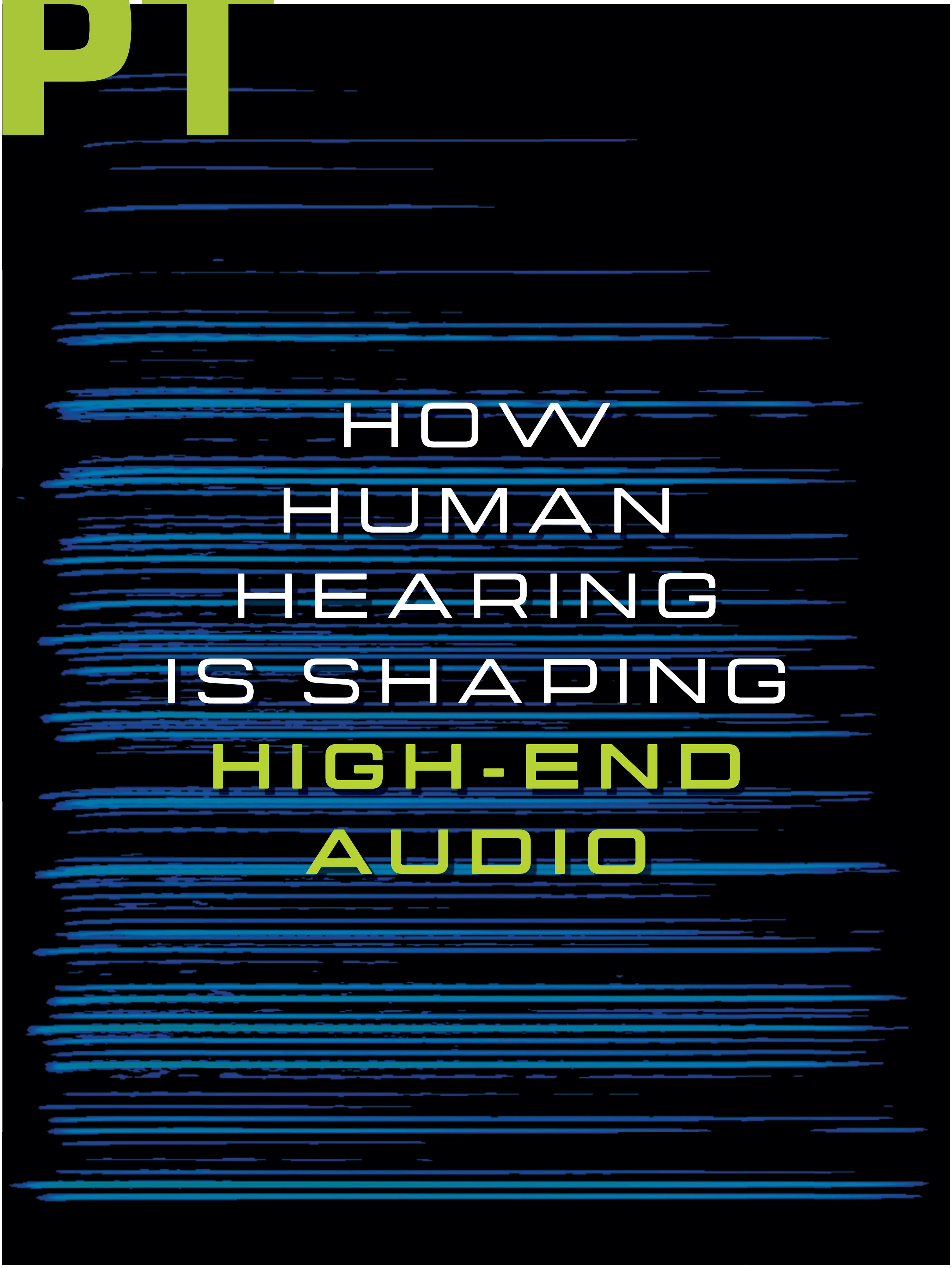
PT PHYSICS TODAY
JULY 2026 VOLUME 79 NUMBER 07



HOW HUMAN HEARING IS SHAPING HIGH-END AUDIO

AIP


HOW STABLE
IS YOUR CRYOSTAT?
LOW VIBRATION
<10 nm peak-to-peak
PRECISE TEMPERATURE CONTROL
1.7 K to 350 K
EXCEPTIONAL FIELD UNIFORMITY
Magnetic Environment
OptiCool®
INTRODUCING THE OPTICOOL® FAMILY.
Cryogen-free optical cryostats for quantum and advanced materials characterization.
7TESLA
High Field Magnet
VECTOR
4-1-1 Vector Magnet
FLEX
Maximum sample space (no magnet)
← Find the right system for your lab
Quantum Design
www.qdusa.com

Precision & stability in an ***Optical Chopper !***

... *only from SRS*

- 0.4 Hz to 20 kHz chopping
- 50 ppm frequency accuracy
- Reproducible phase to 0.01°
- Low phase jitter
- Easy, flexible synchronization
- USB computer interface

The SR542 Precision Optical Chopper is a game changer for mechanical modulation of optical beams. With its long-life brushless motor, low-noise drive, and advanced motion control, the SR542 delivers rock-steady, reproducible chopping.

The SR542 can be synchronized to its internal crystal oscillator, an external reference, or the AC line, making drift a thing of the past.

It's time to rethink the possibilities ...

- ☑ Synchronize multiple choppers? *No problem!*
- ☑ Set optical phase from your computer? *Easy!*
- ☑ Chop at 20 kHz or below 1 Hz? *Sure!*

SR542 Optical Chopper ... $2995 (U.S. list)

SRS Stanford Research Systems

www.thinkSRS.com/products/SR542.html
Tel: (408)744-9040 • info@thinkSRS.com

FEATURES

Physics Today (ISSN 0031-9228, coden PHTOAD) volume 79, number 7. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to *Physics Today*, American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300.

AIP

As a 501(c)(3) nonprofit, AIP is a federation that advances the success of our member societies and an institute that engages in research and analysis to empower positive change in the physical sciences. The mission of AIP (American Institute of Physics) is to advance, promote, and serve the physical sciences for the benefit of humanity.

DEPARTMENTS

ON THE COVER

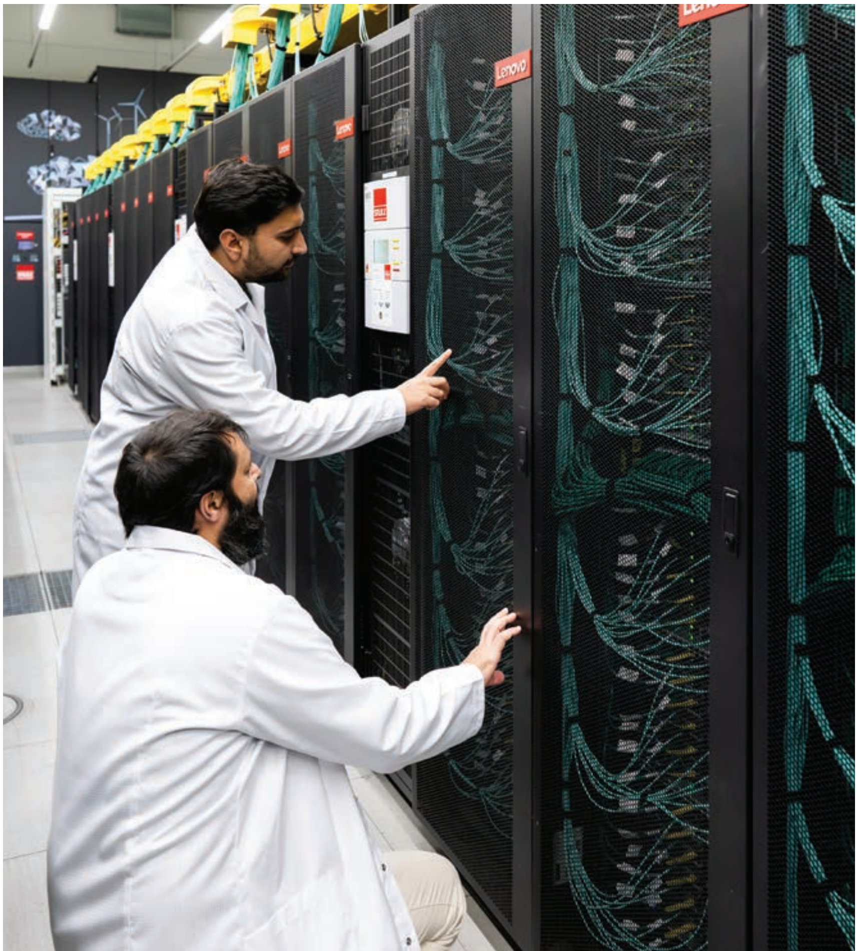
To deliver a convincing concert-hall experience in your living room, some designers of high-end audio systems are focused on developing equipment that preserves the microsecond temporal structure of sounds. In the human auditory system, such timing details convey a sound's tonal quality and spatial information; they are thus critical for distinguishing instruments and perceiving the fine acoustic details in a musical performance. See the Quick Study by Milind Kunchur on **page 52** to learn about how the ears' temporal and information-resolving capabilities pose an extreme technical challenge for audio-system designers.

(Photo courtesy of Milind Kunchur.)

Scan for the latest content

PT PHYSICS TODAY

ADDRESS
American Institute of Physics
1 Physics Ellipse
College Park, MD 20740-3842
+1 301 209 3100
pteditors@aip.org



TO READ ABOUT QUANTUM COMPUTING ENERGY NEEDS, TURN TO PAGE 16

AIP MEMBER SOCIETIES

ASA Acoustical Society of America · AAPM · AAPT Physics Education · AAS · ACA The Structural Science Society · AMS · APS · The Society of Rheology · Optica · AVS

Other member organizations: Sigma Pi Sigma Physics and Astronomy Honor Society, Society of Physics Students

Relativistic plasma could boost intensity of petawatt laser

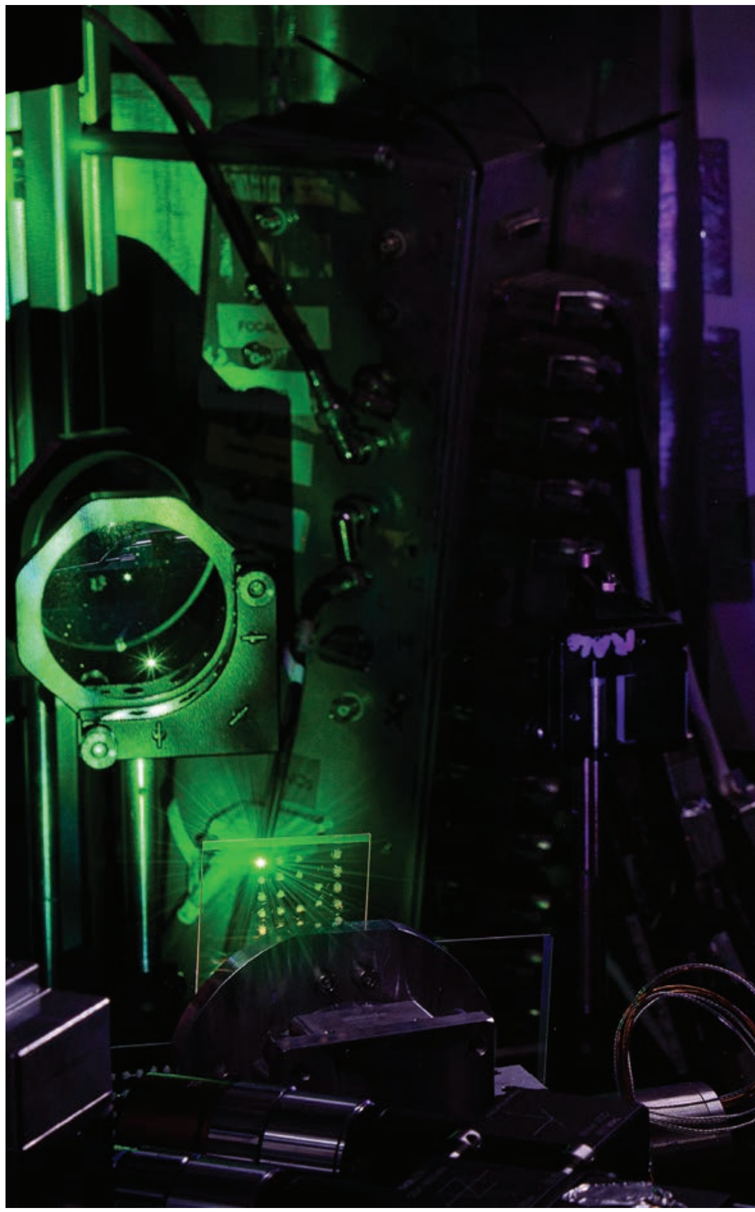
With a new approach to generating powerful laser pulses, researchers may have the means to observe phenomena in quantum electrodynamics.

By Alex Lopatka

A vacuum isn't empty space. According to quantum electrodynamics, virtual particles and antiparticles flit in and out of existence across exceedingly small spaces and in short periods of time.

One way to study quantum vacuum fluctuations is to use an extremely strong electromagnetic field. For intensities greater than 10^{29} W/cm^2, known as the Schwinger limit, the field is able to spontaneously create virtual electron–positron pairs from the quantum vacuum. No source, however, has yet generated an electromagnetic field of that intensity. Robin Timmis and Peter Norreys (University of Oxford), Brendan Dromey (Queen's University Belfast), and their colleagues have now used the Gemini laser system at the Rutherford Appleton Laboratory in the UK to generate bright, coherent extreme-UV light with an intensity of 10^{21} W/cm^2.[1] Although still eight orders of magnitude away, the team argues that the same approach, if implemented at other, high-power laser facilities, could scale up and reach the sought-after Schwinger limit.

A key component for generating a high-intensity field is a plasma that is relativistic—free electrons oscillate near the speed of light—and well shaped. The researchers created such a plasma by shining 5 J, 50 fs pulses from Gemini's petawatt laser onto a glass target. The plasma interacts with the same laser pulse that generated it, and that interaction leads to the emission of coherent high-frequency harmonics of the laser. Under the right conditions, the harmonics become tightly focused. The result is a train of spatially compressed atto-



A high-power laser pulse is focused on a glass target and generates a plasma, appearing here as a glowing green spot. The laser–plasma interaction produces high-frequency harmonics of the original laser. When the harmonics are focused together into a coherent beam, the laser intensity is boosted to levels that approach those relevant for studying quantum vacuum fluctuations. (Image courtesy of Jonathan Kennedy, Queen's University Belfast.)

second pulses whose intensity is many orders of magnitude greater than that of the incident laser.

The challenge encountered in past attempts to generate coherent harmonic focusing was that the harmonic spectrum decayed too fast. Timmis, Dromey, and their colleagues overcame that problem by implementing a specialized plasma mirror. It functions essentially as an optical switch that increases or decreases the reflectivity of the plasma created at the glass target's surface. For years, plasma mirrors have been used for boosting laser intensity. Using material coatings to carefully tune the plasma mirror's reflectivity, the researchers enabled the laser pulse to generate a coherent harmonic beam more efficiently.

Simulations of the Gemini laser's interaction with the relativistic plasma by Timmis, Dromey, and colleagues suggest that the intensity of the incident laser pulse can be boosted even further, to 10^{23} W/cm^2. The coherent harmonic focus should scale with laser intensity, so reaching the Schwinger limit could, in principle, be done with a higher-powered laser. The lasers at the ELI-NP (Extreme Light Infrastructure Nuclear Physics) facility in Romania are 10 PW, an order of magnitude more powerful than Gemini's. Laser systems that are even more powerful, including the 25 PW NSF OPAL (Optical Parametric Amplifier Line) lasers at the University of Rochester and the 100 PW system at the Station of Extreme Light in Shanghai, China, are currently in development. **PT**

Reference

1. R. J. L. Timmis et al., "Efficiency-optimized relativistic plasma harmonics for extreme fields," *Nature* **652**, 1153 (2026).

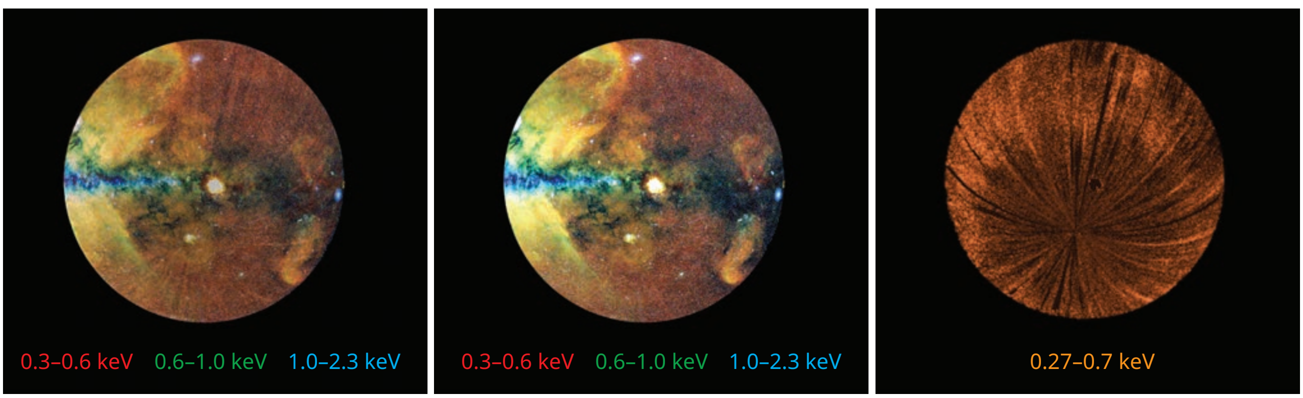
Separating signals in the soft x-ray sky

An analysis of two years of measurements from far beyond Earth's atmosphere has yielded a comprehensive map of x rays that are generated by solar wind.

By Laura Fattaruso

X rays are a valuable source of information about distant, hot celestial bodies, such as supernova remnants and active galactic nuclei. But measurements of soft x rays—which have photon energies of no more than a few kiloelectron volts—have been clouded by local contamination. Gas throughout the solar system emits soft x rays, and so does Earth's outermost atmosphere, which reaches as far as the Moon. And that contamination varies in both space and time.

Far beyond the Moon's orbit, the eROSITA telescope measured x rays outside the influence of Earth's atmosphere. And now, using data from its four full-sky surveys of the western galactic hemisphere, Konrad Dennerl of the Max Planck Institute for Extraterrestrial Physics and colleagues have separated the signals of x rays generated in the heliosphere from those generated beyond it.[1] The resulting map provides a clearer



Measurements from the eROSITA telescope were used to separate soft x rays generated in the solar system **(right)** from x-ray emissions generated beyond the heliosphere **(middle)**. A superposition of the two **(left)** represents the combined x-ray emissions. Because of restrictions on the release of the dark-sky x-ray map, the middle image shows x-ray emissions from the first eROSITA survey, which closely resemble dark-sky x-ray emissions. The right image shows heliosphere x-ray emissions from the third eROSITA survey. (Images courtesy of Konrad Dennerl/Max Planck Institute for Extraterrestrial Physics.)

picture of the x rays generated by solar wind and will help x-ray astronomers better account for them when analyzing distant x-ray signals.

The issue of soft x-ray contamination was identified three decades ago. Though it had long been known that x rays are emitted by ultrahot gas, it came as a surprise in 1996 when they were found coming from a comet.[2] The observation led to recognition of a process known as solar wind charge exchange: When heavy ions in solar wind interact with neutral matter, such as that found in comets, planetary atmospheres, and interstellar matter, the ions capture electrons and emit x rays at the same wavelengths as the ionized gases in ultrahot astrophysical objects.[3] "All observations are contaminated with this extra emission," says Kip Kuntz of Johns Hopkins University, who studies x-ray emissions.

For bright sources under study, the impact is insignificant. But for faint sources, the contamination can make up a significant fraction of the measured emissions. Estimates for the pressure, mass, and other physical parameters of astrophysical objects are affected by the difference. "That has consequences for [studying] dark matter and even for cosmology," says Dennerl.

X-ray measurements by eROSITA began in 2019, when the Sun's activity was at a minimum, and extended over a two-year period. The data, illustrated in the figure on page 9, provide insights into the spatial, temporal, and compositional variability of solar wind. Solar wind has fast and slow components—slow wind is more ionized and is thus the more dominant source of x rays. As solar activity increased over the observation period, slow wind expanded out from low latitudes. X-ray spectroscopy can reveal the wind's heavy-ion composition and highest charge states, both of which are otherwise difficult to measure remotely and typically require *in situ* sampling.

The new data confirm previous observations that as interstellar matter flows into the solar system, the Sun's gravity sends helium from the matter into a ballistic trajectory that produces a concentrated cone of the gas. The measurements also verified the presence of a hydrogen cavity around the Sun that is caused by the interaction of ionized hydrogen with solar wind.

The eROSITA instrument was built by the Max Planck Institute for Extraterrestrial Physics in Germany and is carried on the *Spektr-RG*, a Russian–German satellite launched in 2019. The collaboration included an agreement that data from the western galactic hemisphere would go to the German eROSITA consortium and the Russian eROSITA consortium would retain data from the eastern hemisphere. The instrument stopped collecting data in 2022 because of a breakdown in cooperation between the consortia following Russia's invasion of Ukraine. **PT**

References

1. K. Dennerl et al., "Determination of the solar system contribution to the soft x-ray sky," *Science* **392**, 285 (2026).
2. C. M. Lisse et al., "Discovery of x-ray and extreme ultraviolet emission from comet C/Hyakutake 1996 B2," *Science* **274**, 205 (1996).
3. K. Dennerl, J. Englhauser, J. Trümper, "X-ray emissions from comets detected in the Röntgen x-ray satellite all-sky survey," *Science* **277**, 1625 (1997).

Analysis of B-meson decay hints at new physics

The measured trajectories of the products of a rare B-meson decay deviate from the predictions of the standard model.

By Sarah Wells

For more than 50 years, the standard model (SM) of particle physics has been the prevailing description of the fundamental forces and elementary particles in the universe. But notable omissions from the theory, such as explanations for gravity and dark matter, have motivated experiments, like those at CERN's Large Hadron Collider (LHC), to search for yet-undiscovered physics. Now an analysis of collision data from the LHCb (Large Hadron Collider beauty) experiment, shown in figure 1, has yielded fresh evidence that the properties of some decays of B mesons, which are composed of a bottom antiquark and a lighter quark, deviate from those predicted by the SM.[1] Though the discrepancy is still under the five-standard-deviation threshold that, by convention, is needed to claim a discovery, it adds to growing support for the idea that new physics may play a role in the behavior of B mesons.

The new work focuses on the decay of a B meson into a kaon, pion, and two muons. Known as a penguin decay, it is playfully named for the rough resemblance its Feynman diagram has to the flightless bird, as shown in figure 2. The penguin decay of B mesons is particularly useful for the study of new physics because it occurs only via quantum loops mediated by virtual particles, as opposed to via direct decays. As a result, the process is extremely rare: Only 1 in 1 million B mesons undergo this type of decay. The rarity means that when searching for new physics, researchers have less noise from the signals of SM processes to contend with than when they study more-frequent decays. Additionally, because of its quantum nature, the loop process is susceptible to being infiltrated by potential heavy non-SM particles that would influence the products of the decay in ways that SM particles cannot. Such heavy particles cannot be produced directly by the LHC, but the decay process offers an opportunity to indirectly observe their impact.

Evidence that something unusual is happening in the penguin decay of B mesons has been mounting for over a decade. In 2013, the LHCb collaboration reported a 3.7σ discrepancy from SM predictions in the directions that the final particles fly off, known as the angular distribution, following the decay. CERN's Compact Muon Solenoid collaboration reported similarly anomalous behavior last year but at a lower level of statistical significance.

In the new work, the collaboration analyzed 2011–18 proton–proton collision data, which encompassed about 650 billion B mesons, and reconstructed some 12 000 instances of B-meson penguin decay. The team then analyzed the angular distribution of the final particles and determined that there was a deviation of about 4σ from

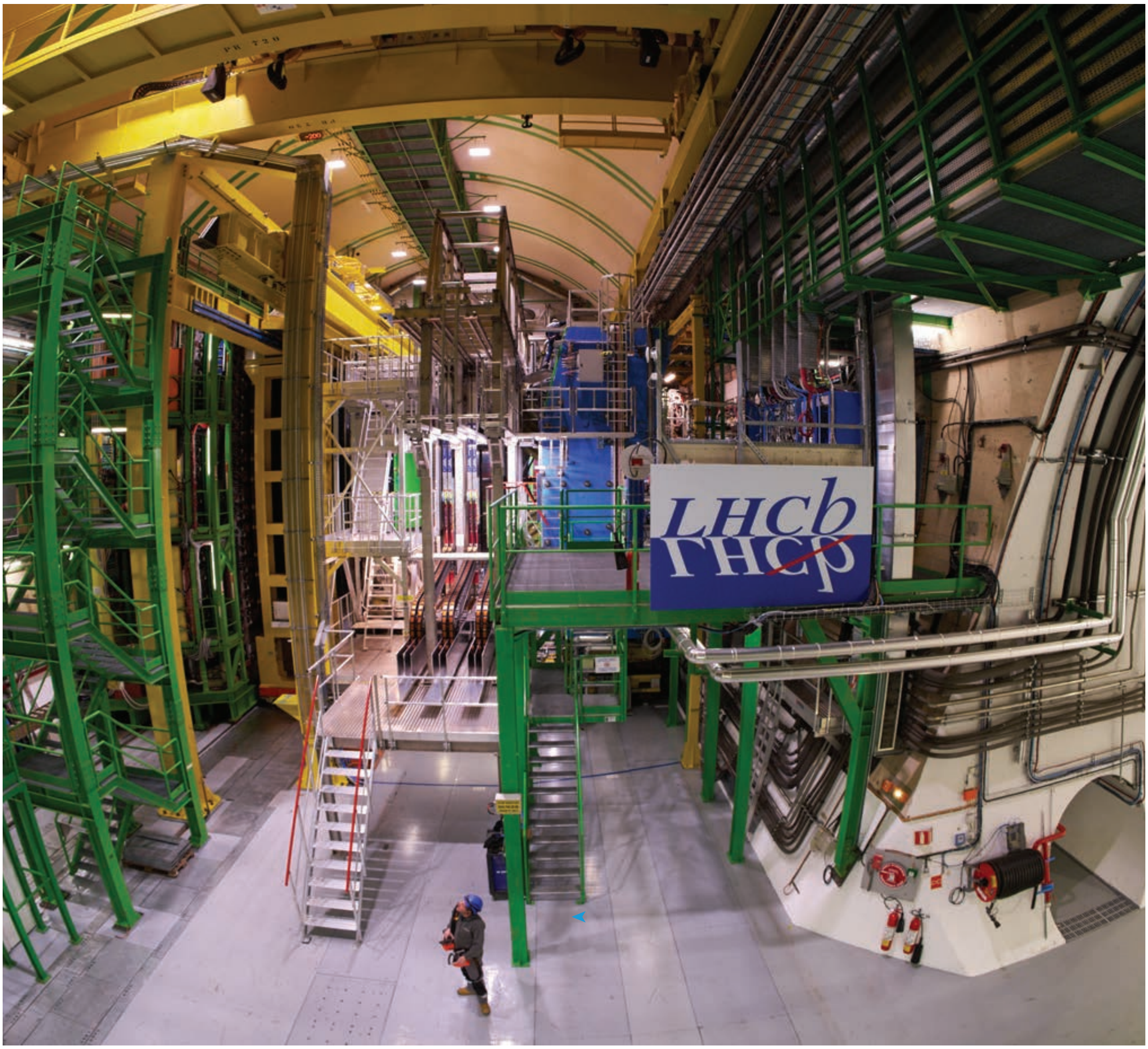


Figure 1. The Large Hadron Collider beauty (LHCb) is one of several detectors installed at the LHC. Researchers at the LHCb study bottom quarks, as well as related particles like B mesons, that are produced in proton collisions. (Photo © CERN.)

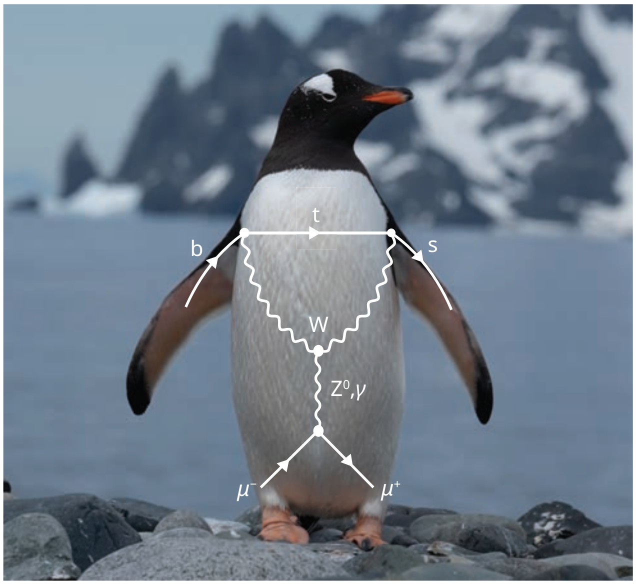


Figure 2. This decay of a B meson is called a penguin decay, with its name the result of a bet that CERN theorist John Ellis lost in 1977. The decay of the B meson's component bottom quark (b) yields a strange quark (s) and a muon and antimuon (μ^- and μ^+). The process is mediated by a quantum loop that includes a virtual W boson, top quark (t), photon (γ), and Z boson (Z^0). (Image by Freddie Pagani with photo by iStock.com/Leamus.)

the predictions of the SM. "This result has a probability of about 1 in 16 000 that it is just a statistical fluctuation from the standard-model predictions," says MIT's Leon Carus, who contributed to the work.

If new physics is responsible for the anomalous angular distributions, there are particle candidates that researchers believe might fit what they see. Those include the Z′ boson, a proposed heavy cousin of the Z boson, and the leptoquark, a heavy particle that would have properties of both leptons and quarks. SM physics is not entirely ruled out, however. One explanation to remedy the B meson's tension with the SM is the existence of an alternative decay path that includes a separate quantum loop that involves charm quarks. Although researchers estimate that the impact of such decays, known as charming penguins, should be too small to fully explain the anomaly, it is difficult to predict.

Ultimately, collecting more data is necessary to better understand the behavior of B mesons. The LHCb collaboration will soon be analyzing data collected during the experiment's third run, which concludes at the end of June and will provide five times as much data as collected in the two previous rounds combined. PT

Reference

1. R. Aaij et al. (LHCb collaboration), "Comprehensive analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay," *Phys. Rev. Lett.* (in press).

UK physical scientists brace for new round of funding cuts

They are advocating for projects and facilities that are threatened by the government's cost-cutting plans.

By Sarah Wild

Researchers, universities, and science organizations in the UK and abroad are preparing for and speaking out against the large proposed cuts to government physics and astronomy funding.

The Science and Technology Facilities Council (STFC), the entity that funds and supports physics and astronomy research and operates large science facilities across the UK, announced earlier this year its intent to slash research funding. Over the next four years, the council needs to find £162 million (about $218 million) in total savings, a spokesperson says. The council's budget is £835 million this fiscal year and is set to reach £842 million in 2029–30.

The council is part of UK Research and Innovation (UKRI), an umbrella funding body. UKRI has received a record £38.6 billion for use over the next four years, and most fields of science are not earmarked for cuts. But the STFC's costs—particularly from the energy costs of facilities and changes in foreign exchange rates—are rapidly outstripping its funding allocation, according to UKRI chief executive Ian Chapman in a February open letter.

The STFC reduced its funding for new grants by 15% in 2025, and now it is looking to make even greater cuts. Earlier this year, Michele Dougherty, executive chair of the STFC, asked scientists in the UK's particle-physics, astronomy, and nuclear-physics communities how their projects would respond to 20%, 40%, and 60% cuts in funding and for the financial point at which they would no longer be able to sustain them. The STFC spokesperson says that the council is consulting the research community and partners and that decisions will be made later this year.

"There is no sugarcoating how damaging the proposed cuts would be for UK physics and astronomy," says Emma Chapman, an astrophysicist at the University of Nottingham who would be affected by the reduced funding. "Groups would close, and early-career researchers would lose their jobs. The UK would lose its footing in current and next-generation international collaborations."

The proposed cuts come as the UK physical sciences community is facing not only the reduced availability of grants but also the shelving of several large projects. Two months before UKRI's chief executive released his open letter, the funding body chose not to contribute to LHCb 2030+, an upgrade to the Large Hadron Collider beauty experiment at CERN. UKRI has also declined to contribute funding to a new US particle accelerator, the Electron–Ion Collider at Brookhaven National Laboratory. And it is pausing plans for two national facilities that have already received government funding: the Relativistic Ultrafast Electron Diffraction and Imaging facility and the Critical Mass UK mass spectrometry center.

Patrick Vallance, the minister of state for science, innovation, research, and nuclear, and UKRI's Chapman wrote in a letter to a Parliament committee in March that the projects were deprioritized based on advice from UKRI's expert infrastructure advisory committee. "It is a feature of competitive grant funding that we always receive many more good ideas than we can afford to fund," they wrote. Regarding the decision not to fund LHCb 2030+, they noted that the UK remains "the second largest overall contributor to CERN."

Researchers push back

The prospect of reduced funding is already having an effect in the UK, according to the Institute of Physics (IOP). "Even the potential of having cuts is having a serious impact, with early-career researcher jobs being pulled and uncertainty playing into an already under-pressure university system," IOP president Paul Howarth says. "If the kinds of cuts currently being flagged go ahead, it would be a huge blow to the foundations of physics research and the physics landscape in the UK."

The Daresbury Laboratory, shown in an aerial photo, is one of two major research campuses operated by the UK's Science and Technology Facilities Council. The UK government has paused funding for the Relativistic Ultrafast Electron Diffraction and Imaging national user facility that had been slated to be built at the lab. (Photo from the Science and Technology Facilities Council.)

The proposed cuts "risk having a disproportionate impact on exactly the kind of research where the UK is currently strongest," says Eloy de Lera Acedo, head of the Cavendish Laboratory's radio astronomy and cosmology group at the University of Cambridge. "Large long-term programs in radio astronomy, particle physics, and cosmology depend critically on continuity, both in funding and in people. These are not systems you can pause and restart without consequence."

The UK has already invested heavily in major international facilities, such as the Square Kilometre Array radio telescope, de Lera Acedo says. "Cutting domestic research capacity just as these begin delivering data is like buying a Formula 1 car and then not funding the team to drive it," he says. "We will still pay the entry fee, but we won't be competitive, and we won't capture the full scientific or economic return."

The funding situation has spurred some researchers to push back against the plans. Several published open letters are urging the STFC and UKRI to rethink the proposed cuts. Dozens of physics department heads have written to Vallance expressing their "deep concern" about the threat to physics. Several other organizations, such as the IOP and the Royal Astronomical Society (RAS), are also speaking out against the proposed cuts. Howarth and RAS president Jim Wild sent a letter to Vallance on 12 May requesting that he commission a comprehensive assessment of the impact of the proposed STFC cuts.

Not only UK researchers are concerned. More than 600 international theoretical and high-energy physicists have written a letter urging the STFC and UKRI to reconsider the physics funding reduction.

One of the signatories is Michelangelo Mangano, a theoretical physicist at CERN. "In collider-based high-energy physics, we only have a handful of big experiments worldwide," he says. Those projects rely on global international participation and the reliability of long-term commitments, he says, adding that the scale and target of the announced cuts could have a big impact on such projects by compromising years of investment and threatening the student pipeline.

The University of Nottingham's Chapman says that current spending levels have already made securing funding "impossible," which is affecting her ability to support PhDs and postdocs. But the pushback against the cuts has been "huge," she says, and she believes that people in government are listening to researchers' concerns: "That is encouraging. I expect there will be cuts, but my hope is that they are spread across a broader range of research areas." **PT**

How much electricity does a quantum computer need?

The question is attracting attention amid rising energy use by classical computing data centers.

By Jenessa Duncombe

Edward Parker was thinking about who might use a quantum computer to hack the controls of a US chemical plant when he noticed something odd in the literature. The physicist was working on post-quantum cryptography recommendations for the US Cybersecurity and Infrastructure Security Agency in 2023 as part of his work at the nonpartisan think tank RAND. But first, Parker needed to answer another question: Who'd be capable of building a quantum computer in the first place?

Parker found that the quantum computing literature focuses more on the number of qubits, short for quantum bits, a system could handle, rather than on the resources—particularly the energy and money—to run one. He wasn't the only one to notice. A small but growing number of researchers, and in some instances, governments and companies, are focusing on the resource needs of quantum computing.

Classical computing data centers' climbing energy use, fueled by AI models, has prompted pushback (see *PT*'s 2024 article "Will AI's growth create an explosion of energy consumption?"). Data centers consumed 1.5% of electricity worldwide in 2024, according to the International Energy Agency, and consumption is anticipated to more than double by 2030. Ireland, where data centers consume over

20% of the country's electricity, has limited the building of future data centers near Dublin. Fourteen states in the US have introduced legislation banning data centers in recent years.

Quantum computers are not nearly as ubiquitous as the classical computers that populate data centers. The technology is so nascent that the most scalable design of qubits is still an open question. Quantum computing today does not reliably solve useful, practical problems. Road maps at several companies say they'll have a useful quantum computer by the end of this decade.

The 54-qubit quantum computer Euro-Q-Exa was networked into this supercomputer at the Leibniz Supercomputing Centre in Germany. Scaling up quantum computing, and the energy it would take to do so, is an emerging topic in scientific circles. (Photo by Sebastian Widmann, © European Union, 2026, licensed under CC BY 4.0.)

Understanding quantum computing energy use requires unpacking how the technology uses energy and exploring efforts to increase efficiency. "I would say it's never too early to be thinking about those things," says David McCollum, an energy scientist at Oak Ridge National Laboratory.

A noisy enterprise

In the future, quantum computers could tackle specific problems in hours that would take classical supercomputers many years to run. A classical bit can only represent 0 or 1, but a qubit can represent 0, 1, or a superposition of both. As more qubits are added, the number of states the system describes increases exponentially, whereas classical bits scale linearly. Because of this, it's tempting to think that quantum computers would be more energy efficient than classical computers.

But quantum computers lag in something classical computers are good at: reliability. Quantum computers use quantum states to hold information, and small disturbances in the physical environment can lead to the destruction of the information through decoherence. Today's quantum computers have error rates many orders of magnitude higher than those of classical processors. Quantum computing today is classified as noisy intermediate scale, as opposed to fault tolerant.

The energy consumed by quantum computers boils down to what's needed to fight noise, says Marco Fellous-Asiani, a quantum computing researcher at Inria, a French national research institute. Safeguards depend on the qubit type: cryogenic cooling for superconducting qubits, high-powered lasers for neutral-atom qubits, and cooling and laser systems for some trapped-ion qubit designs. All require energy-costly quantum error correction.

For instance, superconducting qubits are at their least noisy at temperatures around 10–35 millikelvin, two orders of magnitude lower than the temperature of outer space and of the magnets in CERN's Large Hadron Collider. The cooling system accounts for approximately 80% of the power consumption of a noisy intermediate-scale superconducting quantum computer, according to a May preprint from a group of quantum computing researchers.

Efforts to reduce quantum noise are ongoing, and qubits may rapidly improve in that area in the years to come. Once systems ramp up to thousands or millions of qubits, control electronics that manipulate qubits' quantum states may become the energy-hungry part of quantum computers, says Raja Yehia, one of the authors of the May preprint. Yehia is a postdoc in quantum information theory at ICFO, the Institute of Photonic Sciences in Barcelona, Spain.

"Given the early stage of quantum computing and the lack of clarity as to which type of qubit will become predominant, it is hard to put firm figures on how much energy will be needed," says Celia Merzbacher, the executive director of the Quantum Economic Development Consortium.

Back of the envelope

Still, some early estimates exist. In 2023, RAND researcher Parker calculated the electricity demand for a hypothetical superconducting quantum computer with 20 million noisy qubits to crack a 2048-bit RSA key, a widely used public-key cryptography system. He came up with 890 megawatt-hours, the electricity needed for roughly 85 US households for one year. Parker concluded that it would be difficult for a bad actor to build and conceal a quantum computer anytime soon, let alone afford one. The electricity for that task alone would cost $64 000 in 2023 dollars. He and fellow RAND scientist Michael J. D. Vermeer shared the results in a working paper.

What about the energy use of integrating fault-tolerant quantum computers into classical computing data centers? A new analysis by Oak Ridge's McCollum and colleagues tackled this question using superconducting qubits. The researchers projected that by the 2040s, integrated quantum–classical data centers would have a system-level power demand of an order of magnitude similar to that of today's data centers.

Quantum engineer Olivier Ezratty compared the power consumption of leading quantum computers with existing supercomputers in a presentation last year. He presented rough projections of the future base power of six quantum computers, each scaled up to 4000 logical qubits, that are under development by leading companies. The power ranged from under 1 megawatt to over 100 megawatts. Most landed within range of the top supercomputers today. The calculation was not peer reviewed and was for demonstrative purposes; Ezratty says that most industry vendors do not openly share power consumption information.

Steering the ship

If estimates are so varied today, why go about making them at all? Zeki Seskir, a researcher at the Institute for Technology Assessment and Systems Analysis in Germany, says that quantum researchers have the most control over eventual outcomes now, not later. Seskir cites the Collingridge dilemma: Harmful consequences of a technology may be hard to understand when it is nascent, the dilemma goes, but those consequences become extremely difficult to control after the technology matures.

The Quantum Energy Initiative is addressing the question of what researchers and companies can do today to support energy-efficient design. The group began in 2022 after a call to action was published by Alexia Auffèves, at the time a quantum physicist at the French research organization CNRS. More than 700 people have signed up online to join the volunteer-run community, which has hosted three in-person workshops since 2023.

Counterintuitive results can arise when optimizing for energy efficiency. In a 2023 paper, a group of researchers introduced a method for modeling the connection between computational accuracy and energy consumption. Testing their metric noise resource technique on an idealized full-stack computer, the researchers found in some instances that raising the temperature of superconducting qubits while adding more quantum error correction yielded a larger yet more energy efficient computer, without losing accuracy.

Along with an energy utility, French quantum computing companies Quandela and Alice & Bob received €4.5 million (about $5 million) from the French government to study the energy efficiency of quantum computers compared with that of classical systems. Using the metric noise resource method, Quandela identified energy-efficient regimes for its photonic quantum computer. Its computer was more energy efficient than a classical computer in solving a certain algorithm, despite having a greater runtime, the scientists from the company wrote in a preprint.

A standard under development by an IEEE working group aims to define energy-efficiency metrics for the sector. Working-group chair Fellous-Asiani, speaking in his personal capacity and not as a representative of the group or IEEE, says the standard under development quantifies the energy of solving a given problem at a given accuracy regardless of qubit type. It could one day serve as the basis for benchmarks comparing the energy efficiency of different quantum computers.

Of course, if quantum computers do not achieve widespread use, their energy demands could matter very little. For instance, supercomputers used for weather forecasting, aerospace research, and other research tasks consume paltry amounts of energy compared with what commercial data centers consume, says Ezratty, who is a cofounder of the Quantum Energy Initiative. Even if quantum computers are energy intensive, their impact could be relatively low if they stay in the realm of specialized research.

Another complicating factor is the possibility of the hypothesized rebound effect: when the lower costs resulting from energy-efficiency improvements actually encourage consumption and thus dampen the effects of the innovation. If commercially relevant quantum computing becomes more energy efficient, companies could simply buy more computers or computing time.

To find the answers, Seskir calls for exploring impacts as early as possible. "Technology and innovation are not science," he told the audience during his presentation at the Quantum Energy Initiative's 2023 workshop. "Although we might be scientists, we need to be aware that the consequences are different." PT

Q&A: Amal Kasry works to strengthen science where it's most needed

For the UNESCO section chief, "striking a balance between global coherence and respect for national ownership and cultural diversity is both essential and complex."

By Toni Feder

Amal Kasry left academia in 2021 to become UNESCO's chief of section for basic sciences, research, innovation, and engineering. "Science achievements are cumulative, and you cannot see the impact overnight," she says. "I wanted to do something on the ground that would benefit people directly."

The section aims to advance fundamental science in all 193 United Nations member states. Kasry's team develops programs and policies. In three words, says Kasry, the mission is "science for peace."

Kasry grew up in Egypt, earning her physics bachelor's degree at Cairo University in 1993. A decade later, she went to Germany to pursue her PhD in materials science. Starting with her doctoral studies, she bounced between continents and between academic and private-sector research positions for about 13 years before returning to Egypt as a faculty member at the British University in Egypt. Four years in, she was tapped to serve as director of the university's Nanotechnology Research Centre. She did that for two years until she took the job at UNESCO.

The following interview has been edited for length and clarity.

Why did you go into physics?
I have loved science, and physics, since I was very young. After high school, I started by studying electrical engineering. But I didn't really find myself there, so I switched to physics.

Briefly describe your research.
My supervisor at the Max Planck Institute for Polymer Research in Mainz, Wolfgang Knoll, had developed an amazing plasmonic system to detect DNA and proteins, which helps detect disease at early stages. I developed a technique based on long-range surface plasmon resonance to enhance sensor sensitivity. The approach combines fluorescence with enhanced electromagnetic fields to detect very low concentrations of DNA and to study protein–protein interactions.

Where did your career take you after your PhD?
For about three years, I was a postdoc, first in Germany, then in the US, and then Wales—that was all research related to biosensing. Then, I went to IBM in New York. It was 2009, and graphene was a hot topic. Next, I was recruited by a Japanese company in Singapore. I wanted to go back to academia, so I moved to the Austrian Institute of Technology, where I worked on biosensors using nanoparticles and nanowires.

In 2015, I joined the British University in Egypt as a faculty member in engineering. I taught physics. And then the university selected me as the director of a new research center in nanotechnology. I continued to lead my own research group developing sensing techniques while also managing the center administratively.

That's a lot of moving around. How was it?
Moving around so much was exhausting and expensive, but at the same time, it was a great experience. I learned different techniques in each place. And I met people and was exposed to cultures. That is beautiful.

What drew you to UNESCO?
I always wanted to travel to help people and maybe leave science. Not because I wanted to leave science—it was the idea of finding ways to help people directly that was the main motivation for me.

For years, I had explored opportunities and agencies that have science mandates. UNESCO has a unique role in advancing fundamental sciences within a broader interdisciplinary framework.

(Photo courtesy of Amal Kasry.)

What do you do there?
My section is responsible for helping member states in developing and strengthening capacity in the fields of basic sciences, engineering, and STEM education. We work directly with governments—that's an advantage we have. Part of our job is to advise member states on what they can do to advance in these fields.

What are some of the programs you and your team are involved with?
Generally, we talk with member states and try to find solutions to some of their problems.

We coordinate the needs of the scientists and the equipment. We find the laboratories and the partners who are willing to give access. We follow up with monitoring to see the impact, to see how many benefited and how they benefited.

For example, we developed a program to give scientists in the Global South remote access to sophisticated laboratory techniques that they don't have, such as single-crystal x-ray diffraction. The scientists send their samples abroad, but then they do the work themselves, which makes a huge difference in the quality of the research and their results.

We are trying to work with African member states to explore the possibility of having an African synchrotron facility. This is a long-term plan and a huge investment. African member states are very excited about this. For now, we try to work with some of the existing synchrotrons to give access to African scientists.

What's an example of a program in education?
We started a new initiative on science clubs for STEM education. We launched the first network, consisting of about 200 clubs—and the number is growing—in Africa in December 2025. The clubs are all different, but the goal is the same: Offer hands-on extracurricular training for teachers. The training can be in robotics, 3D printers, and so on.

Besides STEM training, the clubs are an opportunity to enhance scientific literacy. This fits well with our goals for the decade of science for sustainable development.

Please elaborate on the International Decade of Sciences for Sustainable Development.
The International Decade of Sciences for Sustainable Development was proclaimed by the UN General Assembly in 2023. It is the decade from 2024 to 2033, and UNESCO is the lead agency. We came up with five anticipated outcomes. The first is enhancing scientific literacy, to make sure that science reaches everyone in every corner and people really understand the value and importance of science.

The other anticipated outcomes are to develop actionable knowledge; advance basic sciences; advance open science—sharing knowledge and infrastructure; and transform national innovation systems. A key dimension of the fifth outcome is to work with experts to improve how science is measured and evaluated, to make sure that it's not only about numbers but about quality.

Tell me about UNESCO's Global Quantum Initiative.
The IYQ [International Year of Quantum Science and Technology] showed us that there is a huge global divide: More than 150 countries do not have policies or strategies to cope with the changes that will come with quantum technology. We ran a survey to understand and identify gaps when it comes to scientific infrastructure in quantum. That led to our Global Quantum Initiative, which includes capacity-building activities, raising awareness, and working with governments to reduce the divide. For example, under the initiative, we may continue the online courses on quantum algorithms for female African scientists that we organized as part of the IYQ.

What are the challenges to achieving your goals?
One of the key challenges is working across a highly diverse global landscape. UNESCO serves all its member states, which means aligning with a wide range of policies, priorities, and cultural contexts while at the same time ensuring that scientists and governments have the flexibility to implement programs in ways that are locally relevant. Striking a balance between global coherence and respect for national ownership and cultural diversity is both essential and complex. It is also highly rewarding.

Another major challenge is resources. Broader geopolitical dynamics can affect the availability of funding and shape relationships among member states. UNESCO continues to work with all partners, and by engaging directly with the scientific community, we are able to bring people together. That remains one of our greatest strengths. **PT**

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

White House seeks broad authority over federal grants

By Jacob Taylor

The Office of Management and Budget (OMB) proposed a rule on 29 May that aims to deliver on President Trump's August 2025 executive order that gives political appointees the final say on federal grant decisions—including the power to terminate grants that they deem do not meet agency priorities. The OMB is accepting comments on the proposed rule until 13 July.

Under the rule, all discretionary federal awards would be required to pass a "new pre-issuance review." The political appointees conducting the reviews would be instructed to "use their independent judgment" and to not routinely defer to the recommendations of others. The rule states that it does not "discourage" the use of peer-review processes so long as they "remain advisory and are not ministerially ratified, routinely deferred to, or otherwise treated as de facto binding."

The criteria for the pre-issuance review would give appointees broad discretion to block awards. For example, an award could be blocked for promoting "anti-American values" or failing to "demonstrably advance the President's policy priorities." The review would also give preference to institutions with lower indirect cost rates; the Trump administration has repeatedly tried to cap those rates but has been blocked by both courts and Congress.

Other stipulations included in the proposed rule:

- Active and future awards could be terminated at any time if "found to be inconsistent with program goals or agency priorities."
- Agencies would be instructed to prioritize giving awards to "institutions that have demonstrated success in implementing Gold Standard Science."
- Federal awards would no longer be allowed to cover publication costs, processing charges, or open-access fees, unless required by statute or approved in advance by the agency. The use of funds to attend conferences would require express agency approval in the award.
- US researchers would be prohibited, with some exceptions, from using funds for collaborations with certain countries. All foreign entities seeking to collaborate with US researchers would be subject to tighter restrictions.
- Applicants would have to pass "risk assessments" that consider, among other things, their organization memberships and affiliations.
- Awards may not "fund, promote, encourage, subsidize, or facilitate" diversity, equity, and inclusion or "gender ideology."
- Agencies would be encouraged to increase award lengths to reduce the administrative burden caused by recompeting.

Republican lawmakers suggest defunding National Academies

By Clare Zhang

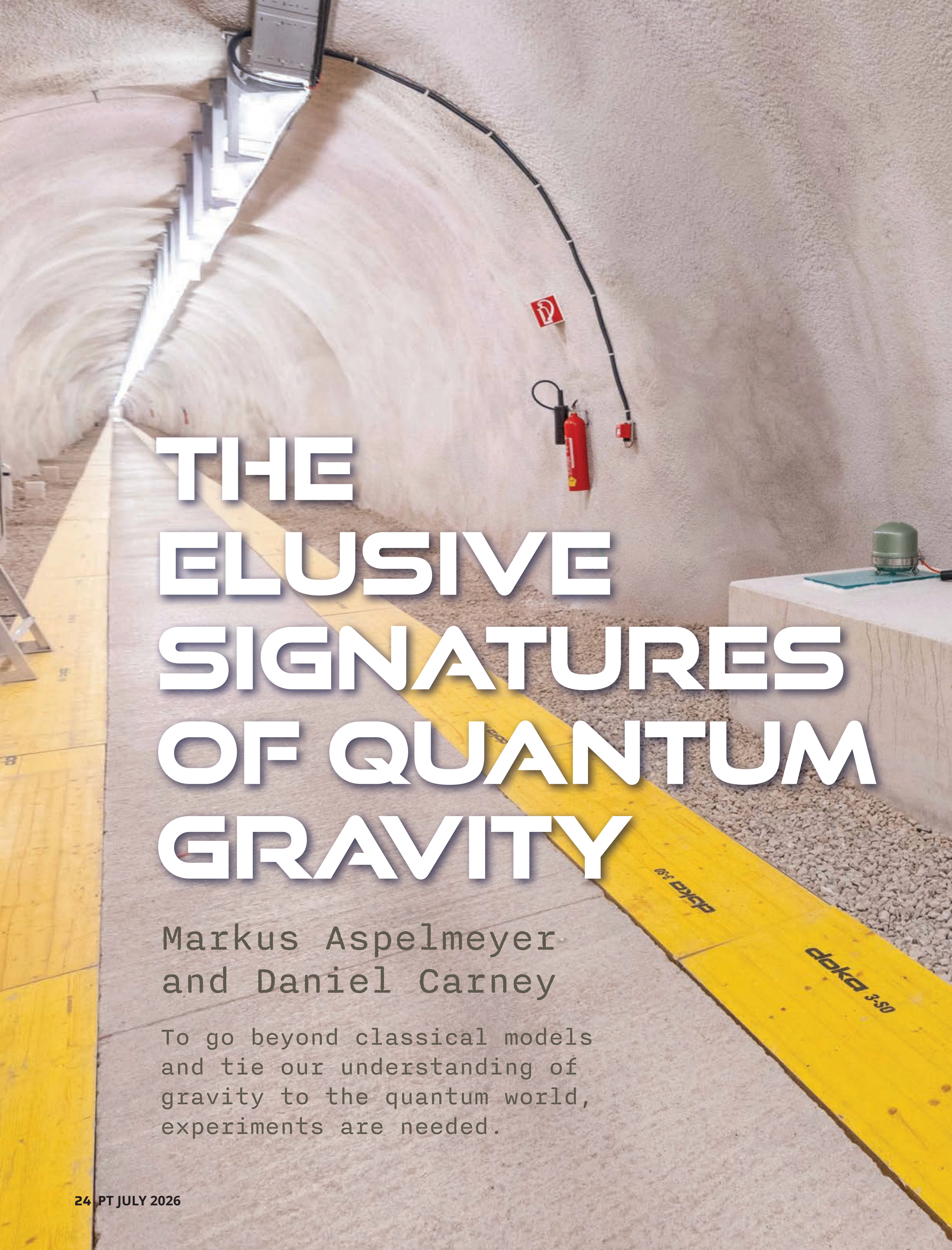
In response to a 4 May letter from 11 Republican lawmakers, the White House has signaled interest in investigating whether the National Academies of Sciences, Engineering, and Medicine (NASEM) should be suspended or debarred from federal funding.

Former White House Chief of Staff Mark Meadows posted an article on X about the letter, which criticizes the climate science chapter of the *Reference Manual on Scientific Evidence*, a major scientific resource for federal judges and that NASEM helps produce. Meadows commented, "The National Academies have weaponized tax dollars against President Trump for far too long. It's time to end their contracts." Russell Vought, director of the Office of Management and Budget, responded, "On it."

The lawmakers' letter argues that the chapter "violates Gold Standard Science" because the peer-review process did not include scientists with differing views on climate science and because its authors and funders had conflicts of interest.

The letter heavily echoes two sent earlier this year by Republican state attorneys general. In January, the attorneys general criticized the chapter and asked the Federal Judicial Center (FJC), which writes the manual with NASEM, to withdraw it. Soon after, the center removed the chapter from its website. Sixteen Democratic lawmakers wrote to the FJC's director requesting its reinstatement.

The chapter remains available on NASEM's website; National Academy of Sciences President Marcia McNutt rebuffed the request for its removal. In March, Republican attorneys general suggested in a letter to three cabinet members that agencies consider suspending or debarring NASEM from federal funding and that congressional committees investigate NASEM. PT



THE ELUSIVE SIGNATURES OF QUANTUM GRAVITY

Markus Aspelmeyer and Daniel Carney

To go beyond classical models and tie our understanding of gravity to the quantum world, experiments are needed.

At an underground observatory near Vienna, Austria, a scientist conducts a miniature version of a Cavendish experiment in the search for quantum gravity. (Photo by Daniel Hinterramskogler/IQOQI Vienna. Design by Masie Chong with artwork adapted from iStock.com artists Visivasnc and MrDannyD.)

Gravity is unique among the known fundamental forces of the universe: Currently, there is no experimental result whose explanation requires a quantum theory of gravity. But physicists, including Albert Einstein,[1] have still argued on empirical grounds that quantum theory must modify theories of gravitation. As early as the 1920s, dimensional-analysis arguments suggested that observing any phenomena that meaningfully involved quantum dynamics of the gravitational field is beyond the scope of what's experimentally possible. Thus, the hope of directly testing ideas about quantum gravity with experiments languished for nearly a century.

Today, the simplest expectation for a quantum theory of gravity is that, at a minimum, states of weak gravitational fields can be in quantum superpositions and be described in terms of gravitons. The hypothesized particles quantize the gravitational field akin to how photons quantize the electromagnetic field. Beyond that simple picture, physicists have quantum gravity models, such as string theory, that support the existence of gravitons at low energy but also work at vastly higher energy scales, where the graviton picture breaks down. How can researchers know if that quantum description accurately models how gravity operates in the real world?

To answer that, experiments are needed. That may be possible now that scientists have made significant advances in quantum-state control and measurement, which provide not only unprecedented spatial and temporal sensitivity but also new ways to prepare quantum states of macroscopic objects. A prime example is using the kilogram-scale mirrors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) to measure gravitational waves, a measurement that is at the limit of sensitivity set by the Heisenberg uncertainty relation.

A vast array of architectures at other length and frequency scales are also rapidly changing what is possible. The developments open the door to realistic tests of the quantum nature of the gravitational field over the next two decades. Equipped with those new tools, many researchers have converged on a set of experimental approaches to definitively address the simple, fundamental question: Is the gravitational field quantized?

Quantum signatures of gravity

To determine whether gravity actually requires a quantum interpretation, researchers first need to ask what constitutes a truly quantum signature of gravity. The question turns out to be exceedingly subtle. Many phenomena can be described by both quantum and classical models. Consider, for example, a dilute gas of helium. It behaves classically at room temperature, fully condenses into a quantum superfluid at 0 K, and behaves with a mix of classical and quantum behaviors at low temperatures near absolute zero. Any given experiment can probe only some set of those behaviors. Ultimately, a barrage of tests of different phenomena is needed for probing quantum behavior. What signs would demonstrate whether they had found quantum gravity?

Inspiration for how to develop tests of quantum gravity can be found in quantum optics questions that ask what kinds of observations can be explained with only a quantized electromagnetic field. Initially, introducing the idea of photons allowed researchers to quantum mechanically describe all relevant aspects of light–matter interactions, including the photoelectric effect, absorption, spontaneous and stimulated emission of radiation, and the Lamb shift. Yet most experimental results associated with those phenomena can also be described with simple classical models of the radiation field.

In the photoelectric effect, shining light on a metal or semiconductor produces discrete electron currents. Einstein himself argued that observations of the effect are evidence of the quantization of light into photons, but others later showed that the same effect can be explained classically by a plane electromagnetic wave of classical light interacting with quantized electrons in a metal.[2] (For more on the quantum theory of the photon, see the 1972 *PT* article by Marlan Scully and Murray Sargent.)

However, more sophisticated photodetection experiments can be explained only with a quantum model of light. One particularly clear set of examples is based on the notion that classical light will be energetically split in half by a beamsplitter, but an individual photon cannot be similarly divided. Thus, in quantum theory, unlike in the classical theory of light, a single-photon state will be observed by only one of two detectors behind a beamsplitter. John Clauser, Alain Aspect, and others made such observations of correlated photon detections requiring a quantized explanation in now historic experiments during the 1970s and 1980s.[3] Similar nonclassical counting statistics were found for other inherently quantum states of light, such as squeezed states, in which the light's quantum mechanical uncertainty is unevenly distributed between amplitude and phase, and entangled states, in which the quantum state must be described by joint properties of multiple particles. Such experiments rule out the possibility that the electromagnetic radiation field can be described with classical states or probabilistic mixtures of classical states.

Fundamentally, the tension between classical and quantum descriptions is based on a quintessential dividing line between quantum and classical behaviors: superposition. The interference fringes seen in the distribution of particles after they pass through a double slit, or the detection statistics of a photon that passes through a beamsplitter, are in direct conflict with a model of the particles, or waves, as classical objects. Instead, the state of a particle needs to be described in terms of a quantum superposition of multiple classical states. A particle that passes through the double slit, for example, is in a superposition of two locations, and the photon that has passed the beamsplitter is in a superposition of two paths.

Similarly, in regard to the gravitational field, the question is whether a demonstration can show that the field itself can be quantum mechanically superposed and thus able to produce a detectable signature of quantum gravity. A gravitational superposition would go beyond classical general relativity and imply that the gravitational field, and thus the geometry of spacetime itself, is not in a single, definite configuration but in some quantum superposition of configurations.

In principle, the familiar double-slit experiment should produce such states because a particle, such as an atom, sent through a double slit is a source of gravity. When an atom has traversed the double slit and is in a quantum superposition of two distinct locations, the simple expectation from a quantized model of gravity would be that the gravitational field produced by the atom would also be in a quantum superposition.

One way researchers can measure a superposed gravitational field is by observing what happens to a passing test mass. Researchers suggested in 2005 that the superposition of millions of atoms in a Bose–Einstein condensate could act as a source of gravity and a passing micrometer-scale object could serve as a test particle.[4] Although that specific proposal appears to be experimentally impossible, various related proposals have been recently suggested that appear to be feasible in the next decade or more.

Searching for signatures

Many experiments already involve gravitational fields that act on quantum systems, such as light and atoms. But those experiments do not necessarily test whether the gravitational field itself is quantized.

In the 1975 COW (Colella-Overhauser-Werner) experiment, for example, a neutron interferometer was used to prepare neutrons in a quantum superposition of two vertically distinct locations. That produces an interference pattern because of the difference in the gravitational potential at the two locations. In other words, gravity acts differently on each neutron wavepacket.[5] The neutrons are clearly quantum mechanical particles, as evidenced by their interference fringes, but the gravitational field of Earth that acts on those particles can be described entirely as a single, distinct classical configuration. Similarly, the LIGO-Virgo-KAGRA Collaboration's observations of gravitational waves can be successfully modeled as arising from classical gravitational waves acting on the quantized light and mirrors of the detectors.[6]

What is truly required is a nonclassical state of the gravitational field itself. A nonclassical state could be sought in two regimes of the gravitational field, as illustrated in figure 1: radiation fields, like the gravitational waves emitted by merging black holes, and static fields, similar to the one sourced by Earth. In the case of radiation fields, the waves can be viewed as having a particle-like nature that can be described using gravitons.

Given the success of photon measurements in electromagnetism, a natural starting point is

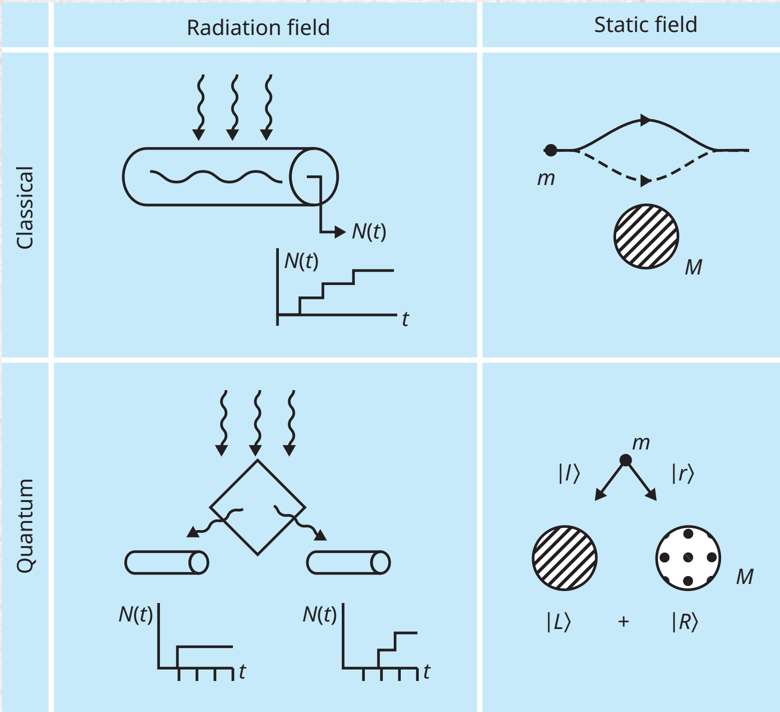


Figure 1. Experimental approaches that can or cannot observe quantum behavior of a gravitational field. On the left, large cylindrical masses known as Weber bars are used to detect radiation fields—that is, gravitational waves. An experiment with a single gravitational-wave detector **(top left)** can be explained with classical gravity; the plots show the total event number of excited Weber bar phonons *N* as a function of time. A hypothetical experiment **(bottom left)** involving a gravitational beamsplitting system and a pair of detectors cannot be explained with classical gravity. The right column depicts an analogous distinction with static gravitational fields. An experiment **(top right)** to detect a changing quantum phase in a detector system placed in the static field of a mass like Earth can be explained with a classical gravitational field. An experiment **(bottom right)** that uses gravity on a test mass *m* to detect a superposition of the location of source mass *M* cannot be explained with a classical gravitational field.

looking for quantum effects in gravitational radiation, but that is exceedingly difficult in practice. Certain astrophysical events could be a source of nonclassical gravitational radiation.[7] But even if such an exotic gravitational state was available, researchers would need to probe the nonclassical statistics of the state, analogous to the photodetection statistics in quantum optical measurements.

The efficiency of photodetectors makes such measurements easy for electromagnetism, but for gravity, the challenge is immense. In a gravitational-wave detector like LIGO, only around 1 in 10^{30} gravitons is effectively absorbed. Consequently, detecting subtle quantum statistics comparable to those available in optical experiments is currently impossible. Researchers would be able to detect only random events, which have statistics that are indistinguishable from those produced by a classical gravitational wave acting on the same detectors.[8]

Unless new ideas for substantially increasing the coupling of gravity to Earth-based detectors are developed, the limited detection efficiency of gravitational radiation experiments means that any result can be explained with classical gravitational waves. Therefore, even if nonclassical sources of gravitational radiation are available, they could not be identified with foreseeable technology.

Creating a nonclassical state

Static fields, like those created by slow-moving masses, are an alternative to gravitational waves for detecting quantum signatures of gravity. If a superposition of a mass in two distinct locations is created and if gravity is quantized, then the Newtonian gravitational field becomes quantum mechanically superposed. One way to probe the gravitational field of a superposed quantum source mass is to use a test mass. Since each branch of the superposed gravitational field acts differently on the test mass, the source and test masses will become entangled, and that entanglement can then be measured.[4,9]

Although less prohibitive than detecting nonclassical gravitational radiation, detecting gravitational entanglement is difficult. Quantum entanglement can occur only when the gravitational field sourced by each branch of the superposition acts differently on the test mass, so large masses and large spatial superpositions are more likely to produce observable effects. Large superpositions, however, easily decohere because of rapid environmental interactions with gas molecules, thermal radiation, and other noise sources.

Such decoherence effectively collapses the superposition's wavefunction before the gravitational state can be measured. (For more on how the environment can decohere a quantum system, see the 1991 *PT* article by Wojciech Zurek.) Two atoms, separated by 100 µm and in a superposition with center-of-mass positions separated by 100 nm, can be kept in a quantum-coherent state for several minutes. But the difference in the states' gravitational energies is so small that the time it takes for the states to gravitationally entangle is longer than the current age of the universe. In contrast, two 50 µm lead spheres, each containing 10^{18} atoms, put in the same superposition and at the same distance would generate observable entanglement in just 10 ms. But no one has ever observed such a state because it would quickly decohere.

Researchers are still far from developing a working experimental system to detect signatures of quantum gravity. The largest mass thus far prepared in a quantum superposition contained 10^{17} atoms in a bulk acoustic resonator.[10] (A version of the resonator is shown in figure 2.) But its superposition size of a few attometers is far too small to resolve any gravitational difference between the superposition states in its vicinity.

On the other hand, the smallest measured gravitational field to date is from a millimeter-sized source mass containing 10^{22} atoms.[11] It's a small gold sphere, shown in figure 3, and would decohere far too quickly in any realistic laboratory environment. Nevertheless, the hurdles to prepare actual quantum source masses seem more technical than fundamental. One promising approach is to control the quantum state of isolated solids trapped in a vacuum.[12] Those objects can be scaled to large masses and large spatial separation of the wavefunction. Another approach is to use miniaturized torsional pendulums for accessing small gravitational fields.[13]

With concerted efforts, a direct test of the

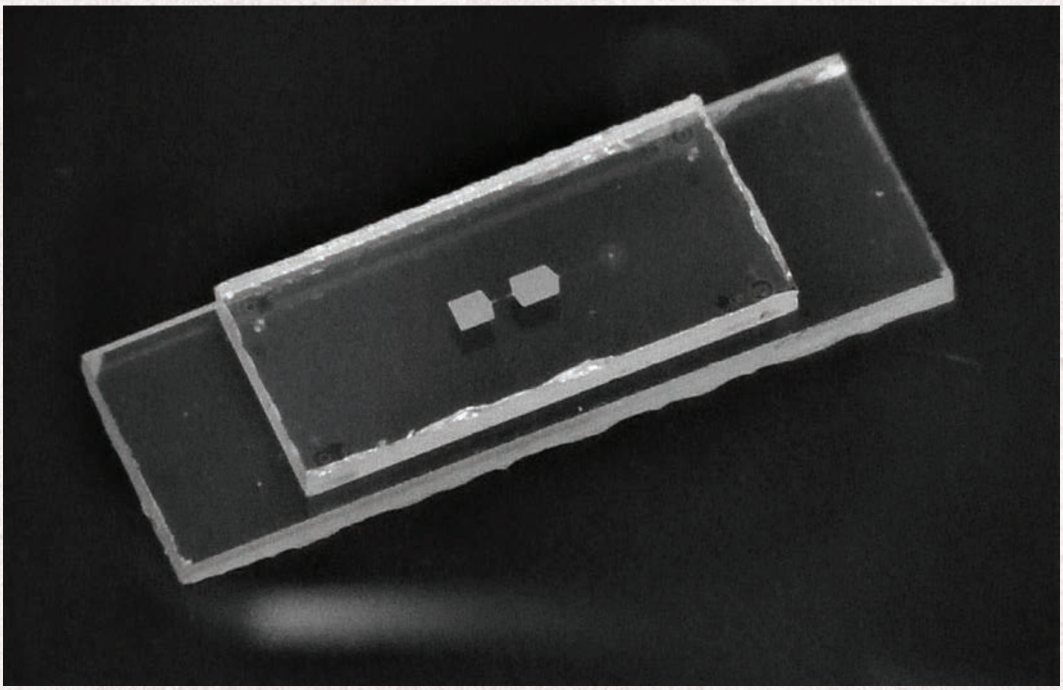
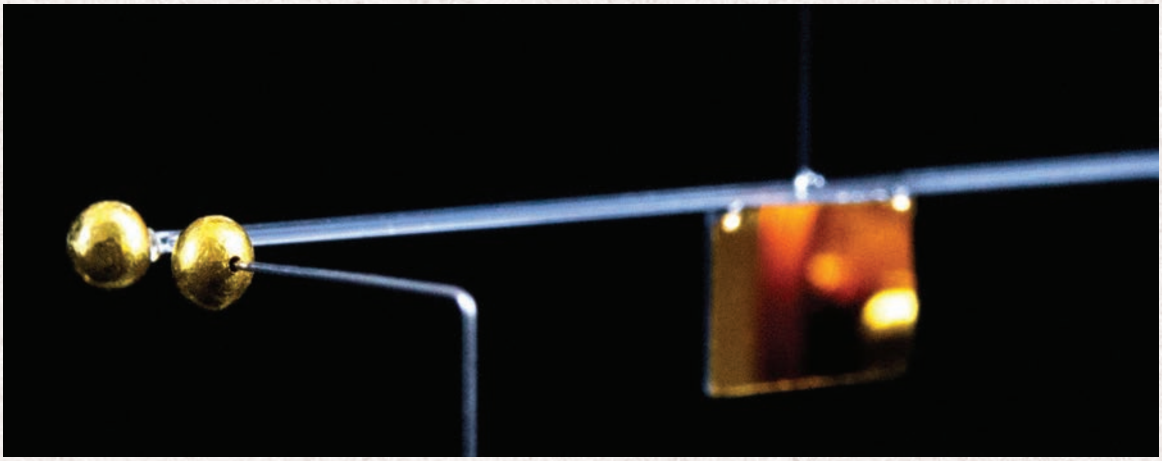


Figure 2. This mechanical resonator made out of sapphire is one of the largest objects that has been quantum mechanically controlled. Its 10^{17} atoms were put into a quantum superposition to wiggle in opposite directions simultaneously. Although the attometer separation between the superposed states is too small for researchers to resolve the states' gravitational differences, future work on such objects could help identify whether gravity has a quantum description. (Image courtesy of Uwe von Lüpke/ETH Zürich.)



▲ **Figure 3.** The rightmost, fixed gold sphere has a mass of 90 mg and a radius of 1 mm. It's one of the smallest objects for which gravitational effects, probed here by a similarly sized sphere mounted on a torsion pendulum, have been measured. Obtaining quantum signatures of gravity for such a small object is exceptionally difficult because of decoherence issues. But if such measurements could be made, some of the most fundamental physics concepts would need revision. (Image courtesy of the Aspelmeyer Group/University of Vienna.)

quantum superposition of static gravitational fields may be plausible in the next two decades. There are somewhat clear experimental pathways to such measurements, although they are undoubtedly filled with unknown difficulties. Perhaps a new solution to the problem is in the mind of an ambitious student. The way to find out is for researchers to push the limits of precision quantum control and measurement deep into the domain of massive quantum systems.

Beyond the quantization of gravity

This article has focused on the simple question of whether the gravitational field is quantized at all. Even for that question, only limited information can be gained in a given experiment. The gravitational entanglement experiments we have discussed, for example, will answer the question of whether the gravitational field can be put into quantum superposition. If so, then a purely classical model of gravity is ruled out. But that would still leave a wealth of possible quantum models. Quantization in the form of gravitons would be consistent with this experiment, but so would more complex models in which gravity, like the low-temperature superfluid phase of helium, arises from emergent behavior of some underlying "atomic" system.[14]

Many other experiments at widely varying scales can provide new information about the quantum nature of gravity, and such experiments will be necessary for researchers to obtain a complete picture. For example, given the rapid advances in precision and architecture of optical and nuclear clocks,[15] researchers may have a path to probe the temporal aspects of gravitational superpositions. Another complementary probe could be measurements of anomalous noise in the gravitational interaction and the spacetime metric; such noise is a generic prediction of nongraviton models.

Experimental signatures of quantum gravity at high energies and, hence, high spacetime curvature scales is an entirely different matter. Astrophysical and cosmological effects of quantum gravity may exist that have no classical counterparts. Although observations of a primordial gravitational-wave background could be explained by classical stochastic models, some cosmological observables may violate Bell's inequalities, which would rule out a classical origin of early universe fluctuations.[16] Or perhaps new physics will be revealed in searches of specific high-energy models and their predictions, such as deviations from Newton's $1/r^2$ force from small extra dimensions.

Obtaining signatures of quantum gravity presents exciting and formidable challenges. Determining whether the gravitational field is truly quantized is one of the most important pieces of information that quantum gravity researchers can obtain in experiments over the coming decades. If evidence is found that gravity is not quantized in the same basic manner as electromagnetism, all the most basic assumptions about the presumed quantum nature of gravity would need to be revisited. That makes it even more pressing to understand what exactly can or cannot be learned about quantum gravity from experiments. **PT**

References

1. A. Einstein, "Näherungsweise Integration der Feldgleichungen der Gravitation" (Approximate integration of the field equations of gravitation), *Sitz. K. Preuss. Akad. Wiss.* (1916), p. 688.
2. J. F. Clauser, "Early History of Bell's Theorem," in *Quantum [Un]Speakables: From Bell to Quantum Information*, R. A. Bertlmann, A. Zeilinger, eds., Springer (2002), p. 61.
3. J. F. Clauser, "Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect," *Phys. Rev. D* **9**, 853 (1974); P. Grangier, G. Roger, A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: A new light on single-photon interferences," *Europhys. Lett.* **1**, 173 (1986).
4. N. H. Lindner, A. Peres, "Testing quantum superpositions of the gravitational field with Bose–Einstein condensates," *Phys. Rev. A* **71**, 024101 (2005).
5. R. Colella, A. W. Overhauser, S. A. Werner, "Observation of gravitationally induced quantum interference," *Phys. Rev. Lett.* **34**, 1472 (1975).
6. R. Weiss, "Nobel lecture: LIGO and the discovery of gravitational waves I," *Rev. Mod. Phys.* **90**, 040501 (2018); B. C. Barish, "Nobel lecture: LIGO and gravitational waves II," *Rev. Mod. Phys.* **90**, 040502 (2018); K. S. Thorne, "Nobel lecture: LIGO and gravitational waves III," *Rev. Mod. Phys.* **90,** 040503 (2018).
7. T. Guerreiro, "Entanglement and squeezing of gravitational waves," *Phys. Rev. D* **112**, L101904 (2025).
8. M. Parikh, F. Wilczek, G. Zahariade, "Signatures of the quantization of gravity at gravitational wave detectors," *Phys. Rev. D* **104**, 046021 (2021); D. Carney, V. Domcke, N. L. Rodd, "Graviton detection and the quantization of gravity," *Phys. Rev. D* **109**, 044009 (2024).
9. D. Kafri, J. M. Taylor, G. J. Milburn, "A classical channel model for gravitational decoherence," *New J. Phys.* **16**, 065020 (2014); S. Bose et al., "Spin entanglement witness for quantum gravity," *Phys. Rev. Lett.* **119**, 240401 (2017).
10. M. Bild et al., "Schrödinger cat states of a 16-microgram mechanical oscillator," *Science* **380**, 274 (2023).
11. T. Westphal et al., "Measurement of gravitational coupling between millimetre-sized masses," *Nature* **591**, 225 (2021).
12. M. Kamba, N. Hara, K. Aikawa, "Quantum squeezing of a levitated nanomechanical oscillator," *Science* **389**, 1225 (2025).
13. C. A. Condos et al., "Ultralow loss torsion micropendula for chipscale gravimetry," *Phys. Rev. Lett.* **134**, 253602 (2025); S. Agafonova et al., "One-milligram torsional pendulum toward experiments at the quantum-gravity interface," *Commun. Phys.* **9**, 80 (2026).
14. D. Carney et al., "On the quantum mechanics of entropic forces," *Phys. Rev. X* **15**, 031038 (2025).
15. A. D. Ludlow et al., "Optical atomic clocks," *Rev. Mod. Phys.* **87**, 637 (2015); M. P. A. Fisher, L. Radzihovsky, "Quantum indistinguishability in chemical reactions," *Proc. Natl. Acad. Sci. USA* **115**, E4551 (2018).
16. J. Maldacena, "A model with cosmological Bell inequalities," *Fortschr. Phys.* **64**, 10 (2016); I. Pikovski, A. Loeb, "Quantum coherent oscillations in the early universe," *Phys. Rev. D* **93**, 101302 (2016).

Markus Aspelmeyer is a professor of physics at the University of Vienna and director of the Institute for Quantum Optics and Quantum Information Vienna at the Austrian Academy of Sciences. **Daniel Carney** is a staff scientist at Lawrence Berkeley National Laboratory in California. Trained as a string theorist, he now works across the theory–experiment intersection.

The pioneering life of

Edward Alexander Bouchet

By Ronald E. Mickens

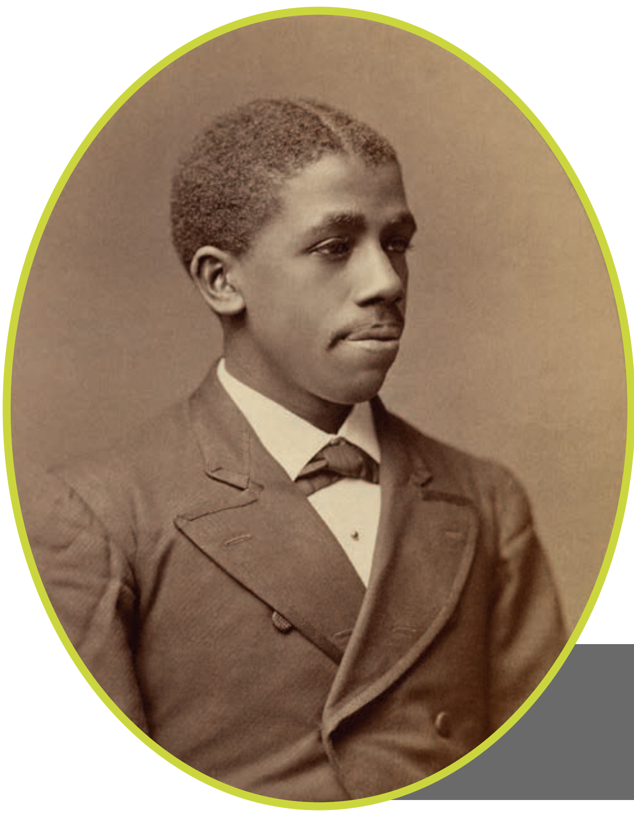
The first African American physicist to earn a PhD made the best of a difficult career path.

Attendees of the 35th reunion of Yale College's class of 1874, pictured in 1909. ➤ Edward Alexander Bouchet is in the second row, third from right. (Image from Yale Classes Photographs, RU 779, Manuscripts and Archives, Yale University Library.)

Edward Alexander Bouchet, born on 15 September 1852 in New Haven, Connecticut, became the first African American to earn a PhD in the US when he completed his doctoral studies in physics at Yale College (now Yale University) in 1876.[1,2] He then spent the next 26 years teaching chemistry, physics, and mathematics at the Institute for Colored Youth (ICY), a Quaker-run private college in Philadelphia,[3] where he established a reputation as an excellent teacher and mentor.

Bouchet resigned from the ICY in 1902 after the institution became embroiled in a national controversy between W. E. B. Du Bois and Booker T. Washington over whether Blacks in the US should focus on collegiate or industrial education.[4] It was a major setback to Bouchet's career: He spent the next 14 years teaching at several high schools and colleges in various parts of the country before retiring for health reasons in 1916 and returning to New Haven, where he died of arteriosclerosis on 28 October 1918 at age 66.[5]

Although Bouchet never formally conducted scientific research after receiving his PhD, he nevertheless maintained a connection to the field through his involvement with scientific societies located in the cities where he worked. This year, 2026, marks the 150th anniversary of Bouchet earning his doctorate, and it is thus an appropriate occasion to look back on his career.



A portrait of Bouchet taken sometime in 1873–74 during his studies at Yale College (now Yale University). (Image from Yale College Class of 1874 Class Album, Yb71 874+ Oversize, Manuscripts and Archives, Yale University Library.)

Early life and college

Bouchet's father, William, was born in Charleston, South Carolina, in 1817 and appears to have come to New Haven at age seven as the enslaved servant of Yale student John B. Robertson.[6] William was emancipated in 1842 and died in New Haven in 1885. Bouchet's mother, Susan, was born as a free Black woman in Connecticut in 1817; she died in 1920, outliving her son. Bouchet was the youngest and only son of their four children. He never married and had no children.[2]

As a child in New Haven, Bouchet first attended the Artisan Street Colored School, which at the time was one of only three schools in the city that accepted Black children. The school's sole teacher, Sarah Wilson, nurtured Bouchet's academic abilities and aspirations. In 1866, he entered New Haven High School, where he spent two years before transferring to Hopkins Grammar School (today Hopkins School), where he graduated as valedictorian in 1870. Hopkins was a prestigious private boys' school that prepared its students in the classics and sciences for entry to Yale.

Bouchet started at Yale that September. During his freshman year, his grade point average was 3.36, with his highest grade being a 3.52 in mathematics. The remainder of his college days were devoted to the study of English, French, German, Greek, Latin, logic, and rhetoric, along with courses in the sciences: astronomy, chemistry, mathematics, mechanics, and physics.

But he did not find Yale to be particularly welcoming. At social events and through to graduation, students sang racist songs and recited racist poems, and Bouchet was unable to join any of the college's famed secret societies because of his skin color.[6] Despite those conditions, Bouchet succeeded academically and graduated summa cum laude in June 1874 as the sixth in a class of 124. Based on his outstanding undergraduate record, Bouchet was selected for membership in Phi Beta Kappa.

Graduate school

Bouchet enrolled in Yale's graduate program in physics in September 1874, an effort that was made possible

Physicist Arthur Williams Wright, Edward Bouchet's PhD adviser at Yale. (Image from W. L. Kingsley, ed., *Yale College: A Sketch of Its History [. . .]*, 1879, p. 431.)

by Alfred Cope,[3] a philanthropist and a member of the ICY's board of managers. Cope probably heard about Bouchet from the scholar's many friends in New Haven, especially those at Hopkins Grammar School and Yale. Cope recruited Bouchet to teach at the ICY but convinced him to remain at Yale to first complete a doctoral degree. Bouchet agreed to do so only after Cope arranged to finance his graduate studies with a $1500 yearly stipend.

In graduate school, Bouchet's research adviser was Arthur Williams Wright,[7] who was one of three Yale students who were awarded the first PhD degrees in the US in 1861. (Wright's PhD was the first in a scientific field.) In addition to taking courses in experimental physics with Wright, Bouchet studied calculus with astronomer and mathematician Hubert Newton and chemistry and mineralogy with mineralogist George Brush. Interestingly, there is no direct evidence that Bouchet had any academic interaction with the contemporaneous Yale physicist who proved to have the biggest historical legacy: Josiah Willard Gibbs.

Bouchet's graduate work focused on measuring indices of refraction,[1,2] which was in line with both Wright's and Brush's interests in gems and mineralogy. Brush had joined the Yale faculty in 1855, first as a professor of metallurgy and later of mineralogy, and immediately began acquiring an extensive research collection of minerals. Later, he was appointed as the first curator of the mineral collection of the Peabody Museum of Natural History, now the Yale Peabody Museum. By the time Bouchet began his PhD, Yale had a vast source of materials at his disposal for his research, in which he used geometrical optics to characterize the physical properties of minerals.

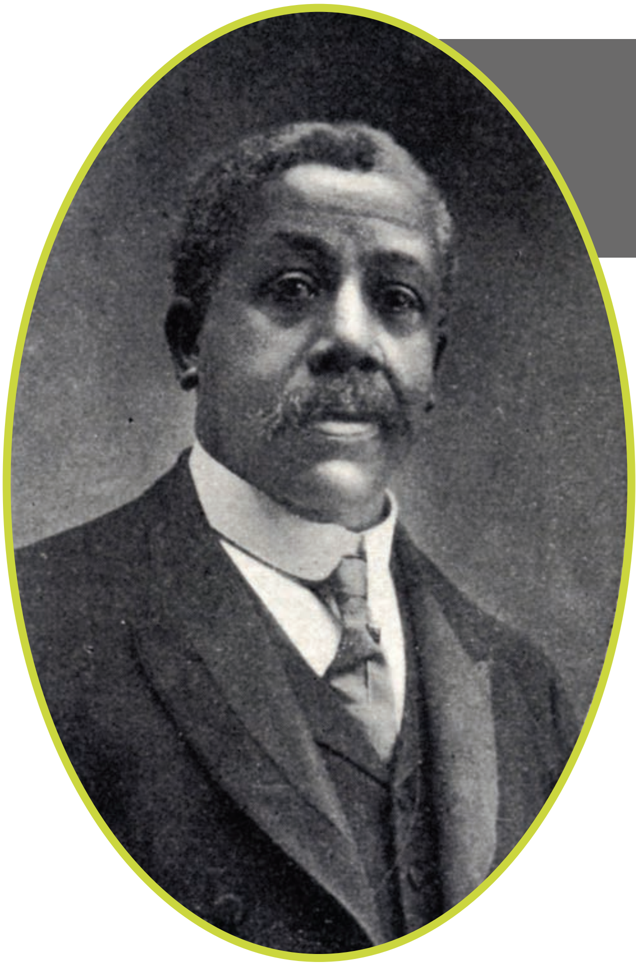
Institute for Colored Youth

After completing his PhD in 1876, Bouchet began teaching that September at the ICY, where he served as the head of its new science program.[2] In that role, he taught courses in chemistry, physics, astronomy, physical geography, physiology, and mathematics. In annual reports to the board of managers, he regularly requested additional laboratory space and equipment for students so that they could carry out experiments. To help both his students and colleagues gain a well-rounded education, he gave lectures on a variety of scientific topics outside his formal work in the classroom.

He also extended those efforts out into the wider community, presenting public lectures at numerous locations, including the church he attended, the African Episcopal Church of St Thomas. Indeed, Bouchet was deeply religious: He was a member of the church's vestry, or governing body; served as church secretary; and was later appointed as a lay reader by the local Episcopal bishop, which meant that he could conduct daily services. Bouchet's involvement in the church was also important because many of Philadelphia's educated, elite African Americans were members of the congregation.

Although Bouchet did not have formal access to any research laboratories, he remained interested in science and kept up with the latest discoveries by becoming a member of two distinguished Philadelphia-based learned societies: the Franklin Institute (now largely known for its science museum) and the American Academy of Political and Social Science. During his time in Philadelphia, Bouchet maintained his ties with Yale through the local chapter of the alumni association.[2,5] He attended many of the chapter's meetings and annual dinners and was readily received and welcomed by the other members.[8]

Around 1900, the ICY became embroiled in a major debate within the Black community. One wing of the Black elite, led by W. E. B. Du Bois, urged the community to prioritize college education for talented individuals at institutions like the ICY. Another, led by Booker T. Washington, argued that in the face of ever-present racism, the community should focus on practical, trade-based education. Ultimately, the board of managers, a



A portrait of Bouchet as an older man, taken circa 1912, which was included in the class book prepared after the 35th reunion of Yale College's class of 1874. (Image from H. W. Farnam, ed., *Biographical Record of the Class of 1874 in Yale College, Part Fourth, 1874–1909*, Tuttle, Morehouse & Taylor, 1912, p. 18; Ybb 874, Manuscripts and Archives, Yale University Library.)

group largely made up of white Quakers, were persuaded by Washington's arguments and decided to change the ICY's classical curriculum to one that emphasized more manual and industrial education.

The ICY closed its Philadelphia building in 1902 and moved to Cheyney, about 40 kilometers outside the city.[3] (Today it is known as Cheyney University of Pennsylvania, and it is the oldest of the US historically Black colleges and universities.) After Bouchet had several heated exchanges with the board of managers, he chose to resign. He was the only ICY teacher or administrator who did not receive severance pay when the institution moved to Cheyney.[1,2]

No destination

Now unemployed, Bouchet began searching for a full-time position. He quickly reached out to two other historically Black institutions: the Hampton Normal and Agricultural Institute (now Hampton University) in Virginia and the Tuskegee Institute (now Tuskegee University) in Alabama. Both institutions replied stating that no teaching positions were available. Their responses were unsurprising: Washington was the president of Tuskegee, and Hampton's leadership was aligned with him in the African American educational dispute. In fact, high-ranking leaders at both institutions had urged the ICY to end its liberal arts educational efforts in Philadelphia and move to Cheyney.

Bouchet was eventually able to find a teaching position—albeit one at the secondary school level—in fall 1902 at Sumner High School in Saint Louis, Missouri, a segregated institution that was the first (and, at the time, only) high school for Black students in the city. However, he left that job after the 1902–3 academic year. From November 1903 to May 1904, Bouchet was the business manager for Provident Hospital, a private medical facility that served the St Louis Black community. That was followed by a position as a US customs inspector at the city's 1904 World's Fair—also known as the Louisiana Purchase Exposition—from May 1904 to March 1905.

Bouchet was again jobless. He returned to his family home in New Haven and decided to see if he could find a job in Yale's physics department. He asked Wright, his doctoral adviser, to recommend him for a position. Wright quickly agreed and wrote to the Yale bureau of appointments, saying that Bouchet had "agreeable personal qualities, gentlemanly manners, and good address" and that he was "eminently well fitted for a Professorship in Physics and Chemistry." Wright closed the letter by stating that he had "entire confidence in Mr. Bouchet's ability and character" and that with his experience, Bouchet "would not fail to be efficient and successful in any position he was called to occupy."[9] Sadly, Wright's efforts were in vain: As far as I am aware, Bouchet never heard from Yale.

Instead, Bouchet eventually landed a job as the director of academics at the Saint Paul Normal and Industrial School, a historically Black college in Lawrenceville, Virginia, in October 1906. He remained there until June 1908. In September of that year, he moved to the town of Gallipolis in southern Ohio, where he became the principal of Lincoln High School, the segregated secondary school for Blacks in the community.

Bouchet remained in Gallipolis for five years, at which point arteriosclerosis forced him to resign his position and again return to New Haven, where his mother cared for him. In about 1914, he accepted a faculty position at Bishop College, a historically Black institution in Marshall, Texas, where he taught science and mathematics. But he was yet again forced to return to New Haven in 1916 for health reasons, and he

remained there until his death in 1918. That same year, Elmer Samuel Imes became the second African American to obtain a PhD in physics, from the University of Michigan in Ann Arbor. (For more on Imes, see my October 2018 *PT* article.)

Legacy

Bouchet never had the opportunity to engage in research after graduating from Yale. He ended up devoting his life to teaching. As he wrote in the class book for his 15th Yale College reunion, “There is every prospect that teaching will be my life-work.”[10] Ten years later, in the book for his 25th reunion, Bouchet wrote that he had “endeavored to discharge my duty as a teacher to those coming under my care, and have aimed to be a good citizen, and to exemplify in my life the mottoes of our Alma Mater.”[11]

It is nearly impossible to assess the influence that Bouchet had on the many people whose lives he touched, all of whom are now long dead. But in 1977, I was fortunate to correspond with Lillian Mitchell Allen, one of Bouchet’s former students during his time as principal of Lincoln High School in Gallipolis:

> I recall hearing my parents … discuss some of the outstanding characteristics of Dr. Bouchet as follows—that he was a fine Christian gentleman, a consummate scholar, one who seemed very knowledgeable in all areas and yet was extremely modest and a person who set a wonderful example of politeness and graciousness for the community.

Allen wrote that when she was in the seventh and eighth grades, Bouchet selected her as the school’s student pianist, which meant that she played for both music classes and at commencement. She ended up pursuing a PhD of her own and became a professor and the head of music education at Howard University in Washington, DC. So it is perhaps unsurprising that more than 50 years later, she saw that as a pivotal moment in her life: “Dr. Bouchet’s selection of me to play for the high school music classes while I was still an elementary school pupil was perhaps one of the contributing factors which caused me to continue my education and achieve the Ph.D. in Higher Education.”[12]

Bouchet’s obituary in his Yale class’s 45th reunion book attests to the impact he had on some of his undergraduate classmates:

> Bouchet came among us at the beginning of freshman year with the prestige of having been valedictorian of his class at Hopkins Grammar School and from the beginning to end of the course was one of our high stand men. He was one of the few among us entitled to wear the Phi Beta Kappa key. … He reflected great credit on his people and demonstrated by his own career their capacity to accomplish worthy things in intellectual fields. In all his associations, both in college and in later life, he showed himself the thorough gentleman. The memory of his quiet scholarly life will long remain as an influence for good among the members of his race and many others who were privileged to know him.[8]

To honor Bouchet’s legacy, several honors, prizes, and awards have been established that acknowledge his contributions to teaching, mentoring, and society. Those recognitions include the American Physical Society’s Edward A. Bouchet Award, which recognizes distinguished minority physicists who have made significant

Ronald E. Mickens at the gravesite of Edward Bouchet, in 2017. The grave was unmarked until 1998. (Image from the AIP Emilio Segrè Visual Archives, Ronald E. Mickens Collection.)

contributions to the field, and the Edward Alexander Bouchet Graduate Honor Society, cofounded by Howard University and Yale University to honor Bouchet's pioneering work in doctoral education and to promote excellence in the academic professoriat. Additionally, as part of the American Physical Society's Historic Sites and Events Initiative—and after a successful nomination from Yale's physics department—a plaque honoring Bouchet was placed on Vanderbilt Hall, one of the two Yale buildings now located on the site of the laboratory where Bouchet did his graduate research.[13]

"Undaunted by enormous odds"

Bouchet was a loner. No significant letters, class notes, or scrapbooks are known to exist; neither is his PhD dissertation. No extant Bouchets can trace their origins back directly to him, for he never married or had children. But his memory still haunts us with the possibilities of what can—and cannot—be accomplished in the face of adversity by individuals of principle who love and seek knowledge. His training, teaching experience, and intellectual interests prepared him to be a potentially outstanding researcher. But he was never given the opportunity to realize that dream. Instead, he led the life of the master teacher and the quiet scholar. His success must be measured by the inspiration that he provided to hundreds of his students.

In the preface to a 1979 report on the status of Black graduate and professional students at Yale, epidemiologist Curtis Patton—at the time, one the few Black faculty members at the university—reflected on Bouchet's experience as the first Black recipient of a Yale PhD:

> Preeminent, humane, undaunted by enormous odds, untouched by self pity, Yale and a young man named Bouchet found their resources and goals compatible more than a century ago. History was made. But no tradition was started.
>
> We may never know the specifics of Bouchet's suppression. We have no documents that give clues to his thoughts on his career. We only know that he lived during a period that can only be called terrible for Black people. His challenges must have been magnificent.[14]

This article is adapted and expanded from my essay "Bouchet and Imes: First Black Physicists," in The African American Presence in Physics, *R. E. Mickens, ed., National Society of Black Physicists (1999), p. 20.* **PT**

References

1. R. E. Mickens, ed., *The African American Presence in Physics*, National Society of Black Physicists (1999), p. 20.
2. R. E. Mickens, ed., *Edward Bouchet: The First African-American Doctorate*, World Scientific (2002).
3. J. Giesberg et al., "History of the Institute for Colored Youth," Falvey Library, Villanova University (ca. early 2015).
4. T. Aiello, *The Battle for the Souls of Black Folk: W. E. B. Du Bois, Booker T. Washington, and the Debate that Shaped the Course of Civil Rights*, Praeger (2016).
5. "Edward Alexander Bouchet, B.A. 1874," *Obituary Record of Yale Graduates, 1918–1919*, Yale U. (1919), p. 919.
6. D. W. Blight, *Yale and Slavery: A History*, with the Yale and Slavery Research Project, Yale U. Press (2024).
7. C. S. Hastings, "Arthur Williams Wright," *Science* **43**, 270 (1916).
8. J. C. Sellers, "Edward Alexander Bouchet," in *Biographical Record of the Class of 1874 in Yale College, Part Fifth, 1909–1919*, Tuttle, Morehouse & Taylor (1919), pp. 81, 83.
9. A. W. Wright, recommendation letter for E. A. Bouchet (9 June 1905), E. A. Bouchet alumni file, box 1042, Alumni Records Office, Yale University, Records of Alumni from the Classes of 1701–1978 (RU 830), Manuscripts and Archives, Yale U. Library.
10. G. L. Dickerman, ed., *Biographical Record with Report of Sexennial and Decennial Meetings of the Class of 1874 in Yale College, Part Second,* A. C. Raymond (1889), p. 13.
11. G. L. Dickerman, ed., *Biographical Record with Report of Quindecennial and Vicennial Meetings of the Class of 1874 in Yale College, Part Third,* Price, Lee & Adkins (1899), p. 14.
12. L. M. Allen to R. E. Mickens (1 February 1977), reprinted in ref. 2, p. 93.
13. A. Cheng, "New plaque honors Edward Bouchet," *Yale Daily News*, 9 April 2017.
14. Ref. 1, p. 24.

Ronald E. Mickens is the Distinguished Fuller E. Callaway Professor Emeritus of Physics at Clark Atlanta University in Georgia. A mathematical physicist by trade, he has also published several articles and monographs on the history of Black scientists.

Visa and Immigration Policy: What's Changing?

- Global talent has long powered U.S. science and engineering
- Shifting policies are reshaping that foundation
- Access our policy guide for the latest developments in this changing landscape

Scan for more in-depth information

AIP

Undergraduate students grapple with an uncertain future

Shannon Clardy, Brad Conrad, and Matthew Wright

Apprehension about career pathways and research funding dominated the list of concerns expressed by physics and astronomy undergraduates in a recent survey.

(Design by Masie Chong with artwork adapted from iStock.com artist Yutthana Gaetgeaw.)

It is an understatement to categorize the past year as a period of significant upheaval for STEM students. Recent changes in science policy have introduced grant retractions, funding cuts,[1] and a marked reduction in graduate program admissions. (See, for example, *PT's* 2025 news stories “Physics, astronomy graduate admissions in the US expected to shrink amid funding uncertainty” and “Funding uncertainties muddle graduate admissions.”) Compounded by the rapid integration of AI and automation, both the physical sciences labor market and the standard physicists' and astronomers' toolkit are shifting. Those developments are fundamentally altering how students and early-career scientists perceive their professional viability.

To evaluate the concerns of the next generation of scientists, the Society of Physics Students (SPS) and Sigma Pi Sigma, organizations of the American Institute of Physics (AIP, publisher of *Physics Today*), conducted a survey last year at the Physics and Astronomy Congress, the largest conference for undergraduate physics and astronomy students. Echoing the surveys that had been conducted at the 2016, 2019, and 2022 congresses, the 2025 survey asked undergraduates to identify the two most important issues currently facing students.

The series of surveys provides a unique pulse check on the concerns of undergraduates in the physical sciences. The last decade of data, shown in the table on page 43, reveal a shifting landscape of student anxiety. In 2016, respondents expressed the most concern over field diversity and impostor syndrome (also known as impostor phenomenon, self-doubt despite evidence of success), whereas in 2019, respondents' concern about mental health had grown sharply. By 2022, students identified burnout as a critical systemic hurdle. (For Conrad and Wright's summary of the 2022 survey findings, see their 2023 *PT* article “Helping the pandemic generation.”)

The most recent data show that the focus has shifted again. Today's students are increasingly stressed by the overarching uncertainty of science's future. One student noted, for example, “the feeling that there aren't enough jobs and that most will be unemployed or forced to work outside the field.” The convergence of fiscal instability, uneasiness about physics and astronomy as a viable career path, and technological disruptions risks a significant brain drain as students may pivot away from research toward more stable or lucrative majors and roles.

An uncertain outlook

The latest survey was administered after students at the conference had discussed their individual concerns in small groups. The survey was completed by 483 students. The first question asked students to identify the two most important issues facing them, their physics and astronomy clubs, and their colleagues. Students couldn't select more than two. As shown in the table, the top five concerns were physics or astronomy as a career, research funding, burnout, impostor syndrome, and science in politics.

Valuable insights were also gained from students' open-ended responses expanding on what they felt was the most important issue facing them and their peers. Across nearly all responses, students described a shared feeling of uncertainty about the future despite strong motivation and love for physics and astronomy. Survey data reveal five pervasive concerns:

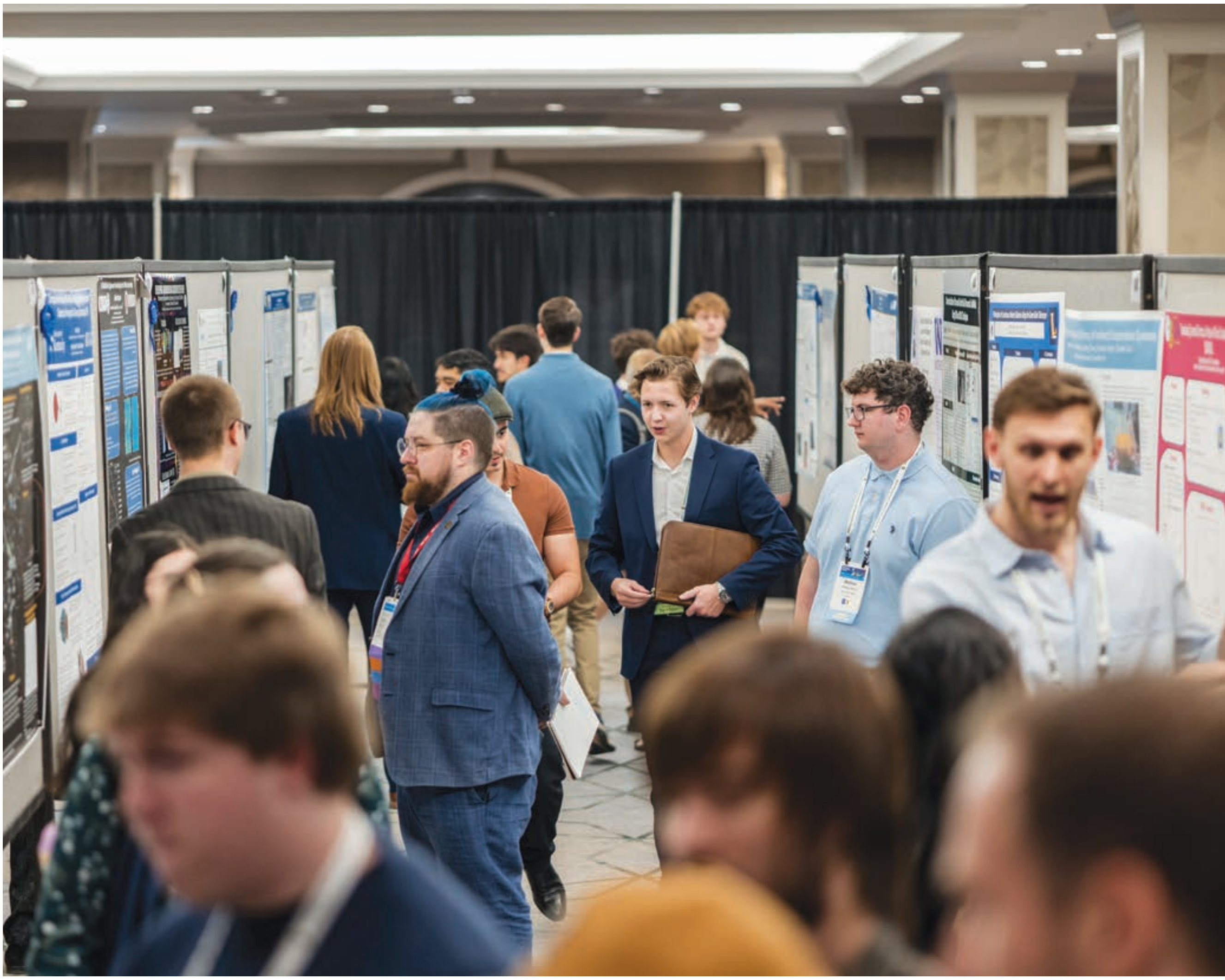
Doubt driven by funding instability. Students overwhelmingly identified unstable funding as a root cause of concern about internships, graduate admissions, and long-term careers, with 31% of respondents selecting research funding among their top two concerns. Many students said that they perceive physics as an elite, shrinking field where opportunity depends more on timing or funding than on merit. For example, one student said,

	Percent who selected response			
	2016	2019	2022	2025
Physics/astronomy as a career	14.9	15.4	16.4	34.0
Research funding	21.6	16.6	8.6	31.1
Burnout	5.4	—	40.8	19.5
Impostor syndrome	25.3	29.6	23.0	16.1
Science in politics	1.5	8.6	4.8	15.1
Professional development	7.1	7.6	7.4	12.0
Graduate school options	7.5	7.0	3.2	12.0
Mental health	5.9	27.8	24.8	8.3
College administration support	—	13.2	11.8	7.7
Support network	9.4	11.6	8.4	7.7
Field perception	1.5	11.2	8.8	7.7
Physics and astronomy outreach	—	—	7.2	6.6
Curriculum	6.1	7.6	6.4	6.2
Field diversity	28.0	16.6	11.0	5.6
Field inclusiveness	22.4	15.8	6.4	4.3
Access to instructors	1.0	3.2	4.8	2.1

Percentage of surveyed students who chose each issue as one of the top two that are facing physics and astronomy students. Surveys were conducted at Sigma Pi Sigma's triennial Physics and Astronomy Congress between 2016 and 2025. Results are shaded according to their rank on the list, with the most chosen answers for a given year in green and the least chosen answers in red. Dashes indicate that a response option was not available that year.

"Students are expected to do internships, REUs [Research Experiences for Undergraduates programs], research, conferences, presentations, et cetera, et cetera, to even have a shot at graduate school or a career, but with so much uncertainty in funding, this makes these opportunities inaccessible for most, if not all, students." Widespread reductions in funding for graduate students and basic science have led to shrinking research opportunities, department closings, and a decreasing number of graduate seats. Many students reported that anti-intellectualism is directly threatening the future of science.

Severe career uncertainty. Many students reported insufficient preparation for pursuing career paths outside of academia. Though most recipients of physical sciences bachelor's degrees end up in the private sector, students said that they feel unprepared to translate their skills to industry, that they lack career pathway exposure, and that they see graduate school as both the only option and increasingly unattainable. One student wrote, "I think that as of today many physics students are worried about finding viable careers. It seems that every job that a physics major applies to requires a PhD or postdoc, leaving many of us who desire to enter industry feeling like backup options to engineering or data science majors." The percentage of surveyed students who chose "physics/astronomy as a career" as the most important issue they are facing more than doubled—from around 15% in 2016 to 34% in 2025—a reflection of how anxious undergrads are about what comes after graduation.



Students at the 2025 Physics and Astronomy Congress in Denver, Colorado. (All photos in this article are from the 2025 congress, courtesy of AIP.)

Burnout, mental health strain, and impostor syndrome. High expectations and competition in research, internships, coursework, and leadership amid shrinking opportunities are producing widespread burnout, anxiety, and loss of confidence, students reported. Students did not frame those struggles as personal weakness but as a consequence of unrealistic norms, inadequate support, and constant pressure to compete in an increasingly constrained system. Many students questioned whether they belong or whether their efforts will ever be enough. Those issues have been present in the four cohorts studied. (For an analysis of the mental health issues faced by physics and astronomy PhD students, see the April 2026 *PT* article "Building graduate programs that support mental well-being," by Patrick Banner, Kellen O'Brien, and Chandra Turpen.)

Inequitable access, lack of advising, and declining inclusivity. Students from small institutions, rural areas, community colleges, low-income backgrounds, other countries, and marginalized groups reported fewer opportunities, inferior advising, and less support than students with more resources or from overrepresented groups. Many said they feel isolated, unheard, or unsupported.

Many students reported a feeling that inequality is increasing and that there is strong retrograde motion against recent gains in inclusivity. (To read about alternative course structures aimed at reducing barriers for physics students, see *PT's* October 2025 article "Reframing the narrative on physics readiness," by Suzanne White Brahmia and Geraldine L. Cochran.)

Erosion of trust in the educational model. Students expressed concern that AI is undermining learning, academic integrity, and critical thinking and that curricula feel disconnected from jobs and societal needs. Many questioned whether their education prioritizes grades and abstraction over understanding, applicability, community, and joy, and that prioritization led students to doubt whether getting a degree is worth it. It was not clear to students whether AI will be beneficial in their future careers.

Though students articulated many concerns, they also demonstrated commitment to problem-solving and a love of discovery. After completing the initial survey individually, students at the conference broke into groups based on their geographic regions and discussed their strengths, concerns, and ideas for solutions. Students from around the country felt they had persistence, perseverance, grit, and resilience. They demonstrated hopefulness, resolve, and a sense of community. Students were deeply interested in helping their colleagues and expressed a need for tangible actions to address the challenges they face.

When prompted with the question, "If you could ask the greatest minds in the world to solve one problem that you've talked about today, what would it be?," students synthesized their concerns into actionable focus areas. Brainstorming sessions revealed a sophisticated understanding of the scientific ecosystem. Rather than requesting passive aid, students proposed solutions rooted in advocacy and communication.

Many proposals focused on restoring public trust in science through grassroots outreach, improving science lobbying, and making complex research more accessible to the layperson. By framing science communication as a solution to fiscal instability, students demonstrated a clear resolve to bridge the gap between the

laboratory and the public sphere. The exercise generated significant, actionable ideas for academic departments. The ideas included engaging with alumni, promoting the full variety of career paths for physics and astronomy students, strengthening connections between courses and industry skills, and highlighting options other than graduate school, since about half of undergraduates go straight into the workforce.

Path forward: Using community resources

The survey confirmed that physics and astronomy undergraduates remain exceptionally bright and eager but are profoundly troubled by the current state of science and a perceived scarcity of career pathways. Though our field excels at solving technical problems, those social and systemic challenges are directly affecting student retention and mental health.

Fortunately, our community has already developed robust, research-validated resources to address those challenges. We urge departments to integrate the following resources into their undergraduate programming:

Effective Practices for Physics Programs (EP3).[2] The EP3 guide provides a framework of effective practices for physics departments. It was developed and reviewed by experts in the physics community under the auspices of the American Physical Society and American Association of Physics Teachers. Beyond curricula, the guide provides evidence-based techniques for student retention and departmental health. It is an essential toolkit for all departments. (For more about the EP3 guide, see the 2025 *PT* article “Helping physics departments thrive,” by David Craig, Michael Jackson, and Theodore Hodapp.)

TEAM-UP report.[3] The TEAM-UP findings on belonging, physics identity, academic support, personal support, and leadership provide a blueprint for supporting all students who are marginalized or uncertain about their place in the field.

SPS Careers Toolbox.[4] This comprehensive, step-by-step guide is designed to help students transition from the classroom to professional roles. It demystifies the job search process for those not pursuing the traditional academic route.

Proactive steps that departments can take to support students include the following:

More career education. Physics and astronomy graduates remain in high demand in fields including quantum science, medical physics, robotics, additive manufacturing, biomanufacturing, semiconductors, cybersecurity, and data science. By highlighting high-growth areas, departments can help students more easily connect their skill sets to a wide variety of career paths. Faculty can host speakers who have common career paths, such as those who work in industry and advanced manufacturing.

Strengthening industry ties. Academic and industry leaders must collaborate to teach career-relevant knowledge, skills, and abilities for future-looking occupations. The academic community benefits from building internships, research experiences, and co-ops, and the community at large should work together to make those opportunities available. Participating in industry-led organizations focused on technology adoption and workforce training can help faculty accelerate course development and student placement in technology sectors.

Advocacy and agency. Encourage science advocacy. Writing letters to policymakers, engaging in science communication, and participating in outreach are some of the many ways that students can improve their self-efficacy and have a sense of control.

The physics and astronomy community is not powerless to address the concerns of students. Scientific research is undeniably affected by a dynamic funding landscape. But professors, department staff, industry leaders, government lab personnel, and the national science societies can take action to help students feel confident in their choice to study physics and astronomy. Though students are currently feeling the weight of macroeconomic uncertainty, we must reassure them that they have indisputable skills that are applicable across broad sectors. By providing the right tools, mentorship, and perspective, we can ensure the next generation of scientists moves from a state of apprehension to one of empowered discovery. **PT**

References

1. J. Mervis, "Exclusive: NSF director to resign amid grant terminations, job cuts, and controversy," *Science*, 24 April 2025.
2. S. B. McKagan et al., eds., "A Guide to Effective Practices for Physics Programs," American Physical Society (2021).
3. AIP National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy, *The Time Is Now: Systemic Changes to Increase African Americans with Bachelor's Degrees in Physics and Astronomy*, AIP (2020).
4. American Institute of Physics Career Pathways Project, *Careers Toolbox for Undergraduate Physics Students & Their Mentors*, 4th ed., AIP, SPS (2017).

Shannon Clardy is dean of the Caver College of Aviation, Science, and Nursing at Henderson State University in Arkadelphia, Arkansas, and a co-chair of the Executive Program Committee planning the 2028 Physics and Astronomy Congress. **Brad Conrad** is a member of the Executive Program Committee for the 2028 Physics and Astronomy Congress and was also on the committee for the 2025 congress. **Matthew Wright** is chair of the physics department at Adelphi University in Garden City, New York. He was a member of the 2025 Physics and Astronomy Congress's Executive Program Committee.

WHAT CAN PHYSICISTS DO?

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

Janine Abyad
oversees airport infrastructure projects

By Toni Feder

Lead civil engineer, Federal Aviation Administration New York Airports District Office

BS, physics, Rowan University, 2014
MS, civil engineering, Rowan University, 2016
Master of engineering management, Rowan University, 2022

How did you figure out what you wanted to do?

I liked physics until we got to the more complex and theoretical part in upper-level classes. I knew I liked practical, hands-on research. I spoke to the engineering department at Rowan and they suggested I look into civil engineering. I began speaking to professors and learned that I could lead my own research project. For my master's, I studied nonnuclear alternatives to the nuclear-density-gauge method for pavement acceptance testing. I was looking into comparable devices that would avoid radiation exposure, inaccuracies, and the need for specialized training.

(Photo courtesy of Janine Abyad.)

How did you get into airport design and construction?

During my master's studies, a classmate told me that their company was hiring civil engineers. The company was providing engineering contract support in pavement R&D for the Federal Aviation Administration. I got hired and was part of a team that collected and analyzed data for nondestructive pavement testing.

I moved to the FAA New York Airports District Office as a civil engineer in 2019. I was responsible for managing and implementing federal airport infrastructure grants for airports in New York state.

How do you spend your time?

Now, instead of R&D, I do design, construction, and grant management for airport infrastructure projects. I've been a part of terminal improvements, runway and taxiway rehabilitations, extensions, and more. While working, I went back for a second master's degree in engineering management.

When I started at the FAA, I was a civil engineer. In 2023, I got into airport compliance work, adjudicating complaints from airport tenants. It was interesting, but I missed the technical work. Recently, I returned to my civil engineering position.

What do you like about your job?

I get to use both my technical skills and my people skills.

How do you use your physics background?

The ability to think through ideas in different ways to resolve an issue. My physics background also gives me credibility.

What new skills did you need when you started working?

Being able to work with people who have different skill sets and learning to communicate effectively with everyone from lab techs to PhDs, other engineers, and managers. PT

Read more interviews in the series at https://physicstoday.org/wcpd.

How human hearing is shaping high-end audio

Insights into how the auditory system processes time and information are guiding audio design beyond traditional measures of fidelity.

By Milind N. Kunchur

Designers of high-end audio systems strive to reproduce music with a realism that transports the listener to a concert hall by conveying the depth, height, and width of a musical performance. But from a physical perspective, certain design choices for those systems may seem extreme.

Some marketing materials, for instance, claim that listeners can perceive microsecond timing information in the sound with high accuracy and with little contamination from the equipment. The conventional upper frequency limit of human hearing, however, is 20 kHz. If you apply the familiar reciprocal relationship between time and frequency, that limit suggests that the human ear should be capable of perceiving time information with a maximum resolution of 50 µs.

Such expectations of perception limitations arise in part from the extension of familiar physics concepts beyond the regimes in which they apply and from incomplete models of the neurophysiological mechanisms that underlie auditory perception. Indeed, the fine temporal and information resolution of human hearing is reshaping the understanding of how sound is perceived and how it needs to be reproduced to achieve the highest-fidelity listening experience.

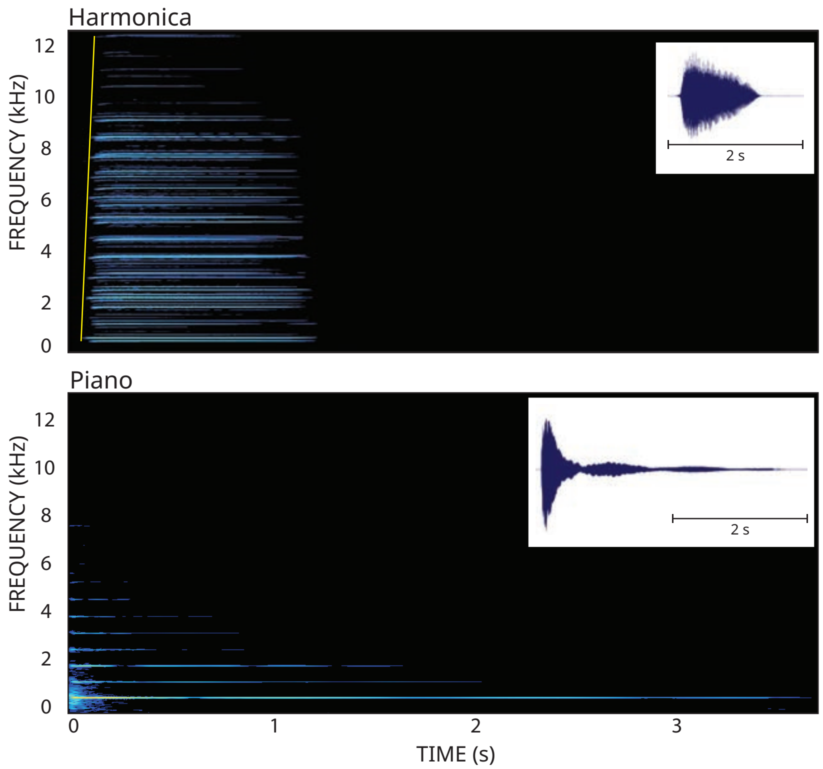


Figure 1. Spectrograms of a harmonica and a piano for the note E_5 show the time evolution of different frequency components of the sounds. The insets show the corresponding waveforms. The time-domain information in the plots is critical for how people perceive the different tonal qualities of the two sounds. The sloped line on the harmonica spectrogram is included to accentuate how the partial frequencies above the fundamental begin at progressively later times at higher frequencies.

Temporal precision

Audio engineers tend to think of musical sounds primarily in spectral terms. They evaluate equipment mainly using measurements such as the frequency response—the audio signals' output-to-input ratio as a function of frequency—and distortions that modify the output spectrum. Those measurements, however, do not provide a complete description of how people perceive sound.

Other properties of acoustic signals, particularly time-domain characteristics, are also important. A musical note is described by four perceptual attributes: pitch, duration, loudness, and timbre (its tonal quality). Reproducing pitch is relatively

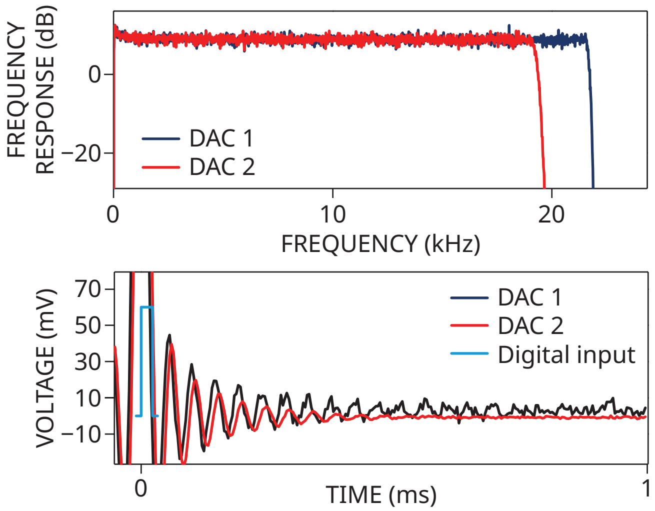


Figure 2. The frequency response **(top)** and impulse response **(bottom)** of two digital-to-analog converters (DACs). Although DAC 1 has a wider frequency bandwidth, its impulse response exhibits higher-intensity noise that persists for at least 1 ms. In listening tests, DAC 2 had higher perceived musical fidelity than DAC 1.

trivial—audio systems rarely struggle to get the notes right. The challenge is in faithfully reproducing timbre, and that's where time-domain behaviors are especially pertinent.

Figure 1 shows spectrograms of a harmonica and a piano playing the note E_5 (the second E above middle C). Compared with the harmonica's spectrogram, the piano's has fewer partials, which are the harmonics and other frequencies above the fundamental of the note, here approximately 659 Hz. Certain temporal differences are more influential than spectral differences for the perception of timbre. The piano's partials start almost simultaneously, whereas the harmonica's partials begin at progressively later times at higher frequencies. As the waveforms in the insets show, the piano produces a more impulsive, faster-rising note than the harmonica does.

The importance of temporal structure for timbre can be illustrated by time reversing a note, which alters the timing without changing the time-averaged spectrum. The video "Time reversing a piano note" (see the online article for the link) demonstrates that a time-reversed piano note sounds like a markedly different instrument—closer to a harmonica. The sensitivity to temporal structure is why high-end loudspeakers strive to provide microsecond synchrony. Multidriver loudspeakers can be time aligned, for example, so that the wavefronts from the different frequency bands of a sound arrive at the listener's ear together.

So how does human hearing encode cross-frequency synchrony, which makes a piano sound like a piano, and with what precision? Let's take a brief tour of the auditory system. Sound vibrations first enter through the outer ear and eventually reach the inner ear's cochlea. There, the vibrations excite the basilar membrane, whose tapered structure gives rise to tonotopic tuning: Different frequencies are mapped to different positions along its length. About 3500 groups of hair cells distributed along the membrane convert the mechanical motion to electric signals that auditory nerve fibers transmit as spike trains to the brain. The arrangement acts as a 3500-channel spectrum analyzer.

Sharp, impulsive sounds, such as piano notes, produce bursts of activity across widely separated frequency channels. Those nearly simultaneous onsets are detected in the brain by octopus neurons, which receive input from many auditory nerve fibers and function effectively as coincidence detectors. Octopus neurons are sensitive to the sharpness of temporal onsets, which is an important cue for perceiving timbres.

Neural analyses by myself and others suggest that a person's transient auditory response has a resolution of about a microsecond. That's consistent with several psychoacoustic experiments. The findings indicate that the pursuit of microsecond-level transient response—and the associated ultrasonic bandwidths that extend beyond 20 kHz—in high-end audio components may be justified, even if they are often regarded as unnecessary in conventional audio engineering.

Information resolution

In digital audio recording, standard 16-bit and 24-bit formats encode each sample at a rate of 44–192 kHz with 2^{16} (about 66 000) and 2^{24} (about 17 million) levels, respectively. Hearing, however, is not based on a single scalar measurement at each instant. Instead, sound is encoded in a distributed pattern of activity across roughly 3500 frequency channels in the cochlea and about 30 000 auditory nerve fibers.

Each cochlear channel senses a range of frequencies, and a channel's range overlaps with about 100 neighboring channels. The overlap, which aids in capturing a sound's dynamic range and temporal definition, can be represented approximately if you group the frequency spectrum into 40 equivalent rectangular bandwidths. Even if you adopt a conservative estimate of 10 distinguishable states per bandwidth, the number of possible instantaneous excitation patterns is about 10^{40}.

The vast information-resolving capacity of human hearing poses an extraordinary technical challenge for audio systems. In complex sounds, such as a symphony performance, listeners can perceive subtle details, including the distinct timbres of dozens of individual instruments, their low-order reflections, and reverberation tails that linger from notes that were played seconds earlier.

The faint, temporally structured remnants of sounds are referred to collectively as low-level detail, and preserving it is critical for reproducing music with the realism of a live performance. In audio components, those subtle temporal features are often smeared by the equipment's lingering decays, such as post-transient ringing in loudspeakers and digital-to-analog converters (DACs), that persist after the signal has ceased.

To mitigate such decays, some high-end speakers have radiating components made of diamond or sapphire. Their high rigidity-to-mass ratios enable a faster and more controlled return to equilibrium. Some manufacturers now specify a cutoff time that characterizes when signals' ringing and other remnants decay completely. The transient response time and the cutoff time provide a more complete predictor of perceived fidelity.

Figure 2 plots the frequency and impulse responses of two DACs, which allow music stored in a digital format to be played through analog speakers. The first DAC has an extended frequency response and a slightly sharper impulse peak than the second, but it exhibits residual ringing that persists for at least 1 ms. The second DAC shows a clean cutoff after 0.5 ms, which better preserves low-level detail. In tests, listeners perceived a higher-fidelity response from the second DAC, illustrating the importance of balancing frequency-domain performance with time-domain behavior.

Optimizing the transient response and the cutoff time of high-end audio equipment can lead to materials and designs that, at first glance, appear overengineered or superfluous. Yet those efforts help preserve the fine temporal structure of sound that underlies how the human auditory system perceives timbre and spatial information. The result is a convincing 3D auditory scene, rather than the illusion of instruments sitting on a line like birds on a wire.

PT

Additional resources

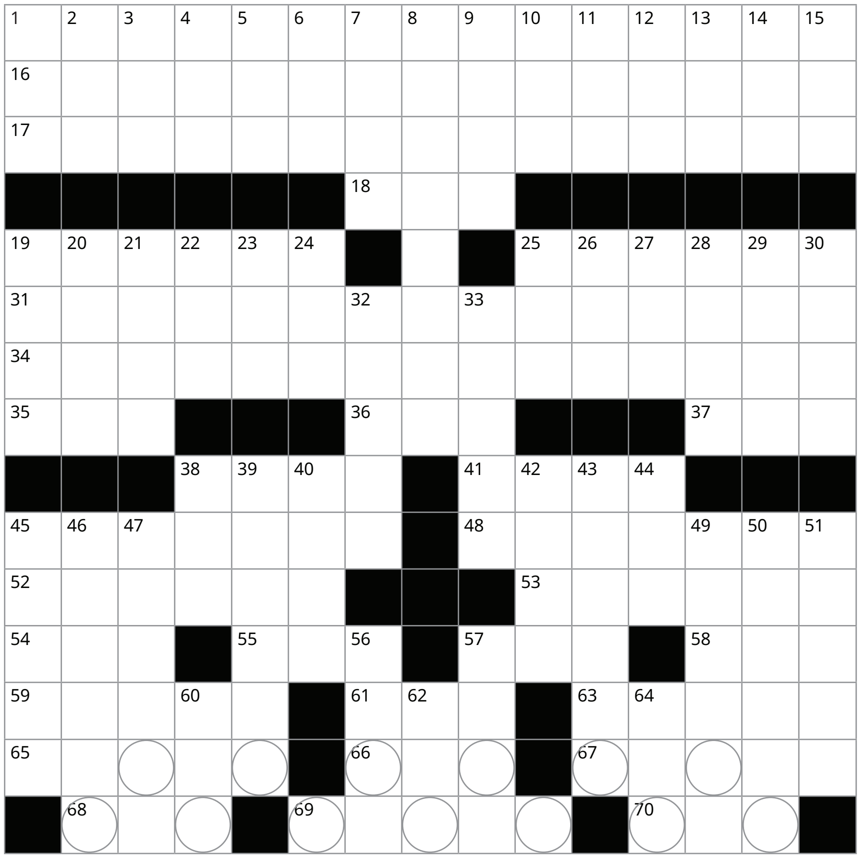
- M. N. Kunchur, "The human auditory system and audio," *Appl. Acoust.* **211**, 109507 (2023).
- D. Oertel, R. R. Fay, A. N. Popper, eds., *Integrative Functions in the Mammalian Auditory Pathway*, Springer (2002).

Milind N. Kunchur is a physics professor at the University of South Carolina in Columbia (www.kunchur.org).

CROSSWORD

Fringe benefits

By Doug Mar



ACROSS

1 Samoan or Fijian
16 Polite request for time
17 Body of water that contains Alcatraz Island
18 Medium with a refractive index equal to 1.0003
19 Internet browser with a compass logo
25 Capital of the Bahamas
31 Field in which you might study fields
34 Football competition recently won by Paris Saint-Germain
35 The Sun Devils' sch.
36 Nonacademic degree?
37 2013 sci-fi romantic drama starring Joaquin Phoenix
38 Behavior of light that generates the structure spelled out in this puzzle's circles
41 Org. that sends you a card for your 50th birthday
45 Type of penguin
48 Iconic 2000 Super Bowl beer ad (var.)
52 Type of current produced by solar cells
53 Useless
54 Prefix with metric and bar
55 Chop
57 What a tournament seed might start out with
58 Sports org. with a five-ring logo
59 That and that
61 Pugilists' grp.
63 The part of DOD that developed GPS
65 More secure
66 It's not free of charge
67 Color for which human eyes have their peak sensitivity
68 "Don't text and drive" ad, e.g.
69 Give 10% to the church
70 Kylo ___ of *Star Wars*

DOWN

1 Opposite of neg.
2 Santa ___ winds
3 100 yrs.
4 It's carried by the solar wind and can trigger auroral activity (abbr.)
5 In favor of
6 "___ Believer" (Monkees hit)
7 Wrestler-turned-actor John
8 Kind of photon that travels toward a location where something happens (see also 38-Across)
9 Bar found in a chemistry lab
10 33⅓ rpm discs
11 Abbr. that appears on wine bottles
12 Sci-fi character whose name anagrams to "one"
13 Little bit, as of ointment
14 User of Ariane launch vehicles, for short
15 Spanish king
19 Agcy. that promotes pet adoptions
20 Sounds of contentedness
21 Herr's wife
22 It's equal to about 15 psi
23 Tear
24 *Vous êtes* ___ (French map notation)
25 Org. where an amateur might fill in for an injured goalie
26 Yes vote
27 Fed. benefits agency
28 Sound of resignation
29 Take ___ from
30 ___-friendly
32 Recluse
33 "Phooey!"
38 ___ Willie Winkie
39 Sagittarius, with "the"
40 Do one's civic duty
42 Greeting at sea
43 Suitable for all moviegoers
44 Greek letter often used to denote the wavefunction
45 Uses CRISPR
46 Unlucky accident
47 Prepublication copies
49 Evening party
50 Major tournament in golf or tennis
51 Butter ___ (ice cream flavor)
56 Conflict that spurred the Manhattan Project (abbr.)
57 ___ mi (Vietnamese sandwich)
60 Environment of the ORCA neutrino detector
62 It might chat or send spam
64 Timetable abbr.

See the solution online at https://physicstoday.aip.org/news/crossword-fringe-benefits

A collider conversion

By Laura Fattaruso

(Image courtesy of Brookhaven National Laboratory/CC BY-NC-ND 2.0)

To submit candidate images for Back Scatter, visit https://contact.physicstoday.org.

The Relativistic Heavy Ion Collider (RHIC), at Brookhaven National Laboratory in Upton, New York, completed its 25th and final run of particle collisions in February. Shown at the top of this aerial image, the 3.8-km-circumference tunnel that contains two ion storage rings used for RHIC will be converted into the Electron–Ion Collider, a facility for studying the strong nuclear force. The project is expected to cost $2.8 billion, and the collider is slated to begin science operations by the mid 2030s. Engineers plan to make use of RHIC's ion source and one of its large ion storage rings, while adding an electron source and accelerator and replacing one of the large ion storage rings with an electron storage ring.

The last run at RHIC, like its first in 2000, began with experiments that entailed smashing together beams of gold nuclei at nearly the speed of light. Those high-energy collisions were designed to melt protons and neutrons into a quark–gluon plasma like the one that likely formed just microseconds after the Big Bang. Researchers announced in 2005 that RHIC experiments had shown that quark–gluon plasma behaves as a frictionless liquid rather than exhibiting the gaseous behavior that had been theorized prior to measurements.

During the 30 weeks of the final run, one of RHIC's detectors, sPHENIX, captured some data continuously rather than through the typical approach of taking targeted snapshots of collisions. The run generated over 200 petabytes of raw data—more than had been collected in all previous RHIC experiments combined. PT


N4150