donated spy tech inspired NASA to build a more expensive and more capable telescope than it had initially planned.

You'd be forgiven for stopping there, since there is plenty to say about the *Nancy Grace Roman Space Telescope* that has nothing to do with its covert origins. The telescope will probe the mystery of dark energy; its coronagraph will allow NASA to peer at exoplanets more directly than ever before. The astronomy community eagerly awaited the telescope's 30 August launch from NASA's Kennedy Space Center.

The donation illustrates a relatively unknown history of the influence of the US's shadow space agency, the National Reconnaissance Office (NRO), on astronomy. Although the government did not formally acknowledge





▲ The primary mirror on NASA's *Nancy Grace Roman Space Telescope* came from an unused spy satellite produced by the National Reconnaissance Office. (Photo by NASA/Chris Gunn/CC BY-NC-ND 2.0/Flickr.)

the NRO's existence until the 1990s, occasional knowledge transfer between it and NASA had been going on for decades. The intermittency "highlights the difficulty of cooperation between a very public, open organization, like NASA, and one whose existence was not acknowledged, like the NRO," says space historian Dwayne Day, who has three decades of experience in space policy roles.

Eyes in the sky

It was 1960. A US spy plane had just been shot down over the Soviet Union, and the US sought more covert methods of espionage. So began the NRO, a Department of Defense agency that would grow into the country's clandestine space agency. Formed just three years after NASA, the NRO had the initial goal of spying on the Soviet Union from space by using sophisticated imaging instruments. Declassified documents reveal that the NRO launched hundreds of satellites in its first two decades.

The NRO built the best space optics in the 1960s and 1970s, says Day. Cameras supplied by optics contractors like Itek and Kodak for the NRO's Corona and Gambit spy satellites delivered images so precise that planes and trucks on the ground could be resolved from more than 150 kilometers above. Notably, one of Itek's founding scientists, Duncan MacDonald, was an astronomer and physicist.

Meanwhile, NASA was focused on human spaceflight. Likely just a handful of people at the agency knew about the existence of the NRO in the 1960s, says Day, but they would have understood the NRO only in the vaguest ways.

In the 1960s, the NRO presented NASA with cameras to photograph the Moon during an Apollo mission. Cameras from the Gambit reconnaissance system had a ground resolution of about half a meter or so. "There were people at NASA who were very intrigued by this technology because it was a much bigger optical system than NASA had ever developed," says Day.

When a change of plans left the cameras unused for the Apollo mission, says Day, NASA wanted to use them to observe Earth. "That made some people at the NRO rather unhappy," he says. The NRO was fearful of its covert technology producing information available to the public. The cameras were never used, says Day.

What about the *Hubble Space Telescope*? Some have speculated about whether NASA's most famous telescope had spy origins, but Day dismisses the idea, saying that *Hubble* was not a direct copy of a reconnaissance satellite. *Hubble* scientists did take advantage of existing spy-satellite mirror-fabrication techniques, which saved the agency fabrication costs, according to a NASA historical account. "A lot of the stuff is still

classified," says Day. The NRO says on its website that it has not declassified most of its programs.

Occasionally, newly declassified documents shed light on the NRO's unexpected contributions. Astrophysicist Jonathan McDowell says that he always had been perplexed by the telescope design of the original Multiple Mirror Telescope, built in the 1970s by the Smithsonian Institution and the University of Arizona. The ground-based telescope in Arizona contained six medium-sized mirrors rather than one single larger mirror. "We were told these six mirrors fell off the back of the lorry," jokes McDowell. Later, the NRO declassified documents revealing that those mirrors were surplus from the canceled NRO Manned Orbiting Laboratory program.

The latest collaboration

NASA received a surprise offer from the NRO in 2011 of two unused spy telescopes stored in a warehouse in Rochester, New York. They came from an unspecified NRO program and were up for the taking. NASA learned that the spy telescopes had mirrors that were the same size as *Hubble*'s primary mirror but much lighter weight. "The donation appears to involve very high quality telescope assets with excellent capabilities, better than the best NASA ultraviolet/near-infrared telescopes operating in space today (e.g., the Hubble Space Telescope)," wrote NASA's advisory council in 2012.

Although the NRO has declined to name the program that the spy satellites came from, "the obvious canceled program was the Future Imagery Architecture," says Day. That program, from the late 1990s, fell apart after the contractor failed to deliver on time or on budget, according to declassified records released in 2020.

The NRO could have just thrown the spy satellites "into a shredder and not cared," says Day. But he believes people at the NRO felt that the nation spent a lot of money on them. "NASA and the NRO are both American organizations that exist to advance American interests. So why not take advantage of it?" he says. "But then, of course, it also comes with risk because people start asking questions, and [the NRO doesn't] want to provide answers."

In 2012, one of the spy telescopes, stripped of its classified equipment, became the building block for NASA's next space telescope. Nearly 15 years and roughly \$4.3 billion later, the repurposed telescope has now been launched.

PT

For a profile of the astronomer the satellite is named after, see David DeVorkin's 2020 PT article "How Nancy Grace Roman shaped Hubble," <https://bit.ly/nancy-roman-hubble>.

NIST neutron source restarts after prolonged closure

The user community is cheering the availability of more neutrons for scattering experiments while also worrying that a budget shortfall will prevent their full exploitation.

By **Toni Feder**



The NIST Center for Neutron Research (NCNR) started up in August after a five-and-a-half-year shutdown. The research reactor that supplies the neutrons is ramping up to its full power of 20 MW, and the facility plans to welcome outside users in late November. But with the president's fiscal year 2027 budget proposal requesting less for the NCNR than its pre-shutdown level, users fear that underfunding will limit staff positions, instrument availability, and hours of operation.

A refueling incident in February 2021 forced NIST to shutter the NCNR (see the 2021 *PT* story "Scientists dismayed by interruption at US's most productive neutron source"). One of 30 nuclear fuel elements was not latched into place, leading to fission products circulating within the reactor's primary cooling system and some escaping into the confinement building. Radiation levels, both inside and outside the building, remained well below regulatory health and safety limits, says NCNR Director James Adams.

▲ The Neutron Spin Echo Spectrometer is among the new instruments coming on line as the NIST Center for Neutron Research reopens after a prolonged shutdown. (Photo by Rich Press/NIST.)

The Nuclear Regulatory Commission (NRC) gave the NCNR the green light to restart in 2023, but Adams opted to do a second cleanup. He says that in addition to the physical remediation at the site, the culture was changed “to make sure everyone feels safe bringing issues to leadership.” The tab for the cleanup and associated activities came to tens of millions of dollars, he says.

Neutrons can uniquely probe the structure, dynamics, mechanics, and magnetic properties of materials in areas such as quantum information, energy storage, superconductivity, and aerospace. The NCNR has 29 instruments, representing nearly 40% of the US’s neutron scattering capability and 10% of the world’s. Before the shutdown, the facility served about 3000 users a year. The NCNR restart

marks the first time that an NRC-licensed reactor has reopened after a significant incident involving the melting of nuclear fuel.

Celebrating more neutrons

Efrain Rodriguez, a professor of materials and solid-state chemistry at the University of Maryland in College Park, is one of the many users excited about the reopening. “I have a generation of students who have never been to the NCNR,” he says. “We are thinking about what experiments we want to do there and what instrument configurations we will need.”

While the NCNR has been down, Rodriguez and his students have mostly used the other main US-based neutron sources—the High Flux Isotope Reactor and the Spallation Neutron Source, both at Oak

Ridge National Laboratory. They have also used neutron sources in the UK, France, and Switzerland; other US researchers got beam time in Japan, Australia, and Europe. One plus of working in other countries, Rodriguez says, is that his international network has grown. But if an experiment doesn’t quite work out, “there is no going back the next weekend.” And, he adds, “I ate through my travel budget really fast.”

Rodriguez estimates that his publication pace dropped by about a quarter while the NCNR has been offline. And, he says, he hasn’t been able to train his students as thoroughly because of reduced beamtime access. “My students may have less of an edge when they look for jobs,” he says.

For physicist Rana Ashkar, the timing of the NCNR’s closure and the



▲ A view of the guide hall at the NIST Center for Neutron Research, which is ramping up after a shutdown of five-plus years that was triggered by a refueling incident. The black infrastructure and the large cylinder are parts of the Very Small Angle Neutron Scattering instrument. To its right is a beamline feeding another instrument, the Disk Chopper Spectrometer. The orange machine at left is part of the High Flux Backscattering Spectrometer. (Photo by Rich Press/NIST.)

resulting slowdown in her research was especially stressful because she was still on the tenure track. Her Virginia Tech group turned to Oak Ridge for their neutron experiments probing the mechanical and dynamical properties of lipid membranes. The demand for beam time at Oak Ridge has been “insane,” she says, but “traveling outside the US was financially prohibitive.” She had to abandon some projects; for others, she turned to alternate techniques, which, she says, offered new insights but “could not address the same scientific questions” as neutrons.

The squeeze on access to neutrons, says Ashkar, “has been disruptive to training, research programs, and grant proposals. It was a cascading problem.” The unpredictable and scarce resources deterred some students from going into neutron scattering research, she says.

Seeking more money

Adrian Brügger is director of Columbia University’s Robert A. W. Carleton Strength of Materials Laboratory and president of the Neutron Scattering Society of America. The US neutron community is in “survival mode” because of the NCNR shutdown, he says. Because of the time it takes graduate students to do their PhDs, he says, “it will take five years for the damage to manifest.” He points to three new neutron sources in China that have come on line “while we blinked.” He notes that for the US to stay a leader in neutron scattering, the NCNR—and the field more generally—needs more federal funding.

At this point, four NCNR workhorse instruments have been mothballed. And another four may also go down, Brügger says. “That would be highly disruptive. It would impact the science community in a wide range of research fields.”

The NCNR’s budget for FY 2026 was about \$53 million, out of NIST’s

total budget (excluding earmarks) of roughly \$1.2 billion. Before the shutdown, the NCNR’s annual budget was around \$55 million. The request in the president’s budget for the next fiscal year is \$45 million.

Operating the reactor costs \$35 million–\$40 million a year, according to Adams. For safety reasons, that part of the budget is untouchable, he says, so it’s the user interface and experimental capabilities that are affected by trimming the total NCNR funding. “If I have more money, I do more,” he says.

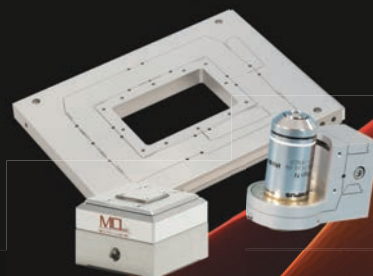
Alongside researchers’ worries about being able to fully exploit the NCNR comes excitement about the facility’s new capabilities. The main ones are three improved guides, which roughly double the flux of neutron beams; automation and upgrades to various instruments; and a spin-echo instrument that can probe dynamics on time scales of a tenth to hundreds of nanoseconds. The spin-echo instrument will allow researchers to probe membranes, gels, polymers, and monoclonal antibodies with improved energy resolution and faster data rates, says Norman Wagner. He is director of the Center for Neutron Science—a partnership between NIST and his home institution, the University of Delaware—which developed the new instrument.

Over the summer, the Neutron Scattering Society of America created an ad hoc committee to lobby Congress to earmark money for the NCNR. A 2024 study by RTI International estimates “that for every dollar invested in U.S. neutron scattering research facilities, \$2.67 in benefits are realized.”

The committee is making two asks, says Brügger. One is for the NCNR to be funded at \$65 million. The other is for the NCNR budget to be allocated as a line item in the congressional budget. “I am cautiously optimistic,” he says.

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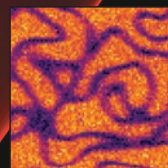


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Robust quantum encryption demonstrated over high-speed internet network

Over a fiber-optic line with state-of-the-art throughput, light carrying the classical information of internet users was joined by photons serving as quantum cryptographic keys.

By **Matt von Hippel**

A collaboration of three companies has demonstrated an exchange of data protected by both quantum cryptographic keys and a next-generation encryption scheme over a high-speed internet link while maintaining the network's regular commercial traffic. The recent demonstration is a key step in showing that an internet capable of supporting advanced quantum encryption is feasible for widespread use, according to Ravishankar Ramanathan, who studies quantum cryptography at the University of Hong Kong and was not involved with the demonstration.

Much of today's internet data are encrypted through the RSA protocol, which is difficult to crack because of how hard it is to factor large numbers. Quantum computers are expected to change that, making it possible to break the codes that keep most data secure. (See the interview with Peter Shor that appeared last year in *PT* about the factoring algorithm named for him.)

To avoid the problem, researchers have explored two options. One, called quantum key distribution (QKD), was proposed by Charles Bennett and Gilles Brassard in 1984. In QKD, a message is paired with a quantum state that serves as a key for decoding. By



▲ Researchers used specialized servers to generate and measure the photons that served as carriers of quantum cryptographic keys. (Photo courtesy of Toshiba.)

sharing a few measurements of the state with the recipient, the sender can verify that the key wasn't measured by an eavesdropper. (For more on QKD, see the 2021 *PT* article "A quantum leap in security," by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo.) Another method, called

postquantum cryptography (PQC), involves designing new encryption schemes, based on different mathematical assumptions, that are expected to be harder for a quantum computer to crack. (See *PT*'s 2023 article on NIST's efforts to finalize new encryption standards.)

For sensitive data, it's possible to use both QKD and PQC to secure messages with physics and mathematics. "Using a hybrid approach—QKD to generate the keys and PQC to encrypt and authenticate the data stream—is a robust, multilayered solution," says Ramanathan.

Several previous demonstrations of the hybrid approach over standard internet lines have focused on the distance of the transmission, specifically the ability to keep photons in a coherent quantum state for hundreds of kilometers over infrastructure that can easily be updated to use new PQC protocols. The new demo is over a much smaller distance: a 21.8-kilometer link between Chicago and Hammond, Indiana.

The new demo, by researchers with the companies Ciena, Quantum Corridor, and Toshiba, competes on throughput. Whereas other hybrid QKD networks have classical traffic at 400 gigabits per second or 800 gigabits per second, this network carries 1.6 terabits per second. The researchers had to manage traffic on different wavelengths to support both the demo and Quantum Corridor's commercial customers. They used Ciena technology to encrypt the signals with PQC and multiplex them across the different wavelengths. Toshiba's QKD servers generated and measured the quantum states that served as keys.

"Until this demo, if you wanted the physical security of QKD, you had to accept lower overall data throughput on the line," says Ramanathan. "The reason why this speed matters is that it proves to the big players—like AWS, Google, or Microsoft—that connect AI clusters and cloud computing hubs that they do not have to throttle their massive AI data pipelines to achieve hybrid quantum safety."

Because it requires specialized sources and detectors, QKD is expensive to implement and so may be limited to high-value links in the near term. And longer-distance links currently require trusted relays, a vulnerability that worries organizations like the National Security Agency. Ciena is optimistic that its technology will be applicable to other geographic areas and network types, says Paulina Gomez, the company's director of portfolio marketing.

Future demos may also expand to different QKD methods. The new demonstration used the original Bennett and Brassard algorithm, but some experts, including Ramanathan, advocate for newer algorithms that are resilient to a wider range of attacks. Toshiba has demonstrated one such procedure, called twin-field QKD, where photon keys are distributed from two different locations.

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Q&A: Missy Cummings strives to make self-driving cars safer

The former fighter pilot wants the designers of autonomous systems to heed the hard lessons from aviation.

By **Jenessa Duncombe**



▲ Missy Cummings (Photo courtesy of George Mason University.)

Mary “Missy” Cummings became a US Navy fighter pilot in the 1980s at a turning point in aviation. New technology was transforming analog aircraft into computer-driven machines.

Over her nine years as a pilot, Cummings mastered how to fly without, and then with, a computer’s help. She witnessed military aircraft accidents caused by human-machine miscommunication. “You’re not sure who’s in control,” she says. “Is it you? Is it the computer? What are you supposed to do?” During her time as a pilot, high-profile crashes from human-autopilot confusion in commercial aviation led to federal investigations. The consequences of the disconnect between human and machine inspired Cummings to go back to school for her PhD in systems engineering.

Now the director of George Mason University’s autonomy and robotics center, Cummings studies how the designers of self-driving cars and other systems can avoid accidents when introducing automation. “A lot of people had to die in the ’80s and ’90s for us to learn these lessons,” says Cummings. Her research applies a human-centered design framework to new autonomous systems.

The following interview has been edited for length and clarity.

What motivated you to become a fighter pilot?

The Berlin Wall had not yet come down, and *Top Gun* had just come out. In my mind, why would you not want to be a fighter pilot? When I found out when I was in the Navy that women could be pilots, then there was no other path.

How did planes change during your service?

In fly-by-wire aircraft, like F-18s, the planes are doing all the flying, meaning the computer commands the plane's ailerons and rudder to go to certain positions. Where you put the plane's center stick is translated by the computer into actually controlling the air surfaces. Whereas in the analog A-4 aircraft that I flew first, I had direct control over the ailerons and rudder.

What were the implications of adding automation?

In the three years that I flew F-18s, one person a month died on average, and it was all human-machine interaction problems. In aviation, that was the first time we took a safety-critical system and put a lot of software in it. Some commercial planes flew into the side of mountains or hit other aircraft.

There's a famous graph of air-

craft accidents. Aviation had just been getting safer over time in general. This little bump of accidents in the '80s and '90s happened while I was in the military flying, and that's what motivated me to go back to school.

Your research looks at the cognitive load on humans when they interact with machines. It's tempting to think that adding more digital information to environments like a car dashboard would help people make better decisions. But your research often finds the opposite is true.

Not enough information can be detrimental, but too many streams of information, especially if you don't know how to prioritize that incoming information, can be harmful. And that's where we find ourselves. If you look at modern-day cockpits, the number of dials, sensors, gauges—you can very quickly overwhelm a pilot by pushing in a lot of information and alarms. For example, there was a case where an Airbus in 2010 en route from Singapore to Sydney had a major engine failure, and it sounded like a Las Vegas showroom in the cockpit because the alarms hadn't been coordinated, and the pilots were just being

bombarded on all sides.

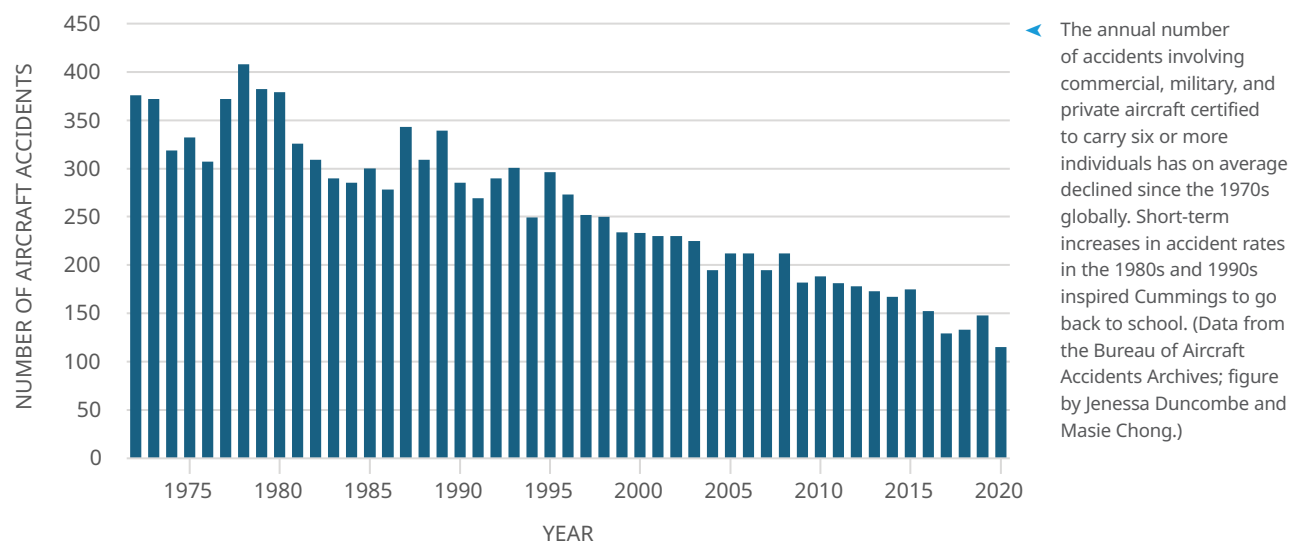
The problem with people having more information in cars is that it diverts their attention from the highly visual task of driving, so there is a balance needed. We want to give people enough information to do their jobs but not too much and overwhelm them, like in the Airbus incident. Or deliver irrelevant, distracting information, like when BMW pushed *Spider-Man* ads on drivers' dashboard screens this year.

We humans are in love with an inflow of information, but unless we really take a human-centered design approach, we can actually make people's jobs much harder, if not impossible.

As a researcher, how do you investigate that?

I've spent basically a decade of my research career showing people that you need to be able to construct a computational model of what information is coming in, what the capabilities are of the people, and what the task demands are from the environment. Then you can dynamically model pretty well when and how you can task-load people.

For instance, we looked at how people's attention waned when driving for long periods. We put





▲ As a US Navy fighter pilot, Cummings felt the computer in early automated aircraft hiccup at times. (Photo courtesy of Missy Cummings.)



▲ Can a car's autonomous alert system spot an inflatable test dummy crossing the street? Cummings put several recent car models to the test as part of her academic research on autonomous systems. (Photo courtesy of Missy Cummings.)

people behind the wheel in a simulated driving scenario and measured their brain activity for four hours. Even when they were in charge of driving, people's brain activity dropped on average after about 20 minutes. Self-driving cars that rely on driver assistance to intervene in unsafe situations will need to find ways to detect how much people are paying attention to know whether a human could really intervene in time.

What other issues do self-driving cars face?

There is no such thing as truly self-driving cars, meaning that all the self-driving cars today have remote operators that are babysitting them. My research on dispatch operations for self-driving cars found that the division of tasks is important. You don't want to over- or underburden someone. In December, there was a power outage in San Francisco and Waymo's self-driving cars came to a halt, putting the city in gridlock, because they were waiting to hear from their remote operators.

What about the safety of automated driver assists?

There are two levels of driver assist. One is a must-have, one is a nice-to-have. The must-haves are safety driver-assist features, like blind-spot warnings or automatic braking. Those are must-haves because they are all passive. They sit in the background, and they help you be safer.

The nice-to-haves are different. Automated driver assist passes cars for you or does automated cruise control. It controls your speed and takes exits.

My issues with driver assist are with the convenience features, not the safety features. We recently tested whether cars in automatic driving mode, in which no driver has hands on the steering wheel, could reliably detect a pedestrian. The cars drove on a test track toward an inflatable dummy at 40 miles per hour. We repeated the test a couple hundred times. Our research shows that one driver-assist system on the market today cannot reliably detect a pedestrian.

What role could generative AI have in automation?

When you play around with a large language model, you can type in a question and then get an answer. If you type in the same question again, you'll get a different answer. Neural nets are nondeterministic by design, which is fine. And indeed, that's what's given us some creative abilities in generative AI, which can be very helpful. But this is why it's two sides of the same coin. You can get creativity out of uncertainty, but you can also get unpredictable performance. The probability that you will have an incorrect answer significantly grows in ways that are not appreciated by the medical, transportation, and defense communities.

There are discussions of putting large language models in charge of controlling weapons. There has never been a worse idea. I even hear questions about putting these technologies inside of nuclear reactors. No, no, no, no, no! Academia and industry have fallen in love with generative AI but don't want to be forced to deal with its messiness, and that messiness is uncertainty. **PT**

Arctic Report Card seeks new home after NOAA pulls support

By **Lindsay McKenzie**

The scientists behind the Arctic Report Card (ARC) are seeking a new sponsor after NOAA announced it would no longer contribute toward the report's production, publication, and promotion. The annual climate assessment provides an overview of the Arctic environment by covering topics such as temperature trends, weather patterns, and the state of major glaciers.

Work on this year's report is well underway. Twila Moon, a lead ARC editor and deputy lead scientist at the National Snow and Ice Data Center at the University of Colorado Boulder, says that all 2026 topics were finalized in early summer, and authors are already working on their contributions. The report remains slated to be presented at a press conference during the American Geophysical Union (AGU) annual meeting in December.

"We are moving quickly to determine alternative pathways to publish the report and ensure that the information and insights make it to decision-makers, educators, community leaders, and the public," Moon says.

The agency informed ARC editors of its withdrawal at a regularly scheduled meeting in August and announced in a public statement that "coordination of the 2026 Arctic Report Card will not be facilitated through NOAA." It said that the data it has historically contributed to the report will continue to be collected and will remain publicly available. NOAA did not explain the rationale behind its decision.

Moon says the agency did not give her or her colleagues advance warning of the decision but that cuts to other federal climate science activities had made such a move conceivable. NOAA declined to issue a press release for last year's report, Moon says, but the report was published as usual, and a press conference at the AGU meeting went ahead as scheduled. Last year was the 20th anniversary of the ARC.

Senator Lisa Murkowski (R-AK) issued a statement saying she understands the 2026 report may continue under another sponsor but called NOAA's withdrawal part of "a troubling federal trend" of undercutting Arctic research. "We need to invest more in the region, not less," she said. House Science Committee ranking member Zoe Lofgren (D-CA) condemned the NOAA decision and urged continued support for the assessment.

Moon says the report's editors remain committed to preserving the ARC this year and beyond, though finding a long-term home will be a larger challenge. "We are motivated to continue the ARC as a timely, trusted resource on Arctic observations," she says. "Continuing the ARC past 2026 is a larger puzzle than tackling 2026, but I hope we find a path forward to do that."

For more from FYI, the science policy news service at AIP, visit <https://aip.org/fyi>.

Fewer NSF graduate fellowships expected next year

By **Clare Zhang**

NSF plans to cut back next year on the number of graduate research fellowships it awards, despite recent White House praise for the program. In a 25 August solicitation, the agency announced that in fiscal year 2027, it expects to award 1500 such fellowships, which provide three years of support for outstanding STEM graduate students. The agency awarded an all-time high of nearly 2600 fellowships in FY 2026.

The solicitation is the latest development in the confusing saga of the Graduate Research Fellowship Program (GRFP) in the second Trump administration. The record number of awardees in FY 2026 came after a sharp drop from FY 2024 to FY 2025. The White House, meanwhile, has asked for deep funding cuts to the program in its 2026 and 2027 budget requests but in a separate document proposed expanding it. The Office of Science and Technology Policy's July report on the future of the US research enterprise praises the GRFP as an example of betting "on people, not just projects." It also says, however, that "more work remains to improve the selection mechanism and further empower students to choose their universities and principal investigators."

The timing of the NSF solicitation leaves applicants with fewer than 60 days to submit their proposals—30 days short of NSF's self-imposed minimum. The solicitation also states that research on STEM education and learning or research that falls under the Social, Behavioral, and Economic Sciences Directorate is excluded from fellowship eligibility. This is the second consecutive year that the agency has added eligibility restrictions to the program.

An NSF spokesperson says that the 1500 estimated awards are consistent with the president's budget request for FY 2027 and that the final number of awards will be subject to congressional appropriations.

"I think 1500 awards would be terrible," says Susan Brennan, a former GRFP program officer. "But I think, basically, they have to go by the president's budget at this stage. So, I think the best thing the community can and should do is to advocate to have 2500 awards at least."

In his proposed FY 2026 budget, President Trump requested enough money for only around 800 GRFP awards. But before NSF made its solicitation, the Senate Appropriations Committee released a bill calling for funding to support 2000 fellowships. NSF ended up exceeding even the Senate committee's target.

Seeing the estimate of 1500 fellowships for FY 2027 might discourage prospective applicants even if the actual number of awards ends up being higher, says Gisèle Muller-Parker, a former GRFP director. "That's going to depress the diversity of applicants and the fields that they come from."

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The Descent of a Thousand Suns, a 2022 painting by Marshallese artist Chapel Capelle, commemorates US nuclear detonations in the Marshall Islands by visualizing the descent of several suns into the ocean. The surrounding sky is depicted as if it is on fire. (Image courtesy of Chapel Capelle and the Marshallese Educational Initiative.)



THE 80-YEAR NUCLEAR LEGACY IN THE MARSHALL ISLANDS

M. X. Mitchell

An interview with a prominent member of the Marshallese diaspora delves into the ongoing impact of aboveground US nuclear weapons testing in the Pacific archipelago.

Between July 1946 and August 1958, the US conducted 67 nuclear detonations in the Marshall Islands, an archipelago in the northwestern Pacific Ocean.^{1,2} The US occupied the islands during World War II and later governed them as a part of a United Nations trusteeship called the Trust Territory of the Pacific Islands.^{3,4}

The Marshall Islands became the site of the largest and most devastating aboveground US nuclear explosions, including the first detonation of a hydrogen bomb, called Ivy Mike and detonated on 1 November 1952, and the most powerful US nuclear explosion on record: Castle Bravo, detonated on 1 March 1954.² Bikini and Enewetak Atolls, the two atolls used as proving grounds, are the most heavily contaminated, but fallout from the explosions reached others. Parts of the archipelago remain contaminated today,⁵ and many Marshallese people continue to experience health effects associated with radiation exposure.⁶

Although the technical and scientific histories of the explosions are relatively well known, the experiences of Marshall Islanders have received less attention. To mark the 80th anniversary of the beginning of US detonations in the archipelago, I sat down with Marshallese civil society leader Benetick Kabua Maddison to discuss how

that history remains an important part of Marshall Islanders' lived experiences today.

Kabua Maddison is the executive director of the Marshallese Educational Initiative (MEI), a nonprofit organization based in Springdale, Arkansas, that serves the Marshallese community in the US by educating audiences about the archipelago and its people, fostering intercultural dialogue, and helping members of the diaspora navigate life in the US. MEI also works to raise public awareness of the history and consequences of US nuclear operations in the islands. Under Kabua Maddison's leadership, MEI contributed to the Office of the United Nations High Commissioner for Human Rights' 2024 report on the nuclear legacy.⁷ It is also providing input for the follow-up UN report, which is scheduled for release later this year.

I first met Kabua Maddison in connection with my research on the legal history of US nuclear operations and colonialism in the archipelago.^{3,4,8} We were introduced in 2015 at the American Historical Association's Pacific Coast Branch meeting, where he presented a paper on how Marshallese communities affected by nuclear explosions understand connections to their ancestral atolls.

We got together for another conversation about nuclear history on 29 June 2026, two days



◀ Benetick Kabua Maddison, executive director of the Marshallese Educational Initiative, participates in a discussion at the United Nations in New York City on 27 November 2023 as part of the Second Meeting of States Parties to the Treaty on the Prohibition of Nuclear Weapons. (Photo courtesy of the Marshallese Educational Initiative.)



◀ A map of the Marshall Islands, identifying all the major islands and atolls. The US nuclear detonations occurred on Enewetak and Bikini Atolls, but fallout from the explosions reached other atolls. (Map adapted from iStock.com/PeterHermesFurian.)

before the 80th anniversary of the Able explosion on Bikini Atoll—the first nuclear detonation in the Marshall Islands. Part of Operation Crossroads, the detonation was the first peacetime nuclear detonation and the fourth-ever nuclear explosion, after the Trinity test and the two bombs dropped on Japan.⁹

The transcript of our discussion follows. It has been condensed and edited for clarity.

Iqkwe, Benetick. We're, of course, meeting to discuss nuclear weapons, but I thought we could start on a happier note. Could you tell *Physics Today's* readers a little bit about the Marshall Islands? What are some of the wonderful and special qualities of the archipelago and the Marshallese people?

The Marshall Islands are located in the North Central Pacific between Hawai'i and Australia. The archipelago has six islands and over 29 atolls within a territory that's about 1 million square miles. So, about the size of Kazakhstan. And, right now, the population is 42 000.

Unfortunately, the majority of Marshall Islanders, including myself, are living outside the Marshall Islands. But in the islands, the weather is warm all year round. The water is turquoise blue. White, sandy beaches. Friendly people all around. It's just an amazing paradise that, unfortunately, has this dark history.

You mentioned that you are living in the US. I wonder if you could tell us a little bit about yourself and about the Marshallese community in the US.



▲ A beach on Majuro Atoll, pictured in 2016.

* The Compact of Free Association transitioned the Marshall Islands from a US-governed status of trusteeship to a self-governing status called free association. Under the agreement, the US required the Marshall Islands to accept a global settlement of all nuclear claims. The US furnished a \$150 million settlement trust fund but stripped its federal courts of jurisdiction over pending and future nuclear claims. The fund did not come close to covering the damages subsequently adjudicated by the international tribunal established to handle the claims: Almost \$1 billion worth of those awards remain unfunded. Federal courts have dismissed litigation over the settlement, and the US government has declined to reopen negotiations.

I was born in the Marshall Islands on the atoll of Majuro, which is the capital, and moved here to Springdale, Arkansas, with my parents and my siblings in 2001. We got to Arkansas on 4 March, and it was a culture shock for someone coming in from low-lying atolls to the Ozark Mountains of northwest Arkansas. In fact, when we landed, it was cold. It was snowing outside. And I was nervous because I was wondering to myself, “What is this? What is this white stuff falling from the sky? And why are there so many Caucasians?” So it was a cultural shock for me.

My family has lived here ever since. We came here for employment, for education, for health, and for other reasons that attract Marshallese people to the

US. Today, Arkansas is home to the largest population of the Marshallese diaspora. We’re at 25 000 now and growing. I believe we already surpassed the population of Majuro.

Wow! That’s a very large community living in Arkansas. What first brought Islanders to Springdale? Do you have a sense of why folks wanted to come to this mountainous part of northwest Arkansas?

Marshallese people are able to come to the US through the Compact of Free Association, which is this international agreement between the Marshall Islands and the US that stems from the nuclear testing program.* This agreement initially [came into effect] in 1986. Prior to that, we were governed

by the US as a United Nations trust territory. Therefore, we had people from our community come to the US for education. We had a lot of Marshallese here in the US attending college and vocational schools during the period of trusteeship.

One of them attended college in Oklahoma. His name was John Moody. After Moody was done with his education in Oklahoma, he moved up to northwest Arkansas, where Springdale is, and he found a job at the Tyson chicken company. He told families and friends back home about the job opportunities and the low cost of living in Arkansas. Marshallese people continue to move here, not just from the islands but also from the West Coast, places like California and Hawai'i.¹⁰

So Springdale has become a hub for the Marshallese community in America even for people living elsewhere in the diaspora?

Absolutely. We have people here who tell me, “You know, there’s this person that I used to live with in California, and I just found out recently that they’re here.”

How did you first learn about US nuclear operations in the Marshall Islands? How did that come into your life in Springdale and into your work?

Growing up, I always heard about the US nuclear testing program in the Marshall Islands, but it wasn’t something that I really delved into. I became much more aware of the nuclear legacy when I joined the Marshallese Educational Initiative. I was still in high school. On Nuclear Victims Remembrance Day in 2014, I was invited to the Clinton Presidential Library in Little Rock, Arkansas, to attend [an event commemorating] the 60th anniversary of the Castle Bravo disaster.[†] I was asked to speak on the importance of youth engagement and the impact of climate change,

† Nuclear Victims Remembrance Day is held annually on 1 March, the anniversary of the Castle Bravo detonation, which exposed hundreds of Marshall Islanders to radioactive fallout. It is a national holiday in the Republic of the Marshall Islands.



▲ Independence Day celebrations on Majuro Atoll on 4 July 1944, shortly after the US occupied it during World War II. (Image from box 2, folder 50, Photographs of the Civil Affairs Activities in the Trust Territory of the Pacific Islands, record group 38, National Archives at College Park, MD.)

connecting that to the nuclear legacy.

From then on, I've been involved in raising awareness about the ongoing impact of the tests, as well as participating in international conferences—not just to raise awareness but also to demand that the world abolish these weapons of mass destruction.

I noticed just now, and I've heard on other occasions, that you often speak about these nuclear bomb detonations as a legacy rather than as a history. What does the term legacy convey that the term history doesn't capture?

I think when people hear the word history, they often think about what happened in the past. And so for us Islanders, we use the word legacy because these are issues that we're still dealing with to this day—issues that we are literally dealing with in our own homes, in our own bodies. Many of us continue to take care of loved ones who have cancer, who have diabetes, heart disease, and other chronic illnesses that are tied back to what happened in the Marshall Islands.⁶ And it's not something that we can ignore, or forget about, because it's here. It's the reality for all of us.

And so that's why we call this the nuclear legacy instead of nuclear history. Because these issues are intergenerational. Our islands are still contaminated, and they will be for tens of thousands of years, impacting thousands of generations down the road.^{11–13}

Could you speak to some of the other ways that Marshallese communities living in the US are still affected?

The most obvious one is migration. Before the Compact of Free Association, there was the UN Trust Terri-

tory of the Pacific Islands, which was this [1947] agreement between the US and the UN.³ Under that agreement, the US was supposed to take care of us. It was supposed to take care of the development of our islands, of our well-being. But that was not the case. Instead of investing in the Marshall Islands, the US was investing in nuclear weapons. We move here to the US seeking opportunities that should have existed over there [in the Marshall Islands] in the first place. When we think about the destruction of lands, you cannot do any economic development on those lands because they're poisoned.⁴ And so people have to come here for jobs.¹⁰

We're also dealing with a health-care system back home that is not sufficient. Yes, it is universal health care where people do not have to worry about health insurance or high medical bills. But we don't have oncologists. Sometimes the dialysis machine breaks down. And so people have no choice but to come to the US for these opportunities or to seek help.^{14,15}

There's also cultural loss. A lot of the children who are born in the US or who come here at a very young age, like myself, lose their language. They lose their ancestral ways. Many do not know the ancient chants. Many do not know how to make traditional medicines or how to navigate or how to build traditional homes. And so these are some of the larger consequences of the testing.^{12,13}

What are some of the things that the Marshallese Educational Initiative is doing to address some of these issues?

We don't just talk about the nuclear legacy. We also provide programs and services to uplift Marshallese

‡ The kinds and levels of radiological contamination vary across the archipelago's atolls and islands. Bikini, Enewetak, and Rongelap Atolls have the highest levels of contamination.⁵ A remediated portion of Enewetak is home to a Marshallese community, but Bikini and Rongelap do not currently have full-time residents.



community members. For our youth, we provide programs that connect them to our elders, where they can learn the language, the culture, the history. And, in fact, just from our experience with that, a lot of young Marshallese are interested in knowing more about who they are and where they come from.

What's also interesting is that when you ask a Marshallese child born here in the US, "Where are you from?," they automatically say, "I'm from the Marshall Islands." They don't say "I'm from the US," despite the fact that they were born here. That shows that we are still connected to our islands in some ways, and we're trying our best to maintain our identity despite everything that we've been through and are still going through. This is where MEI steps in to ensure that opportunities [to learn] our history, our culture, and the language are provided to our community, so that

they can continue to embrace who they are.

It's a really big year with the 80th anniversary of the beginning of US nuclear detonations in the Marshall Islands. What is MEI doing to commemorate the anniversary at home in Springdale and far beyond?

We're hosting the Solidarity concert, featuring MARK Harmony, which is a Marshallese local boy band here in Arkansas. [The concert was held on 30 June.] We've been collaborating with the band since last year on creating a 10-song album. [The album was released on 10 September.] And the songs are really moving, powerful, and all connected to the nuclear legacy. So that's one of the ways we're trying to remember the past but also educate others that these issues are not history; these issues are ongoing. We also plan to take the band on a nuclear-free-world tour, launching in

▲ Members of the Marshallese community in Springdale, Arkansas, and staff from the Marshallese Educational Initiative pose with a delegation from the Office of the United Nations High Commissioner for Human Rights during a meeting in Springdale on 21 May 2025. (Photo by April L. Brown, courtesy of the Marshallese Educational Initiative.)



▲ The Marshalllese band MARK Harmony (from left, Kairo Langrus, Raygon Jacklick, Arsi Lokot, and Matthew John) performs at the 2023 Nuclear-Free Future Awards in New York City. (Photo by April L. Brown, courtesy of the Marshalllese Educational Initiative.)

§ The US government states that it has declassified more than 10 million pages of documents relating to nuclear detonations in the Marshall Islands. But the 2024 UN report notes that the US acknowledges that 40 million–80 million potentially relevant pages remain unprocessed and therefore undisclosed. The latter figure is drawn from a comprehensive 2022 study by a US governmental advisory committee that examined the feasibility of declassifying all as-yet unprocessed records relating to nuclear operations and cleanup in the archipelago.

Geneva later this year when the Office of the UN High Commissioner for Human Rights introduces its [upcoming] report on the Marshall Islands nuclear legacy to the UN Human Rights Council. [The tour started on 25 September.]

Why is song such a powerful way of speaking to the nuclear legacy?

Yeah, so, these are lived experiences. It's hard to talk about these things. And so we find other mediums to try to get the message out, whether that's poems, movies, or songs, and so forth. We decided, well, let's use songs, but also artwork and storytelling for this Solidarity concert. It's

a blend of everything that we try to use to convey how we feel about these issues and how they impact us.

And songs are traditionally a very important part of Marshallese culture, right?

They are! I mean, when you're in the islands, you'll see people with their ukulele ready to sing. We sing at home, in churches, at community gatherings. It's a really important part of who we are.¹⁶

If you could leave *Physics Today* readers with something that you wish scientists, historians, and the general public would keep in mind, what might that be?

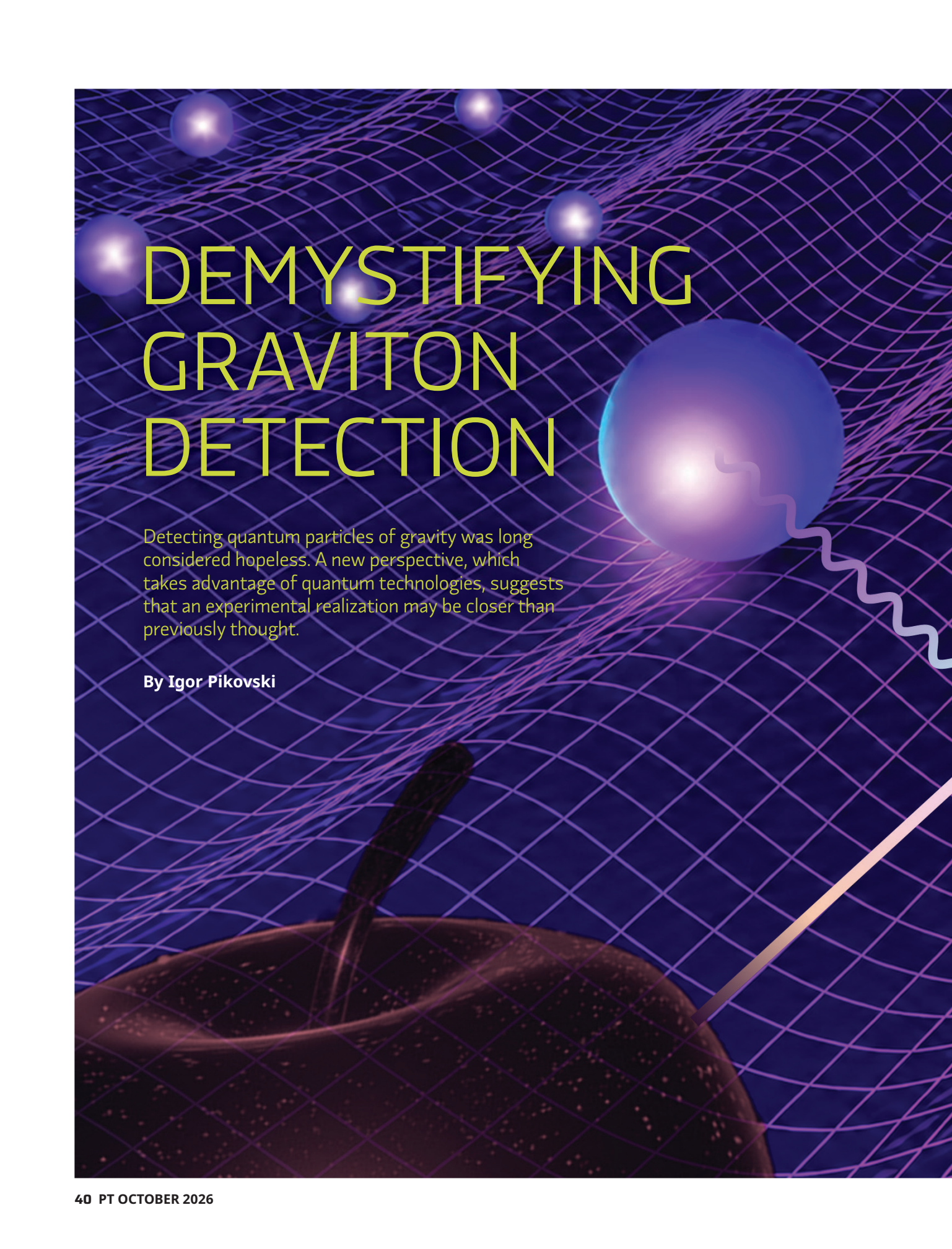
That's a very good question. It's really important to note that we are still trying to seek justice. But I think the most important thing that needs to happen is that we need these documents about nuclear explosions and contamination that the US continues to withhold from us. In its [2024] report,⁷ the UN Office of the High Commissioner for Human Rights noted that there are 80 million documents that the United States continues to withhold from the Marshallese people.⁸ The first step that needs to happen is the release of all these documents in order for us to determine what is owed.

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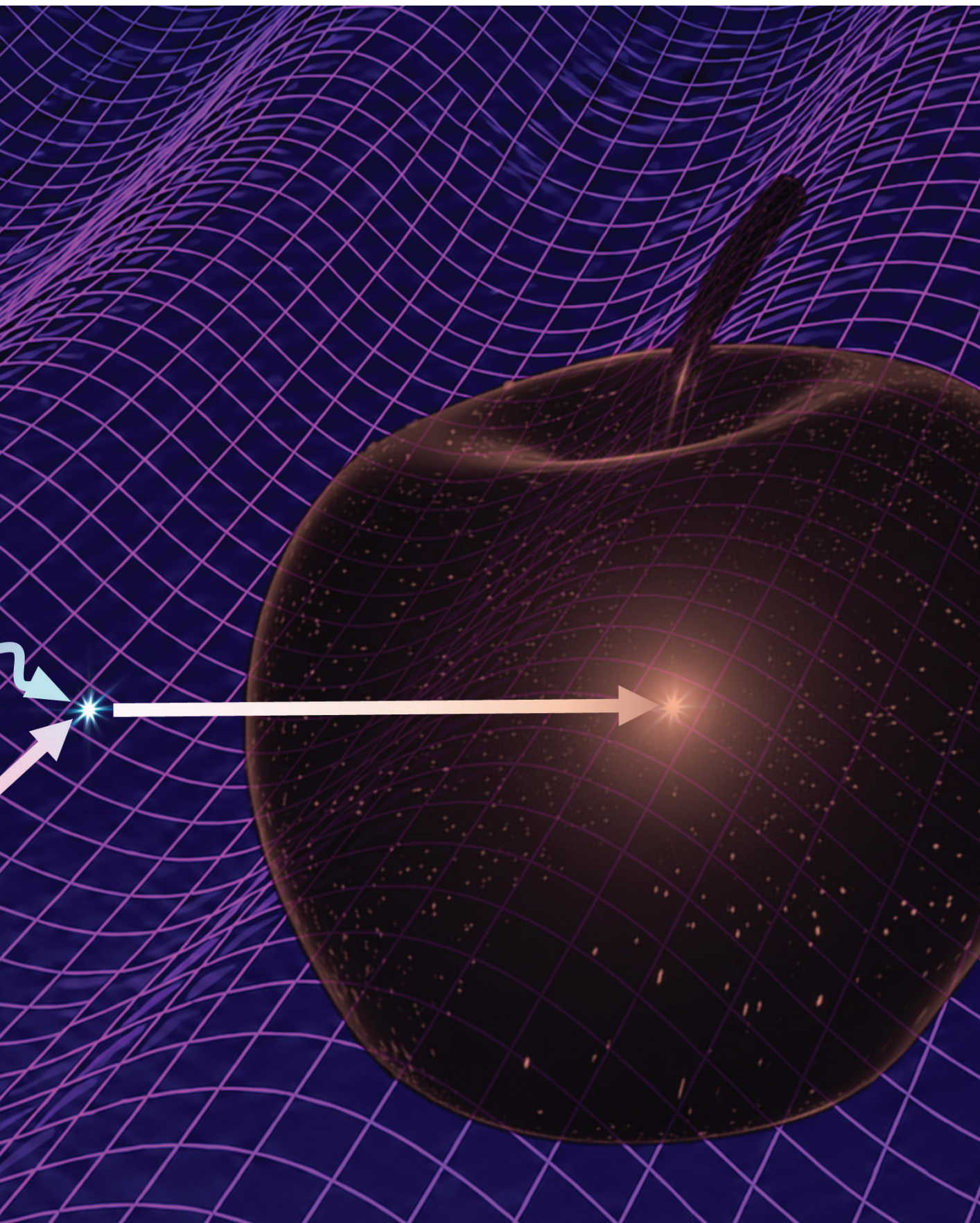
M. X. Mitchell is an assistant professor in the federated department of history at the New Jersey Institute of Technology and Rutgers University–Newark in New Jersey. Her 2026 book *Unsettling Sovereignty: International Law, Nuclear Weapons, and US Extraterritorial Power in Postwar Oceania* explores the legal history of US nuclear colonialism in the Marshall Islands.

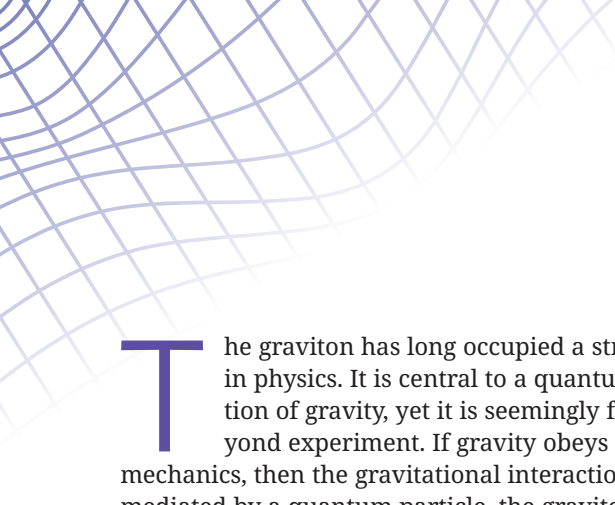


DEMYSTIFYING GRAVITON DETECTION

Detecting quantum particles of gravity was long considered hopeless. A new perspective, which takes advantage of quantum technologies, suggests that an experimental realization may be closer than previously thought.

By Igor Pikovski





The graviton has long occupied a strange place in physics. It is central to a quantum description of gravity, yet it is seemingly forever beyond experiment. If gravity obeys quantum mechanics, then the gravitational interaction should be mediated by a quantum particle, the graviton, analogous to the photon and other bosons that mediate the other fundamental forces. But gravity is much weaker than those other forces, and detecting gravitons has appeared unattainable.

Steven Weinberg, for example, calculated that an atom would take far longer than the age of the universe to spontaneously emit even a single graviton.¹ And although the Laser Interferometer Gravitational-Wave Observatory has detected classical gravitational waves, Freeman Dyson has shown that for a LIGO-like detector to sense a single graviton, it would have to be so massive that it would collapse into a black hole.²

Another avenue that Dyson and others considered is a gravitational analogue of the photoelectric effect. Similarly to how an atom can absorb photons from electromagnetic radiation, an atom interacting with passing gravitational waves may absorb a single graviton and transition to a different electronic state.^{2,3} But that method would require a detector the size of Jupiter orbiting a neutron star.³ Notwithstanding the challenge of background noise, such analyses (and common sense) suggested that graviton detection may forever be out of reach.

Yet a new approach, fueled by quantum optics and emerging quantum technologies, suggests that such difficulties can be circumvented.⁴ Like the photoelectric

effect, the new approach is based on the premise of energy absorption. The critical advance is the emerging ability to resolve individual quanta of energy in macroscopic systems.

The approach opens a realistic experimental avenue for graviton detection. A successful detection would not provide final proof of a quantum theory of gravity. (For more about the signatures of quantum gravity, see the June *PT* article by Markus Aspelmeyer and Daniel Carney.) That is because particle detection can be interpreted through a semiclassical model if energy conservation is abandoned. But in the quantum framework, graviton detection would provide direct access to the single-particle regime of the interaction between gravity and matter and thus open the door to broader experimental exploration of quantum gravity.

Catching gravitons

Mathematically, gravitons naturally emerge from the quantizing of the linearized, weak-field limit of general relativity, as summarized in box 1. What makes single-graviton detection potentially realizable is the resonant exchange of energy between a gravitational wave and matter. The interaction can be described in terms of the cross section σ , which is the ratio of the absorbed power to the incident flux of gravitational energy. The cross section captures how efficiently matter absorbs passing gravitons.

Atomic transitions have an extremely small cross section $\sigma \approx L_p^2 \approx 10^{-70} \text{ m}^2$, where $L_p^2 = \sqrt{\hbar G}/c^3$, with $\hbar$ being the reduced Planck's constant, G the gravita-

Box 1. Linearized quantum gravity

General relativity describes gravity through nonlinear field equations that are the manifestation of spacetime geometry. But for weak gravitational fields, general relativity looks like an ordinary field theory on flat spacetime, similar to the other interactions of particle physics's standard model. Despite its simplicity, the linear approximation reproduces much of the observed phenomenology of general relativ-

ity, including gravitational waves.¹

Quantizing the linearized gravitational field introduces graviton particles, which are analogous to photons in electromagnetism.¹⁵ Gravitons play two complementary roles: As virtual particles, they mediate gravitational interactions; as real particles, they carry gravitational waves' energy quanta $E = \hbar\omega$, where $\hbar$ is the reduced Planck's constant and ω is the wave frequency. Whereas photons are spin-1 particles that couple

to electric charge, gravitons are spin-2 particles that couple to mass and energy.

Linearized quantum gravity is a mathematically consistent framework that breaks down once gravity becomes strong enough that the gravitational field interacts nonlinearly with itself. Any successful theory of quantum gravity is expected to reduce to linearized quantum gravity in the weak-field limit—and thus to contain gravitons.

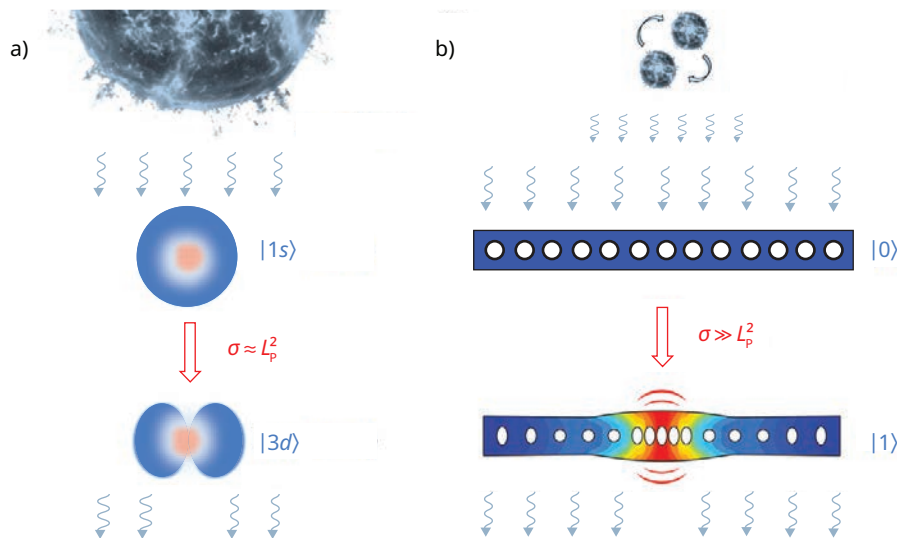


Figure 1. Detecting a graviton, the hypothesized quantum of energy that makes up gravitational waves. **(a)** When a star or another source of gravitational waves emits radiation (squiggly lines), single gravitons can be absorbed by an electron in an atom and result in an electronic quadrupole transition from the 1s to 3d orbital.^{1,2,3} The cross section σ is roughly equal to the tiny Planck area $L_p^2 \approx 10^{-70} \text{ m}^2$, and few gravitons are expected near the frequency of the atomic transition. Graviton detection through that approach, therefore, is nearly impossible. **(b)** A more realistic approach could measure lower-frequency gravitons from a binary star merger using a macroscopic acoustic resonator (blue bar).⁴ When the resonator absorbs a single graviton from a passing gravitational wave, the energy is converted to a detectable phonon, and that process has a much larger cross section.

tional constant, and c the speed of light.^{2,3} Here L_p , the Planck length, is the length at which quantum gravity effects are typically expected. An atom, whose physical area is roughly the Bohr radius squared, approximately 10^{-20} m^2 , is essentially transparent to gravitons. The small Planck-scale cross section, which is a direct reflection of the weakness of gravity, is often cited as the fundamental obstacle to detecting gravitons.

Yet that obstacle can be circumvented. The Planck-scale cross section applies only when an electron in an atom absorbs a single graviton from a passing gravitational wave. That process is illustrated in figure 1(a). But it isn't the only possible process to consider for graviton detection—nor is it the most suitable one.

What if the detector were, instead of an electron, a much larger mass that could still undergo measurable quantum jumps in energy? Massive quantum systems, such as superfluid helium resonators, can serve as modern variants of the resonant bars pioneered by Joseph Weber for conventional gravitational-wave detection.^{5,6} In such systems, transitions between individual quantized energy levels could be measured, much like transitions in an atom can be, but these systems would involve a vastly larger mass. The possibility of that measurement arises from recent experimental developments that bring increasingly macroscopic systems into the quantum regime—quantum effects have been observed in systems with milligram-scale masses.⁷

And that's precisely where the long-standing intuition about graviton detection gets overturned.

Building on the reasoning described above, my group and I calculated a macroscopic system's exact transition probabilities for when a single graviton is absorbed.⁴ The essential scaling can be understood from a simple argument described in box 2: The general cross section of gravitons interacting with matter is not fundamentally the Planck area L_p^2 . Rather, it is given by $\sigma \approx G\omega Q/c^3$, where ω is the frequency and Q is the detector's mass quadrupole, which is a measure of its mass and size.

With that expression, an electron in an atom indeed yields the above result of $\sigma \approx L_p^2$, which led Dyson and others to conclude that a Jupiter-sized detector is required. But that cross section describes only how an electron absorbs energy from the gravitational wave. Physically, that is like trying to generate electricity from passing gravitational waves!

Instead of electrons, other systems with vastly larger mass quadrupoles can be considered. A resonant bar of length L and mass M , for example, yields $\sigma \approx G\omega ML^2/c^3$. In that case, the energy is absorbed not by an electron but by a phonon, the quantum of sound, which results in graviton-to-phonon conversion. The cross section for that process can be roughly 40 orders of magnitude larger than that of the electronic transition because of the bar's larger mass quadrupole. Because of

Box 2. The graviton cross section

Albert Einstein's quadrupole formula describes how a changing mass distribution emits gravitational waves with power $P \approx G\ddot{Q}^2/c^5$, where G is the gravitational constant, c is the speed of light, and $\ddot{Q}$ is the third time derivative of the emitter's mass quadrupole, which scales with mass m and size x as $Q \approx mx^2$. The same expression can

also predict how a detector would absorb energy, which led Joseph Weber in 1960 to propose the first gravitational-wave detector.⁵ The difference for single-graviton detection is that only a single quantum of energy $\hbar\omega$ is absorbed. That results in a detector strain on the order of $\sqrt{\hbar/m\omega}$.

For a monochromatic wave resonant with the detector, the power P

associated with a single-graviton transition becomes $P \approx \hbar\omega^5 Q/c^5$. The single-graviton flux is $F \approx \hbar\omega^4/c^2$, which corresponds to one quantum of energy spread over roughly one wavelength during one oscillation period. Together, those results yield the absorption cross section $\sigma = P/F \approx G\omega Q/c^3$. That general expression, which depends on Q , captures the key to graviton detection.

that difference in scale, a possible graviton detector—sketched in figure 1(b)—can be brought from astronomical dimensions to laboratory-sized ones.

Quantum sensing at the macroscale

The ability for macroscopic matter to absorb gravitational-wave energy has been well known for decades.^{1,5} The novelty is that if that energy absorption is observed in discrete steps, similarly to how a quantized electron transition in an atom is measured, then a graviton could be detected. (Many particles, including photons in photon counters, are registered through discrete energy exchange.) But detecting a single graviton requires a different kind of measurement than conventional gravitational-wave detection does. Rather than measuring the continuous displacement caused by a passing wave, which is the standard approach used by LIGO, it requires monitoring the resonant detector's energy and resolving a change by a single quantum of energy $E = \hbar\omega$.

In recent years, such capabilities have begun to emerge through the quantum control of macroscopic systems. One example is in the field of quantum acoustics. Quantum acoustic systems come in many forms, and the phonons can be controlled and measured by auxiliary superconducting qubits, photons, or other coupled systems. Although phonons have been essential to solid-state physics for at least a century, the ability to manipulate, detect, and count individual phonons has been demonstrated in various platforms only recently because of advances in opto- and electromechanics.⁸

Although the new capabilities suggest that detecting gravitons may now become a quantum engineering problem, the task still remains difficult. Existing systems are still too small to be practical for graviton absorption and would need to be scaled up in mass. Additionally, the energy resolution must be improved if quanta at kilohertz frequencies are to be detected. But

the tools are developing rapidly, and those goals may well be achievable.

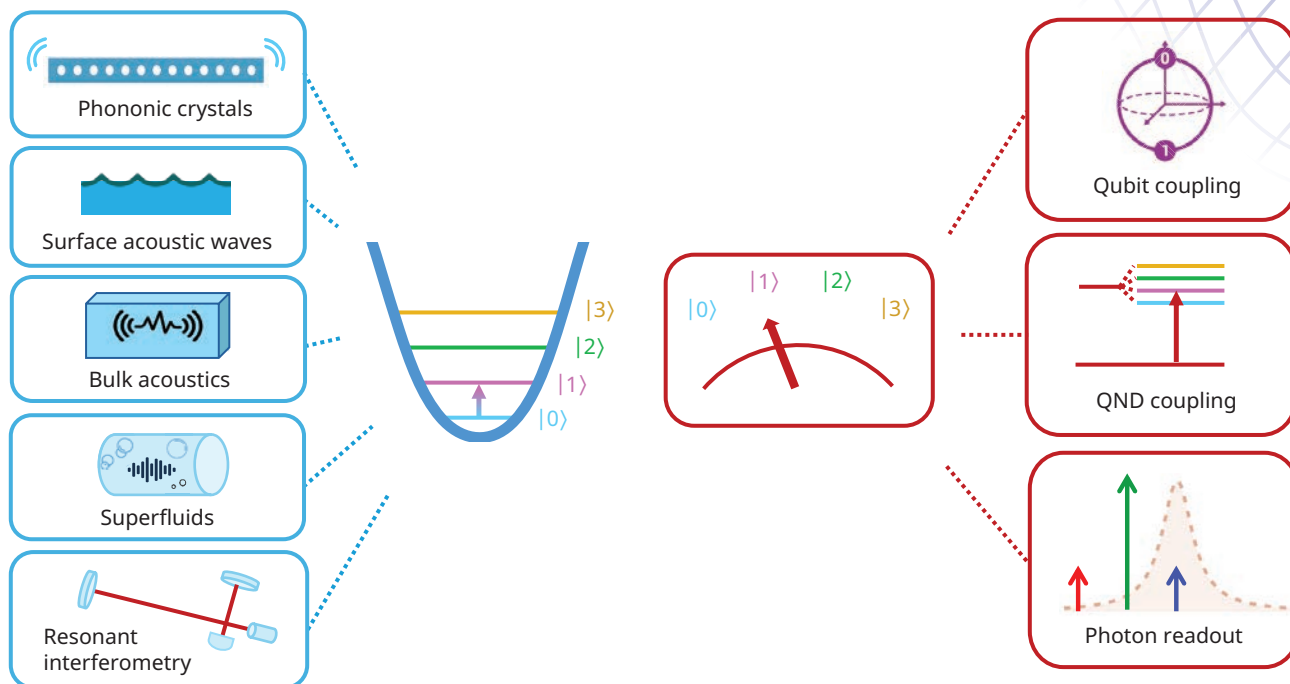
Where the gravitons come from

Using macroscopic quantum systems and monitoring their changes in energy provides a blueprint for detecting gravitons. The approach, based on a resonant exchange of energy, is illustrated in figure 2. It's generic and can take many forms. In addition to graviton-to-phonon conversion, resonant detection could also be achieved through graviton-to-photon conversion, for example, via strong magnetic fields⁹ or light beams.¹⁰

Another challenge remains, however: A large flux of background gravitons is needed. But whereas many potential kinds of detectors, including electronic transitions, operate far above kilohertz frequencies, no strong sources of gravitons are expected in that frequency range. The graviton flux from the stars that Dyson and others considered is exceptionally low at those frequencies and would thus require a large detector to be placed in close orbit.

But the flux problem can be solved in the same way as the cross section issue. The best graviton sources are the gravitational waves already detected by LIGO. Compact binary mergers produce a tremendous flux of gravitons at subkilohertz frequencies. For typical detected gravitational waves with strain amplitudes of about 10^{-22} , the graviton flux $F \approx 10^{28} \text{ s}^{-1} \text{ m}^{-2}$ is substantial enough to compensate for the small (although no longer Planck-scale) cross section. Because acoustic resonators can operate at those subkilohertz frequencies, the graviton-source problem is also solved: A macroscopic resonant detector in the frequency band of standard LIGO detections can register the absorption of a single graviton from the same wave that's measured by conventional methods.

Most known gravitational waves sweep through the detector's resonant frequency too quickly to deposit



▲ **Figure 2.** Two essential ingredients of a graviton detector are a macroscopic system and a means to measure individual quanta of energy. A graviton can be converted from a passing gravitational wave into a single excitation of a harmonic mode of some massive system (blue boxes, **left**) through resonant energy transfer. The excitation can then be read out through a quantum sensing technique (red boxes, **right**), such as the excitation of a coupled superconducting qubit, quantum nondemolition (QND) measurements, or a photon conversion technique.⁸

energy efficiently. But waves from one type of source, neutron star mergers, could be detectable. They last long enough for a kilogram-scale system to absorb a single graviton.⁴ With detectors that have sufficiently good phonon-number resolution or with transduction, gram-scale systems might even be sufficient.

Solving noise through correlation

With the cross section and graviton source addressed, the remaining, seemingly insurmountable challenge is background noise. How can one distinguish genuine graviton absorption from any other source of energy?

One solution is to cross-correlate the graviton detector output with standard gravitational-wave detections. The gravitational-wave signal from the final stages of a compact-binary merger lasts only an exceedingly short time, typically less than a second. During that interval, the enormous graviton flux far exceeds that of other potential sources. And only specific detector modes—those that couple to a spin-2 particle—are excited. The critical step is to characterize the detector when no wave is present.

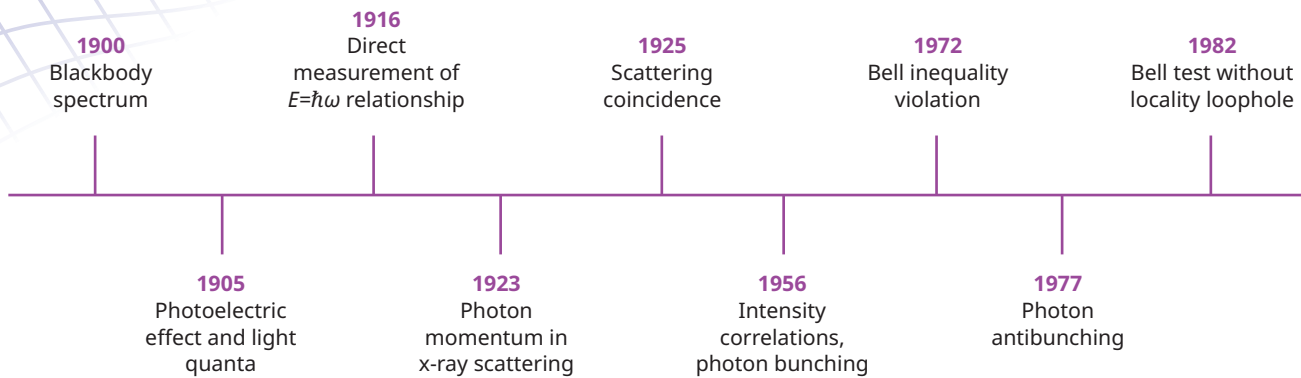
Taking again the example of an acoustic resonator, the desired mode must be cooled to its ground state. Cooling of macroscopic systems to their ground state has already been achieved,^{7,8} and ground-state lifetimes of minutes or more are realistic.^{6,7} For graviton detection, only the selected mode needs to be in its

quantum ground state. Adequate noise suppression requires the rest of the system to be cold and sufficiently isolated from that mode. The required damping and overall cooling of the whole system to about 1 millikelvin are also in reach and have already been demonstrated in related systems.⁷ The noise is thus becoming manageable enough for energy jumps and LIGO detections to be cross-correlated.

Beyond classical wave physics

Graviton detection appears to be a viable experimental goal. But even once achieved, it would not by itself constitute final proof of a quantum theory of gravity. That reflects a fundamental feature of physics: An experiment can show consistency with a theory, but it cannot unambiguously prove it. Proof would require ruling out all possible alternatives, which is rarely how physics progresses. The real question is how contrived the alternative explanations would have to become before they are no longer scientifically compelling.

The photoelectric effect offers a helpful perspective. The effect is often interpreted in two opposing ways, but neither captures its full significance. The first is that the photoelectric effect by itself proves the existence of photons. The second is that the interaction of classical radiation with quantized matter is sufficient to explain the effect, so photons are not necessary. Both views are subtly inadequate.



▲ **Figure 3.** A timeline of landmark experiments that probed the quantum nature of light. The sequence represents a hierarchy of increasingly refined tests that make classical explanations less natural and more constrained than a quantum description. Detecting gravitons would be a first step in such an experimental progression for quantum gravity. That feat would enable researchers to conduct more refined tests, such as probing the quantum statistics of gravitational waves.^{11,12}

The photoelectric effect can be described without an explicit quantization of the electromagnetic field, and the same is true for graviton detection and the gravitational field. With suitable statistical assumptions, specific semiclassical models can reproduce the signal that gravitons would produce in any type of particle detector. Such semiclassical models could be ruled out by refined correlation measurements, but those are more challenging than particle detection alone.

Semiclassical models, however, do not describe ordinary, classical wave physics. For individual particle detections, those models face a problem with energy conservation: Energy is deposited in the detector while the classical field remains unchanged. Conversely, if energy conservation is assumed, the field must lose exactly one quantum of energy, and graviton detection is inferred. It was Albert Einstein's correct insight in 1905 that to reproduce all the hallmarks of photoelectric observations in a consistent framework, a full quantization of both matter and light is most natural. Indeed, even today, most photon detectors rely on the photoelectric effect. It is a bona fide particle-detection method.

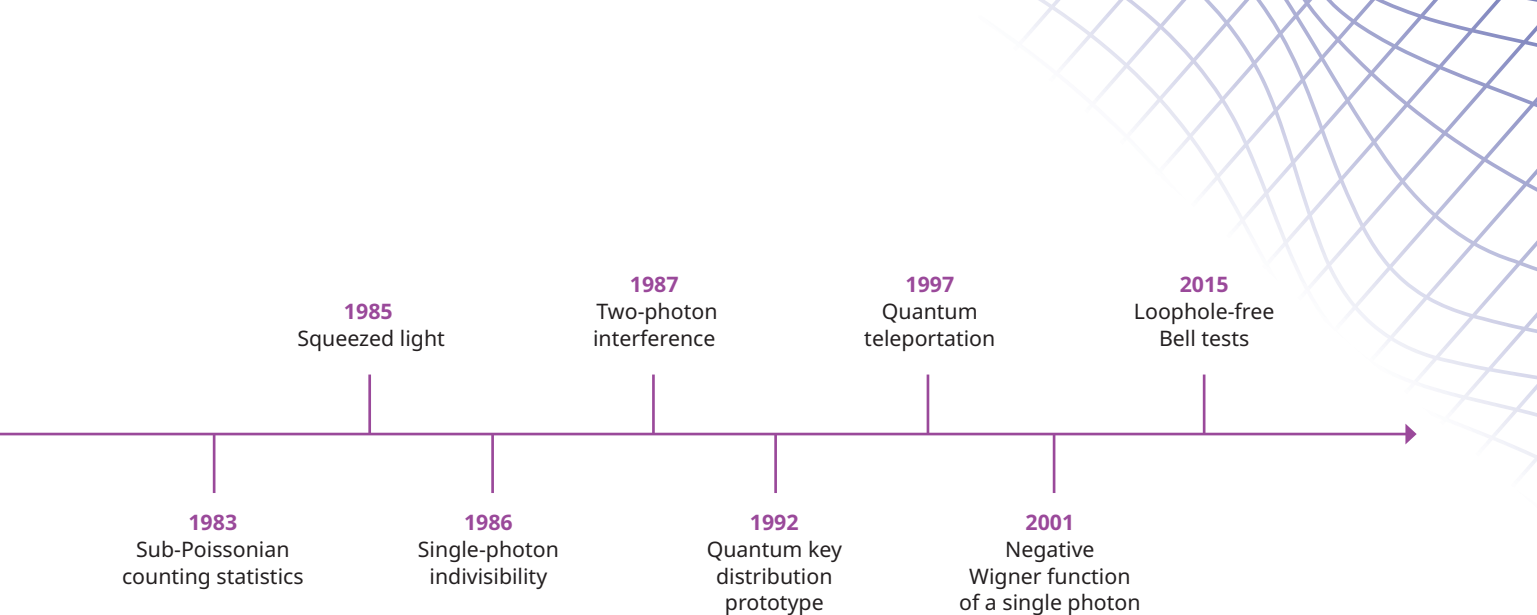
Similarly, the detection of gravitons cannot rule out some semiclassical explanations of gravity. But neither is graviton detection a classical phenomenon that's being reinterpreted in quantum language. Graviton detection would be a measurement of how a single quantum of energy is absorbed and converted from a gravitational wave, and such a detection would provide direct access to the single-particle process at the quantum level. Although not a final proof of a quantum theory of gravity, detecting gravitons would mark the first empirical input of the expected quanta of gravity.

From the beginning of quantum physics, a hierarchy of increasingly stringent tests of quantum phenomena have made a purely classical picture increasingly untenable—the timeline in figure 3 highlights some of the critical experiments for light. The strongest evidence to date against a fully classical description comes from loophole-free violations of the correlation limits, known as Bell inequalities, that are imposed by underlying, local classical models. But even those violations do not rule out underlying superdeterministic and nonlocal classical models. Particle detection is similarly not the final word, but it would be a nontrivial early step.

Toward tests of linearized quantum gravity

As gravitons become poised to move from a theoretical curiosity to a realistic experimental target, a broad experimental program is emerging. Does the graviton carry the expected spin-2? Does it have mass? Does it obey $E = \hbar\omega$? Such particle properties would reveal themselves through selection rules governing observable transitions, excitation probabilities, and the coupling of gravitons to specific detector modes; the study of photons through atomic spectroscopy offers several parallels.

Potential quantum features of gravitational radiation may also become accessible. Excitation probabilities involving more than one graviton can reveal whether the radiation field differs from a coherent state.¹¹ In fact, the full statistical properties of the wave are accessible in the detector even when only a few gravitons are deposited.¹² That possibility opens the door to quantum-state characterization of gravitational radiation, which might carry nonclassical statis-



tical features. Graviton detection could, therefore, reveal a new layer of information in gravitational waves and act as a quantum-level probe of both gravity and its astrophysical sources.

Additionally, graviton detection is part of a broad transformation in fundamental physics. Independent ideas for probing other quantum features of gravity have emerged over the past decade. Those ideas have included looking for quantum noise from gravitational radiation¹³ and testing whether gravity could generate entanglement and thus act as a quantum channel.¹⁴

A new experimental program is beginning to take shape, one in which the quantum nature of gravity can be tested step by step, with each experiment revealing a different facet of the interface between quantum physics and gravity. Dyson—who was skeptical that gravitons could ever be detected—also wrote in a 1995 article in *The New York Review of Books* that “the great advances in science usually result from new tools rather than from new doctrines.” With new quantum tools, quantum gravity may now be advancing toward experiment. **PT**

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An interview series that profiles scientists who opted for careers outside of academia.

Konrad Schwenke keeps banks honest

By **Toni Feder**

Senior manager for forensics and financial crime, Deloitte

*Diplom, physics, Technical University of Dresden, 2010
PhD, physics, ETH Zürich, 2014*

What was your research area?

Computational soft-matter physics. My PhD was on absorption of nano- and microparticles at soft interfaces.

How did you get into consulting? And forensics?

I looked into consulting because I wanted exposure to different topics, and from my experience in science, I enjoyed the international work environment. My entry angle was big data. I applied for positions

(Photo courtesy of Deloitte AG.)



in IT consulting. At one company, the human resources office forwarded my application to a group in forensics and financial crime.

The forensics manager was convincing, and the position sounded interesting—it reminded me of Sherlock Holmes. And the work environment seemed good.

How do you spend your time?

My team works to prevent and detect money laundering, fraud, and manipulation of the stock market. Our clients are mostly banks and insurance companies. They have to make efforts to protect their customers and the financial system, as regulatory compliance is essential to their operation. We support them with risk assessments, calibration of their detection systems, development and validation of detection models, and investigation of incidents. Every payment that goes through a bank should be monitored, and we look for patterns. We analyze data, code, test, and present results.

This is my third job in forensics and financial crime consulting. As a senior manager at Deloitte, my internal work includes business development, presenting for clients, staying on top of emerging regulations, and team management.

What do you like about your job?

The diversity of the tasks and the diversity of the clients.

Do you use your physics?

I'm not doing quantum mechanics, hydromechanics, or statistical physics. But I use my skills in structured thinking and in computer coding and modeling. And it's surprising how often it's helpful to be able to look at numbers and say quickly whether something makes sense.

What new skills have you needed?

Communication and presentation skills and social adaptability. And, of course, I had to learn the whole business side of things.

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How and why to measure a quantum state

With quantum state tomography, researchers in the booming field of quantum information science are able to characterize essential operations and devices.

By **Michael G. Raymer**

Ultraprecise sensing, secure communication, and quantum computing are key aspects of the fast-growing field of quantum information science (QIS). The careful measurement of quantum states plays a key role in QIS. Whether researchers are exploring the foundations of quantum physics or verifying and calibrating quantum-enabled technologies, it's important that they understand what a quantum state represents and how to measure it.

While there are ongoing debates about the deepest meaning of quantum states, the operational rules for preparing, using, and measuring them are clear. The no-cloning theorem, for example, demonstrates that, unlike a classical state, an arbitrary quantum state cannot be copied perfectly (as explained by Bill Wootters and Wojciech Zurek in their February 2009 *PT* article). Such a statement is profound: It implies that the quantum state of a single quantum object, such as an electron, photon, or mode of the electromagnetic field, cannot be determined by any measurement scheme if no information is known about the object's state beforehand. Yet scientists have shown that for a large collection of identical and identically prepared systems, a state can be assigned through a sufficient set of measurements. That process is quantum state tomography.

What, then, can be learned about the state from making a single measurement on a single quantum object? Very little, actually—only that the probability of obtaining the observed outcome was not zero. How researchers think about probability is thus foundational to how they think about a quantum state. Probability can be interpreted either as a frequency of outcome possibilities from multiple repeated and identical trials or as a subjective assertion about the likelihoods of possible outcomes.

The former view is useful when estimating a probability distribution from a set of repeated measurement trials. The latter is preferred by most QIS practitioners, with the estimates of probability based on all available information, which includes an understanding of the

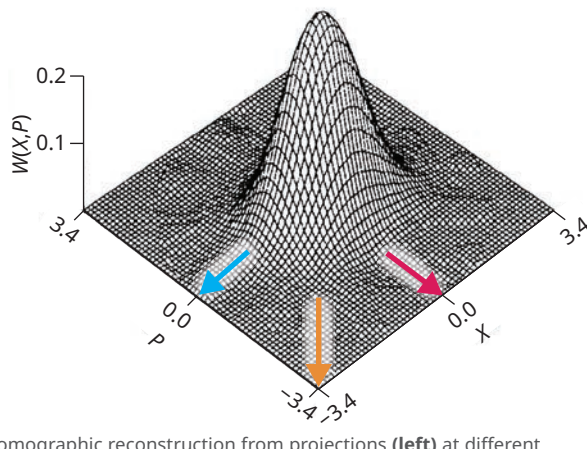
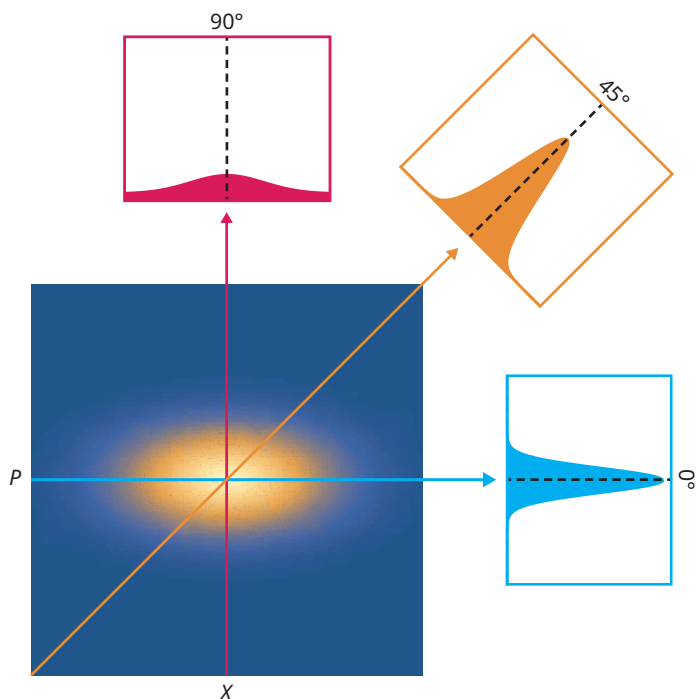
present state of physics theory and all available prior experimental knowledge. In that view, the quantum state becomes a kind of weighted catalog of possible outcomes. It is profoundly different from a classical catalog in that the observed outcomes are not preordained but emerge spontaneously during the measurement process. And, of course, the Schrödinger equation is the means for predicting the time evolution—forward or backward—of the quantum catalog of possible outcomes between measurements.

Reconstructed states

The possibility of measuring a quantum state—that is, determining the full quantum catalog of possible outcomes—was discussed by several of the founders of modern quantum theory. In the Copenhagen interpretation of quantum theory, a single precise measurement of a particular quantity, such as position or momentum, changes the state by causing collapse. That is one way to appreciate why researchers need to make many different measurements on a large collection of identically prepared systems to determine a full quantum state. The question of how to achieve that had been considered for half a century when, in 1987, Jacqueline Bertrand and Pierre Bertrand proposed a scheme for reconstructing the state of a set of freely propagating particles by measuring position distributions at various free-propagation times.

Karl Vogel and Hannes Risken soon thereafter showed that the same scheme for reconstructing a state from an ensemble of measurements also applies to the state of a single mode of the electromagnetic field, which has the same dynamics as a harmonic oscillator. In both cases, the reconstruction method uses the same process—the inverse Radon transform—that is used in computed tomography in medicine to reconstruct a 3D image from a suitable set of transmission images (often called shadows).

The first experimental demonstration of that method for quantum state tomography was carried out in my



◀ Tomographic reconstruction from projections (left) at different phases with respect to a reference field is used to characterize the quantum phase-space distribution W (right) for a squeezed state of a single-mode light field. X and P are the amplitudes of the in-phase and out-of-phase components of the light field with respect to the reference field. The contour plot has a maximum at $X = P = 0$, meaning that the highest probability occurs for zero optical field amplitude. (Right figure adapted from D. T. Smithey et al., "Measurement of the Wigner distribution and the density matrix of a light mode using optical homodyne tomography: Application to squeezed states and the vacuum," *Phys. Rev. Lett.* **70**, 1244, 1993.)

optics laboratory in 1993. In that experiment, led by Daniel Smithey and Mark Beck, we generated a squeezed vacuum state in a large number of light pulses. A squeezed vacuum state, like an ordinary one, has a vanishing average electric field. Unlike an ordinary vacuum state, though, the squeezed one has unequal quantum fluctuations in the amplitude X of the electric field component that oscillates in-phase with a given reference field and in the amplitude P of the component that's 90° out of phase with the reference field. The amplitudes X and P are mathematically analogous to the position x and momentum p of a harmonically oscillating particle.

The pulses were measured using optical homodyne detection, in which the weak squeezed light is interfered coherently with a strong reference laser pulse, similar to how a lock-in amplifier works. The output signal gives the amplitude of the squeezed light field at a selected phase relative to the reference laser field.

By collecting X and P amplitude values over repeated trials and for various relative phases, we built up a set of estimated probability distributions, a process that we named optical homodyne tomography. From that set of distributions, we reconstructed the state of the light, as shown in the figure. The results confirmed that one amplitude component—for the example shown, the out-of-phase component—of the squeezed light held smaller quantum fluctuations than the other, complementary component. (That kind of squeezing of quantum noise is now used to increase the sensitivity of the Laser Interferometer Gravitational-Wave Observatory.) While the reconstructed quantum phase-space distribution W is not a true probability distribution—for example, it can take on negative values—it uniquely

represents the quantum state, as initially pointed out by Eugene Wigner.

Modern work in QIS often uses the polarization of single photons—described in terms of two possible complementary states, such as left and right circular polarization—to serve as a two-state qubit, the workhorse of quantum computing and communication. Quantum state tomography for optical polarization of photons was first demonstrated for entangled photon pairs in the optics laboratory of Paul Kwiat.

Kwiat and colleagues' measurement involved passing each member of the pair through polarization-selective devices and recording each photon with one or the other selected polarizations. Data were collected for a large ensemble of photons, and instead of using the inverse Radon transform, the team processed the data using a maximum-likelihood algorithm designed to yield a mathematically rigorous best guess for the polarization state of the ensemble. Maximum-likelihood algorithms search numerically for the distribution that is most likely to generate the observed statistics. They often proceed from an initial estimate that is refined iteratively to find the best fit.

Applications and more

Modern applications of quantum state tomography, which typically use the maximum-likelihood method, are by now ubiquitous in quantum information science and technology. The technique spans a wide range of quantum states and applications for quantum computation and quantum information storage, such as microwave photons in superconducting circuits, magnons in spin ensembles, and mechanical vibrational modes in solids.

Beyond practical applications, the ability to estimate, reconstruct, determine, or assign a quantum state for an ensemble of identically prepared systems plays a significant role in discussions about the foundations of quantum mechanics. While there is still some tension between objective and subjective interpretations of quantum mechanics, the idea that a quantum state is equivalent to the set of specified probabilities for all possible measurement outcomes on a quantum system provides insight into the very workings and meaning of the theory.

For example, Borivoje Dakić and Časlav Brukner have proposed that the foundational principles of quantum mechanics can be inferred from just a few simple axioms, one of which is that “the state of a composite system is completely determined by local measurements on its subsystems and their correlations.” That axiom is describing quantum state tomography.

That the measurements are local is key: When entangled but spatially separated systems are each measured locally, the measurements’ outcome correlations can be stronger than allowed by any local theory that obeys ordinary classical probability predictions. (Experimental demonstrations of such nonclassical correlations earned Alain Aspect, John Clauser, and Anton Zeilinger the 2022 Nobel Prize in Physics; see *PT*’s December 2022 report on their prizewinning work.) That a quantum state can be used to predict those nonclas-

sical correlations and that an ensemble of such measurements can reveal the entangled state seemingly point to a deep aspect of nature.

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Additional resources

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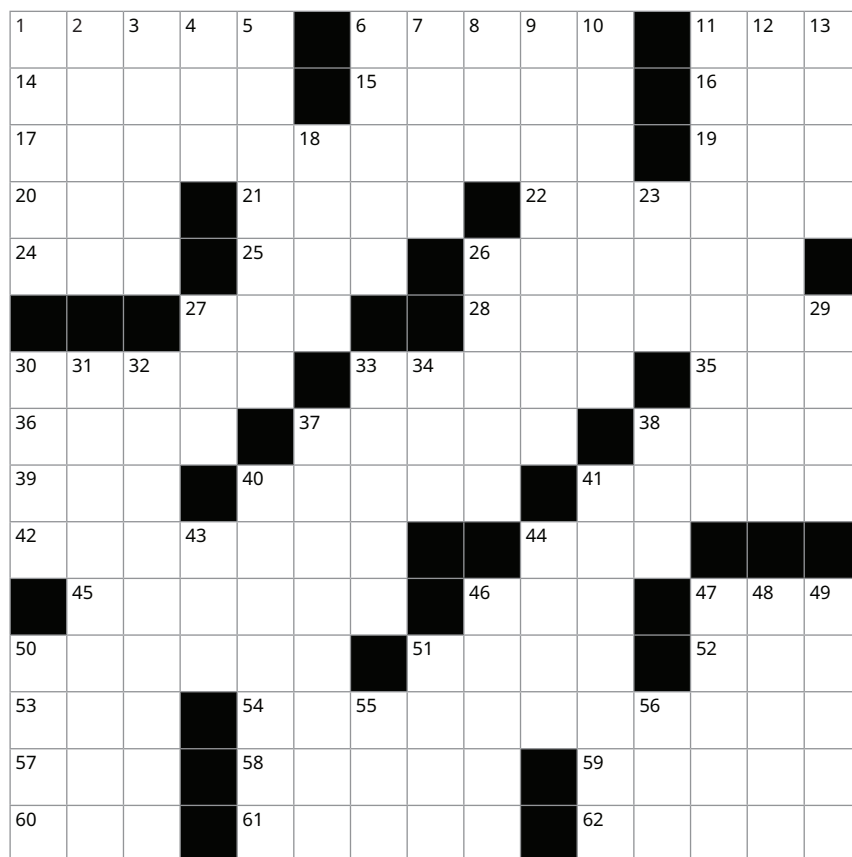
CROSSWORD

And beyond...

By Doug Mar

ACROSS

- 1 Output of a camera
- 6 *Grey's Anatomy* airer
- 11 Econ. stat
- 14 Planetary scientist who wrote "Our planet is a lonely speck in the great enveloping cosmic dark" and inspired 54-Across
- 15 Minor role for a major star
- 16 Important resource in the board game *Catan*
- 17 Milestone distance between 10-Down and Earth to be reached on 18 November 2026
- 19 Sister
- 20 Architect Maya ____
- 21 NOAA satellites that provide continuous weather data, for short
- 22 Planet with a hexagonal storm system first seen by 10-Down
- 24 Make a scene?
- 25 Angry
- 26 Enduring aspect of the past
- 27 Take in calories
- 28 Radar of *M*A*S*H*
- 30 Sun phenomena
- 33 Musical instrument featured in the Rolling Stones' "Paint It Black"
- 35 ____ de toilette
- 36 Starting from
- 37 Spanish toast
- 38 Fictional Scully of *The X-Files*
- 39 Lang. in which the annus mirabilis papers were written
- 40 Cuts down
- 41 Sound that is sometimes used to illustrate the Doppler effect
- 42 Pens
- 44 Dump
- 45 Many US federal agencies are based here
- 46 Fragrant evergreen
- 47 After 10-Down crossed the heliopause in 2012, it became immersed in this (abbr.)
- 50 Color of the object on 10-Down that contains, among other sounds, whale song and greetings in 55 human languages
- 51 Actress Kunis of *Jupiter Ascending*
- 52 ____/her pronouns
- 53 Game with Reverse cards
- 54 Iconic picture taken on 14 February 1990 by 10-Down
- 57 *Street Fighter* protagonist whose name means "dragon" in Japanese
- 58 Cherish
- 59 Sans ____ (carefree)
- 60 NCAA sch. that is nearest to



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 - 61 Unit of magnetic flux equal to 1 volt second
 - 62 Looks for
- ### DOWN
- 1 Island, to an Italian
 - 2 In a frenzy
 - 3 Operative
 - 4 Unit equal to 1 cm/s², or another equal to 3.785 L
 - 5 They're hard to figure out
 - 6 Felt sore
 - 7 Cricket clubs
 - 8 Windows .exe program that opens a shell terminal
 - 9 Buzz-creating promo
 - 10 Mission with a pair of space probes launched in 1977 and the subject of this puzzle
 - 11 Become wildly enraged (or use plutonium-238 as an energy source?)
 - 12 Where the Muffin Man lives
 - 13 Actor Sean of *Milk*
 - 18 Member of genus *Capra*
 - 23 It can precede chi
 - 26 Word that no longer appears on Biscoff cookies
 - 27 Investment option such as Vanguard's VOO, for short
 - 29 Currency denoted by ¥
 - 30 Epic tale
 - 31 "Mr. X," for 14-Across

- 32 Long-period comets originate from this region, where 10-Down will arrive in several hundred years
- 33 Tortilla chip dip
- 34 Under the weather
- 37 Mozart's 13th is known as *Eine kleine Nachtmusik*
- 38 Home project inits.
- 40 What a dog "shakes hands" with
- 41 Composer Richard of "Sunrise," the opening fanfare used in *2001: A Space Odyssey*
- 43 Possessed
- 44 Sunny window spot for a cat
- 46 Telecommunications conduit
- 47 Needs to be submitted, like for a homework set
- 48 Termination ____, where the solar wind encounters the 47-Across (about 100 AU from the Sun)
- 49 Innermost moon of Jupiter, discovered in 1979 by 10-Down
- 50 Wise teacher
- 51 Only
- 55 Badminton shot also known as a clear
- 56 Fair-hirer abbr.



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A close-up of the Sun

By **Sarah Wells**

Using the world's largest solar telescope, researchers have for the first time observed vortices called Kelvin-Helmholtz instabilities (KHIs) on the Sun's photosphere, the layer of the star commonly referred to as its surface. The structures, which are visible where the surface appears to billow, were captured by the NSF Daniel K. Inouye Solar Telescope in the highest-resolution image to date of the Sun's photosphere. The KHIs stem from the convective plasma layers' flow past each other and around points of magnetic flux concentration at different velocities. The interactions at the interface of those fluids create shear forces, which produce the swirling features.

Although theorists had predicted the existence of KHIs in the Sun's photosphere, previous observations lacked the spatial resolution necessary to discern the structures. The 4 m aperture of the Inouye Solar Telescope, located in Hawaii, allowed researchers to re-

solve much smaller features—as small as 19 km—than they could with other solar telescopes, which typically have apertures under 2 m. Identifying the vortices as KHIs, which are well-understood processes for fluids flowing at different velocities in contexts including ocean waves and Jupiter's magnetosphere, may shed light on solar behavior. The researchers propose that the constant churning of the instabilities in the photosphere may act as an engine to drive the twisting of magnetic field lines, which may power coronal heating and space-weather events, such as solar flares and coronal mass ejections. (D. Kuridze et al., "Ubiquitous Kelvin-Helmholtz instabilities driving plasma mixing on the Sun," *Nature* **656**, 595, 2026; image by NSF/NSO/AURA/MPS/CC BY-NC-ND.)

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