Berkeley Physics

Leading the Way for Quantum Research

In this issue:

From the Chair

The Berkeley Physics family continues to probe the universe at its most micro and macro corners without fail. In this issue, we highlight some of the latest advancements in quantum information science where we seek to transform the quirky thought experiments proposed in the last century into trailblazing technology that is poised to revolutionize communication, computation, and sensing. What's remarkable about quantum mechanics is that it touches so many aspects of the physical sciences—in this case we have a collection of condensed matter, atomic, and high-energy physicists discussing the power of quantum entanglement with a common scientific language.

Entanglement is a key element of how the fabric of the universe may be intricately woven with threads of mass and energy. However, not all those threads are visible, and the search for dark matter continues. As Professor Ben Safdi explains, we may be very close to a turning point in this nearly century-old saga, with scientists either finding axions which couple ever so weakly to the world around us, or it may be time to go back to the drawing board.

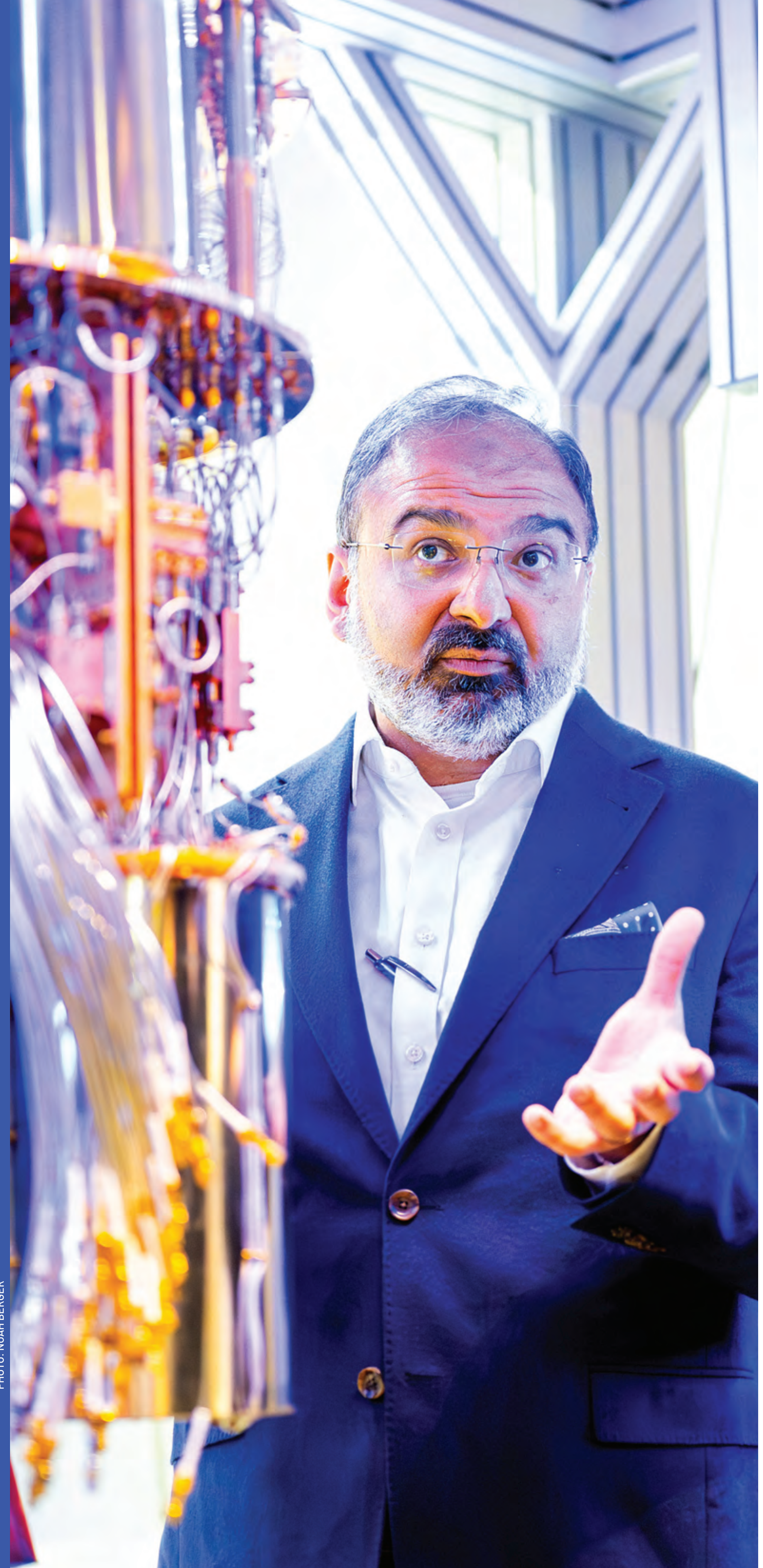
While some probe the fabric of the universe at the cosmic scale, Professor Steve Louie and his colleagues around the world are reincarnating the two-headed Roman god Janus in nanoribbons of graphene—this particular deity has novel magnetic properties which can be precisely engineered by mortals. Carbon also enters this issue of the magazine in a much more ordered form with diamond-based sensors setting new sensitivity records.

This year also marked the passing of many close colleagues, and we will celebrate their contributions throughout the semester. The cycle of life continues, and we are ecstatic to have our newest faculty members in our halls, and new lights shine bright as they explore science careers. In times where the value of basic research is constantly being put under a microscope, we are very fortunate to be a thriving nexus of intellectual excellence. We are thankful to our large extended family of supporters who remain committed to science. This year will mark the inauguration of the Leinwber Institute for Theoretical Physics—we are all so very excited.

With that, I extend my best wishes for our collective success in the 2025-2026 academic year.

Irfan Siddiqi, Chair

PHOTO: NOAH BERGER



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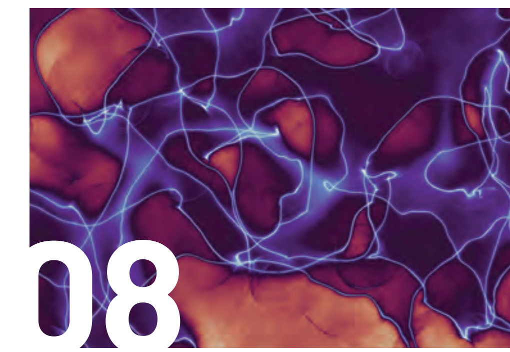
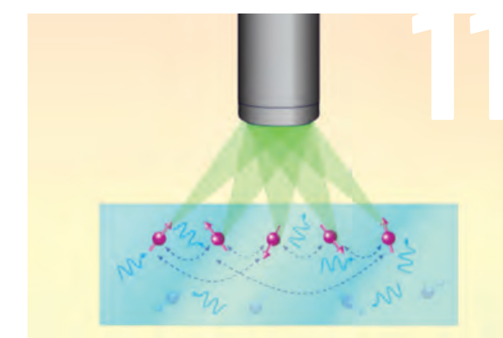




Leading the Way for Quantum Research

From table-top experiments to theories about the universe, Berkeley Physics guides diverse efforts in quantum information science

A century ago, science went quantum. In recognition of the progress made since this initial development of quantum mechanics, 2025 is being celebrated as the International Year of Quantum Science and Technology.

According to the quantum view of nature, matter absorbs energy in tiny discrete packets. And seemingly disconnected objects can be entangled, their properties correlated by intangible links—even if they are light years apart.

Initially, quantum mechanics was something specialized physicists thought about, including posing philosophical questions like whether Schrödinger's quantum cat is simultaneously dead and alive. Beginning in the 1970s, however, these theories were tested by experiments that proved entanglement is real and fundamental to nature. The first definitive proof of quantum spookiness took place experimentally in Birge Hall and was recognized by the 2022 Nobel Prize in Physics. Since the 1990s, lots of quantum research focuses on how to develop quantum technologies.

"Quantum mechanics has transformed from a philosophy to an engineered product—that's a very big deal," says Irfan Siddiqi, Berkeley Physics professor and chair. "Bringing these technologies to the market to change our everyday world requires people from industry, academia, and venture capital to come together. Berkeley is at the center of this convening effort, because it offers a unique entrepreneurial ecosystem with broad and diverse efforts in quantum information science."

Cutting-edge researchers at Berkeley Physics lead investigations of all competing technologies for creating and manipulating qubits, the basic unit of information in quantum computing—including research on cold atom arrays by Professor Dan Stamper-Kurn, superconducting circuits by Siddiqi, trapped ions by Professor Hartmut Haeffner, and advanced quantum materials by various faculty. Berkeley also has world-leading theoretical physicists such as Professor Raphael Bousso, mathematicians, and computer scientists exploring fundamental aspects of quantum information. We highlight only a few of these efforts here.

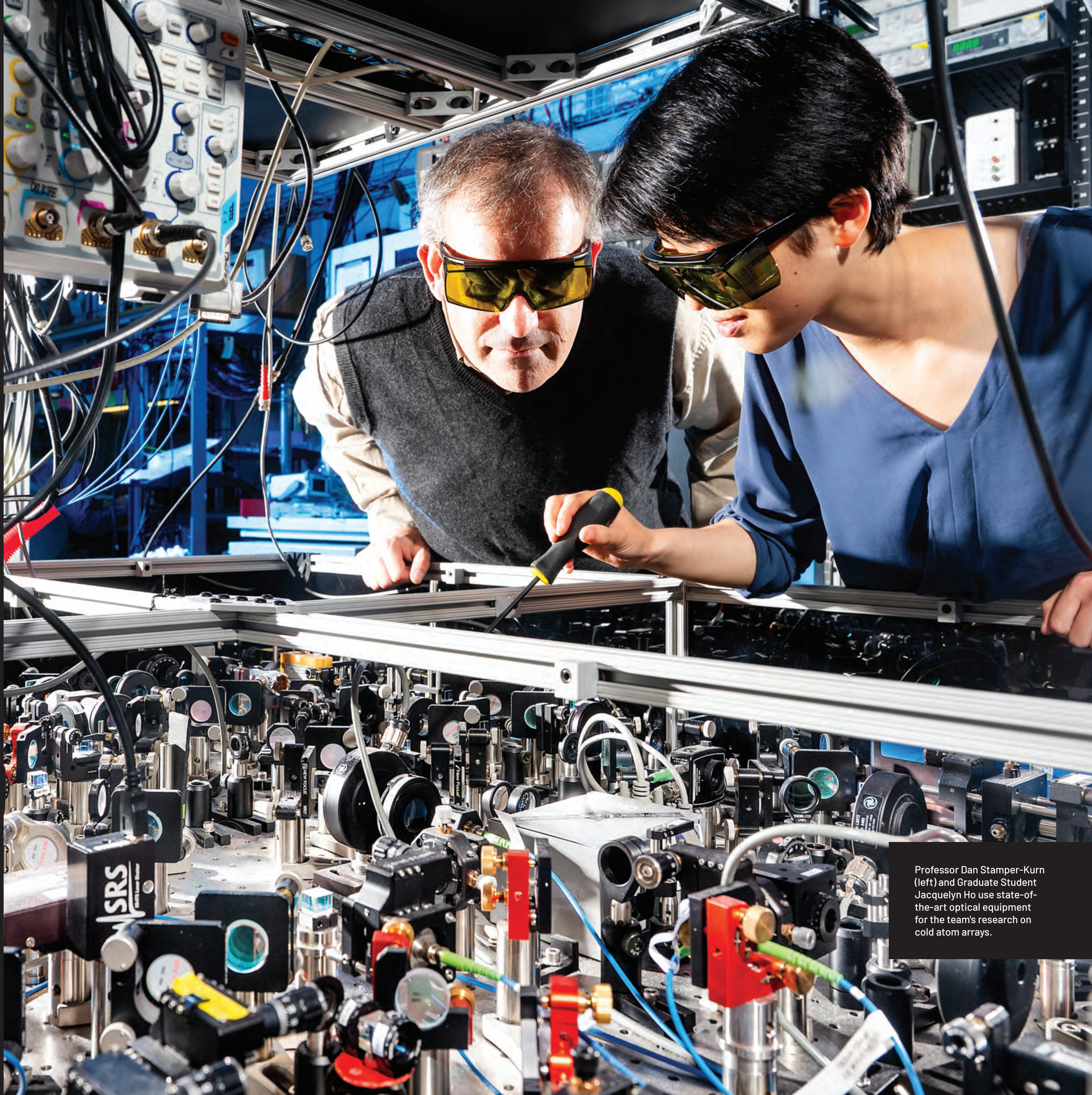


PHOTO: NOAH BERGER

Professor Dan Stamper-Kurn (left) and Graduate Student Jacquelyn Ho use state-of-the-art optical equipment for the team's research on cold atom arrays.

Table-Top Experiments with Ultracold Atoms

Although quantum research has made amazing progress over the last 100 years, we're still really far from building a quantum computer that you could use at home, according to Stamper-Kurn.

"We also still don't know if a quantum computer is good for much. We know they can factorize large integers and simulate quantum mechanical systems, which classical computers will never be able to do at the same scale," he explains. "We take it on faith that this is just the tip of an enormous ice berg, but that isn't proven yet."

However, needing to tackle these big challenges means Berkeley physicists have tons of interesting research ahead, including work led by Stamper-Kurn at the NSF Challenge Institute for Quantum Computation (CIQC).

"We use the term institute because we're trying to do something more curiosity-driven and longer-term than a single research project with a specific deliverable. I think academia's role should be to know where the road is taking us, but to also be willing to look at the side roads—find technology breakthroughs by stumbling around and bring them to the fore," say Stamper-Kurn.

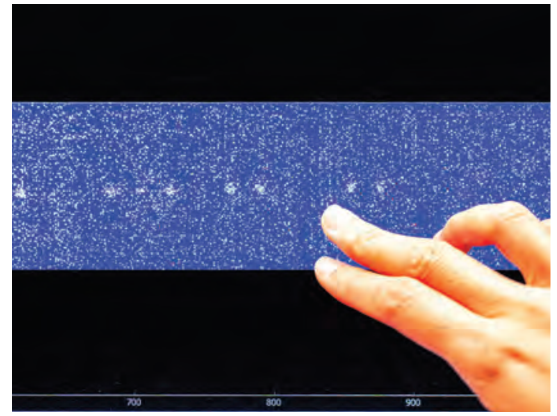


PHOTO: NOAH BERGER

At CIQC, his multidisciplinary team of physicists, computer scientists, mathematicians, chemists, and engineers pursue three overarching goals. The first is to engineer large-scale coherent quantum systems, which is where Stamper-Kurn and Siddiqi overlap a lot. The second goal is to realize the quantum computer and figure out what it can do, which leads CIQC researchers to interact with a wide range of physicists and computer science theorists. The third goal is to use concepts of quantum information science to understand the natural world, and that's where Stamper-Kurn learns from Bousso.


PHOTO: NOAH BERGER

Above: Graduate Student Noah Goss in the Siddiqi Lab.

Top right: A graduate student researcher in the Stamper-Kurn Lab points to an image showing the positions of single optically trapped rubidium atoms. Using these data, the research team can rearrange the atoms into geometric arrangements suitable for quantum information processing.

More specifically, Stamper-Kurn's group performs table-top experiments using light and ultracold atomic gases—perhaps the coldest matter in the universe. At temperatures below one nano-kelvin, noise is "ironed out" and the quantum mechanical properties of these atoms are uniquely accessible and visible. Their goal is to image, with high resolution, individual cold atoms to provide extremely sensitive quantum measurements.

In the E6 ultracold atoms lab, his team studies how a single or array of ultracold atoms interact within the optical field of a high-finesse optical cavity, where light shined into the cavity bounces back and forth thousands of times between two end mirrors. Since light is trapped in the cavity for so long, it interacts very strongly with any atoms inside.

Optical tweezers, consisting of highly focused laser beams sent through a high-resolution lens, are used to control the atoms. They precisely trap atoms in different locations of the cavity or manipulate the state of an individual atom. The team also uses the high-resolution lens to collect light from the atoms as it comes out of the cavity, which then passes through an imaging system and is focused onto a camera.

"We use arrays of optical tweezer traps to position arrays of neutral atoms within a cavity, achieving unprecedented control of the position, internal state, and optical response of each individual atom," says Stamper-Kurn.

"This setup has allowed us to realize breakthroughs in quantum computing, including our recent rapid mid-circuit measurement of atom tweezer arrays," he explains. "We use the very strong interaction between atoms and light to read out the state of an atom very rapidly—about 1000 times faster than previous experiments using optical tweezers. But real applications require measuring part of a quantum processor while the rest of it keeps computing. Our technique is also very selective, where only the atom we measured was disturbed."

Additionally, CIQC supports the entire campus in its development of quantum science, including funding and organizing "Quantum Gatherings" attended by students, postdocs, and faculty from various departments. Held every other Friday, someone from the broader Berkeley quantum community gives a provocative 20-minute spark talk followed by an hour-long discussion.


PHOTO: SARAH WITTMER

Above: Professor Raphael Bousso's work as a theoretical physicist investigates quantum on the scale of the universe. He is pictured here with graduate students Elisa Tabor (left) and Sami Kaya (far right).

A Berkeley undergraduate student who attended the gatherings sent Stamper-Kurn a note saying, "Thank you for sparking my interest in quantum science. I came for the pizza, and I stayed for the science."

These gatherings are the "sweet place" where Stamper-Kurn, Siddiqi, Bousso, and their groups interact. "We can be seen chewing pizza and talking about physics every two weeks outside of Campbell Hall. We understand this is a long-term and necessarily multidisciplinary effort to create an ecosystem for quantum information science," Stamper-Kurn says.

Full-stack Applications with Superconducting Systems

While Stamper-Kurn performs table-top cold atom experiments, Siddiqi's Quantum Nanoelectronics Lab (QNL) works on a larger scale with full-stack quantum computers using superconducting devices. This comprehensive program includes developing materials and processors and integrating them into platforms with controls and applications layers.

QNL has its own clean room and cryogenics for building and operating large superconducting systems on campus. Siddiqi is also the director of the Advanced Quantum Testbed at Berkeley Lab, which offers white-box access to superconducting quantum computers through a user program.

"My large team has fingers in many pots. We have many quantum computers running based on a range of superconducting hardware," says Siddiqi. "We're still at a stage where we haven't figured out what the right qubit is, how to use it, and how to connect it—before scaling up."

Siddiqi focuses on superconducting platforms because they are open quantum systems that naturally exchange information with the environment. These systems already have many "knobs," so the challenge is figuring out how to interface with them properly, he says.

"This is a new chapter in quantum mechanics, originally a theory of closed quantum systems. We're now looking at how to measure and engineer open quantum systems, both for computation but also to explore the most fundamental questions," says Siddiqi.

One technology QNL is developing is a quantum information processor that uses entangled three-level quantum systems, or qutrits.

In a classical computer, a bit is a 0 or 1, represented by on-off switches in hardware. But what if the switch could exist as a coherent superposition of 0, 1, and the states in between simultaneously—think, the Schrödinger cat is both alive, dead, and a zombie? And what if the switches in a computer could consult each other before outputting a calculation?

For example, a quantum computer with an entangled array of N two-level qubits can represent 2^N possible states—far more than the N states of a classical computer—enabling it to perform calculations on many possibilities in parallel. And that's just a binary system.

A three-level qutrit system offers an even larger and more connected computational space that increases with 3^N. But as you add levels, it becomes more challenging to control and entangle them while making them robust against undesired noise, crosstalk, and errors.

Siddiqi's team tackled these challenges, experimentally implementing faster, flexible, and tunable microwave-activated entanglement with three or more levels.

Using their new approach for entanglement, Siddiqi's team developed two types of high-quality two-qutrit gates, a controlled-Z gate and a controlled-Z inverse gate—decreasing the gate's error rate by a factor of four over previous efforts, leading to higher computational performance.

"In a static case, when the qutrits are not driven by electromagnetic fields, they're not coupled. But if we periodically drive the qutrits, like a pendulum back and forth, we can create entanglement on demand—and that's a powerful tool," says Siddiqi. "That obeys different rules, so we're able to create this N-body entanglement."

This significant step forward for operating multi-qutrit devices will help pave the way for a deeper understanding of ternary quantum logic, which can encode more information in quantum processors than qubits.

More generally, Siddiqi is also leading efforts to create a horizontal ecosystem for quantum technologies at Berkeley and beyond, including founding the consortium Berkeley Quantum Works, which fosters partnerships between the device fabrication and measurement facilities housed on the Berkeley campus and startup-stage companies who make quantum processors, components, and software.

> *"It's a whole new ecosystem that we're developing."*

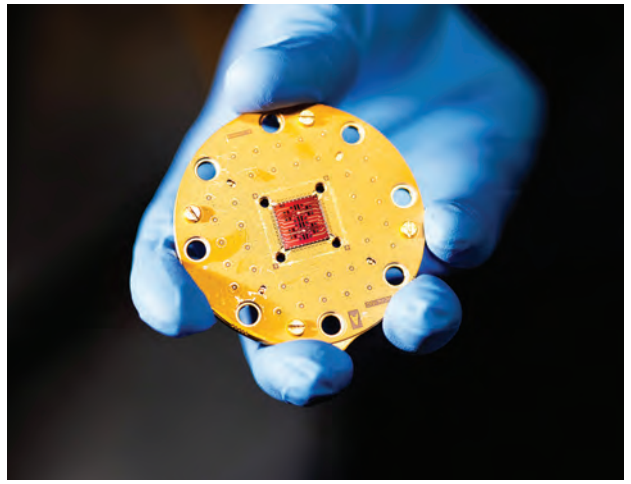
Theories on Quantum Information in the Universe

Berkeley's quantum efforts go beyond developing and using advanced technologies for quantum computation. Colleagues like Bousso are investigating quantum on the scale of the universe.

"Raphael is thinking about the universality of quantum information as a currency to describe the physical world—both in the celestial, gravitational, and cosmology sense and in the computing sense," describes Siddiqi.

The Bousso group uses diverse tools and techniques to investigate the increasingly important intersection of quantum information and quantum gravity.

The field of quantum gravity seeks a unified theory of our universe that includes both quantum mechanics and general relativity. It generally focuses on the interplay between spacetime geometry, quantum information theory, and relativistic field theory. However, according to Bousso, this theoretical challenge is really



A superconducting chip designed and fabricated at the QNL. Cooled to cryogenic temperatures, the circuits patterned into the chip are isolated from their environment and behave similar to individual atoms.

PHOTO: NOAH BERGER

about how quantum information and gravity are intertwined.

"It's about hunting the thrill of quantum gravity. Once we really understand it, there's every reason to believe it's going to revolutionize how we think about the world," says Bousso, who is the Chancellor's Chair in Physics.

Much of Bousso's research focuses on black holes, which are massive deformations of the shape of space and time.

"Black holes are where we can sharpen what we don't understand about quantum gravity—where we can turn vague confusions into a sharp paradox," says Bousso. "For example, in the black hole information paradox, either black holes destroy quantum information in which case quantum mechanics is terribly wrong or you can't cross a black hole's horizon in which case general relatively is terribly wrong. These paradoxes force us to make stark choices, like which principle to give up, and that blossoms progress."

Another fundamental question concerns a black hole's singularity, the point of infinite density and gravity within its event horizon where all concepts of time and space break down. Can you evade that singularity with quantum corrections?

Some theoretical models of quantum gravity suggest that the singularity inside a black hole is not a true point of infinite density, but instead a region where spacetime undergoes a bounce, potentially transitioning to a white hole. This could resolve the information paradox. Other theorists suggest that the universe is infinitely cyclically bouncing between contraction and expansion, replacing the "big bang" with a "big bounce" theory.

Bousso recently ruled out these sorts of cyclic cosmologies with his Robust Singularity Theorem, showing that you cannot get through such bounces.

"People have tried playing with many ideas like this, formulated at various levels of rigor and with varying levels of plausibility. What's nice is that my theorem rules them out regardless of the details," he says.

His Robust Singularity Theorem expanded the validity of the Penrose-Wall singularity theorem, which showed singularities really exist and they arise in many situations in general relativity when spacetime contains a trapped surface and specific conditions are met. Whereas the Penrose-Wall theorem applied to a mathematically idealized case, Bousso's more general theorem represents a big advance.

Bousso's work largely focuses on black holes and gravity, but he's ultimately exploring fundamental questions of entanglement and quantum information. And he's using ideas from other fields, including quantum information theory and quantum communication protocols, that were motivated by seemingly entirely different problems.

And what he learns about these fundamental questions has the attention of his experimental colleagues. In addition to working with Berkeley Physics experimentalists, he is part of the GeoFlow consortium that includes experimentalists at Stanford and Duke universities.

"The depth at which really sophisticated concepts in quantum information theory are baked into gravity has led us to have something to say to people who are interested in benchmarking their quantum computing platforms," explains Bousso. "It's a whole new ecosystem we're developing, connecting people like me studying quantum gravity to condensed matter theorists and even atomic, molecular, and optical physics experimentalists. It's fun and has been the best part of my career."

Irfan concludes, "At first the people from different fields working on quantum spoke different languages, but now they are all very fluent."

Research **Highlights**

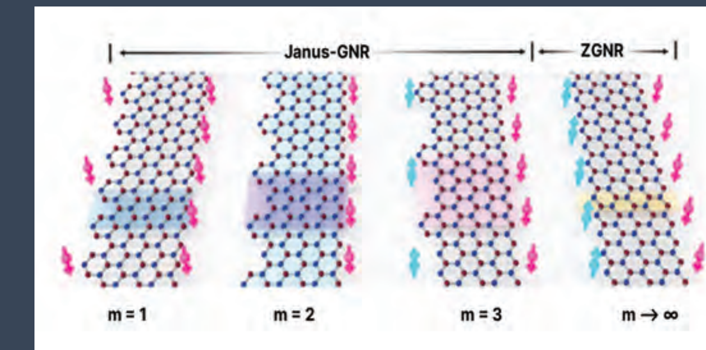
Making Janus Graphene Nanoribbons with Novel Magnetic Properties

In condensed matter physics the term "Janus" (after the two-faced Roman God) has come to describe materials with different properties on opposite sides. Because of their potential utility, designing and fabricating Janus graphene nanoribbons (JGNRs) with complex structural and desired magnetic properties has been a major challenge.

Now, a joint experiment-theory study, co-led by Professor Steven Louie and published in Nature, describes the creation of such JGNRs that have unforeseen and tunable magnetic behaviors. The novel materials, the team says, offer exciting possibilities in quantum magnetism and spin-based technologies.

Guided by previous research in topological classification theory by Louie's group, it was predicted that unique and tunable magnetic behaviors could be achieved with graphene nanoribbons with zigzag edges known as ZGNRs. The design employs topological quantum edge states, featuring GNRs with one pristine zigzag edge and another edge decorated with a pattern of defects.

Experimentalists (co-led by Professors Jion Lu in Singapore and Hiroshi Sakaguchi in Kyoto) working with Louie's theory group used innovative "Z-shaped" precursor molecules for successful synthesis of JGNRS, controlling the structure of the two edges independently. Two kinds of JGNRs were fabricated, both with one edge having a benzene motif array and the other a conventional zigzag edge. The Louie group's theory predicts that the magnetic behavior of such JGNRs may be controlled, ranging from antiferromagnetism to ferrimagnetism to ferromagnetism, by varying the value of m—a robust design principle for the JGNRs. In particular, the configuration of m=2 is predicted to be a ferromagnet, with electron spin polarization localized entirely on the pristine zigzag edge. Realizing such JGNRs expands the design space for precise engineering of exotic quantum magnetism.



Right: Design principle of Janus graphen. One edge retains the zigzag structure, while the other is decorated with defects. m denotes the number of missing six-fold rings between additional benzene rings. Red and blue arrows represent the occupied spin-down and spin-up topological edge states, respectively, leading to varying magnetic orders with m.

IMAGE: COURTESY STEVEN LOUIE GROUP

Right: A schematic map showing a possible location for the Future Circular Collider

IMAGE: CERN

A Faster Route to a More Powerful Collider

It's been more than a decade since researchers at CERN's Large Hadron Collider (LHC) announced observation of a new particle with properties consistent with the Higgs boson. Now, planning is underway for a larger tunnel-size (90 km), higher-energy (84 TeV) Future Circular Collider (FCC) at the same site. But the FCC is not expected to become operational until the 2070s following the operation of an electron-positron machine in the FCC tunnel.

In the meantime, CERN plans the High-Luminosity Large Hadron Collider (HL-LHC), an increase in the luminosity of the LHC, and thus the number of particle collisions possible per amount of time. It's expected to become operational in the mid-2030s, and to allow greater study of the Higgs boson because more of them will be produced—some 15 million per year compared to today's 3 million per year.

As a faster, more cost-effective path to the FCC, Associate Professor Heather Gray and coauthors propose a near-term—operational in the 2050s—proton-proton collider that they say would keep theorists and experimentalists engaged in physics research beyond the Standard Model. "A future circular hadron-hadron collider (FCC-hh)," they write, "would enhance the exploration of particle physics at the electroweak scale and beyond, potentially uniting the community around a common project." Their proposal was published on April 2 in arXiv.

The study proposes an FCC-hh machine to directly follow the HL-LHC. To reduce the timeline and costs to reach the next hadron collider, they evaluate lowering the energy of the collider down to either 70 or 50 TeV, which could leverage existing advanced magnet technology. Gray and co-authors write that costs and timescales "depend most strongly on the magnet field strength and the tunnel size." They say the FCC program should include in its decision-making process "the possibility of reducing energy targets and staging the magnet installation to spread out the cost profile."

PHOTO: KEEGAN HOUSER

Drawing a Bead on Dark Matter

Left: Associate Professor Benjamin Safdi at the National Energy Research Scientific Computing Center (NERSC) at Lawrence Berkeley National Laboratory. The resources at the NERSC are used for many of the calculations in Safdi's dark matter research.

It may be the most elusive substance in the universe. Starting in the 1930s, when astronomer Fritz Zwicky observed that galaxies in the Coma cluster were moving too quickly for the visible material alone to hold them together, researchers have been on the hunt for a mystery material he dubbed "dark matter," the estimated 85% of matter in the universe not visible through telescopes.

In the 1970s, astronomer Vera Rubin picked up the mantle to find dark matter via her work on galaxy rotation curves. Rubin's observations strengthened the case for dark matter by showing that stars in the outer regions of galaxies were moving too fast to be held together by the visible stuff of the cosmos alone. In the late '70s, theoretical work on a dark matter candidate, a hypothetical particle dubbed the axion, further pressed the case for discovery.

Fast forward to today when theorist and Associate Professor Benjamin Safdi is among the most recent generation to join the hunt for dark matter. And the axion is one of his leading candidates (fun fact—it was named after a laundry detergent because it "cleaned up" a physics problem). Recent research has touched off potential new lines of investigation with both Earth- and space-based instruments.

Safdi describes his approach to finding dark matter (and other problems in physics) as one that uses astrophysical observations, modern laboratory techniques, and modern understanding of particle physics and instrumentation to try to find ways of detecting particles like the axion. "That's where most of my contributions have been," he says.

Safdi has also participated in wider efforts to find evidence of dark-matter particle candidates including weakly interacting massive particles, or WIMPs. The work has necessitated the resources of some of the world's best-known science-user facilities; for example, the Large Hadron Collider at CERN, in Switzerland, or space telescopes like the Chandra X-Ray Observatory operated by NASA—to name a few.

"The two models of dark matter that are thought to be the most well-motivated, the most likely to be true—and, of course, we could all be wrong—but the two which people put the most stock in at the moment are axions and WIMPS," Safdi says.

The properties of the WIMP are predicted to be very similar to the properties of ordinary matter, Safdi says. WIMPs would interact, for example, through the same electroweak force that ordinary matter does.

"And WIMPs are a beautiful framework in which you can naturally explain the observed abundance of dark matter by hypothesizing that you had this new particle of nature, which was produced in the early universe after the Big Bang, and they kind of co-evolved in a very natural way after the Big Bang with the rest of the ordinary particles," Safdi says. "The issue with WIMPs is that we haven't seen them yet. It has been predicted for the past two or three decades that WIMPs are kind of always 'just around the corner.'"

WIMPs have been dropping in popularity as dark matter candidates because they have yet to be detected. Axions have been rising as candidates because the likeliest places physicists think they may be found have yet to be probed experimentally. "But that will change soon," Safdi remarks, "and we'll either detect them or we won't, and then we'll have to go back to the drawing board and think of something else."

Axions could also be the long-sought dark matter that holds the universe together. They would have been produced in the early universe following the Big Bang.

But there are other sources of axions, Safdi says. "They're being produced by our sun right now, and it's just that the interaction strength of axions with ordinary matter is very weak. So, it's hard to see those axions coming from the sun. But if you could see the axions in our universe, and you looked up at the night sky, it would look very similar to how it looks visibly to the naked eye, because axions are produced in stars. They're produced in hot gas clouds. They're produced in all of the normal ways that electromagnetic radiation is produced, but in much fewer numbers, and it's much harder to see them."

Axions are a requirement of string theory, which Safdi calls "our best theory of quantum gravity. You can't have string theory without axions. So, in addition to solving these very practical problems of dark matter... they're deeply tied to the nature of quantum gravity as we understand it. They're just very hard to find and are predicted to interact extremely weakly."

A variety of lab bench experiments

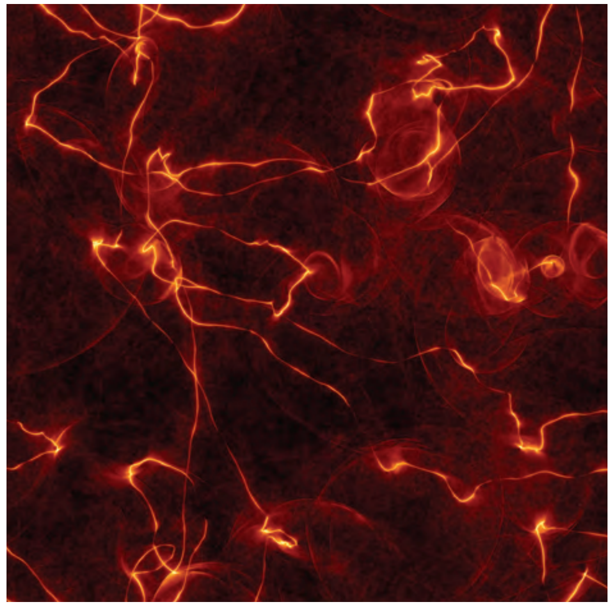


IMAGE: COURTESY BEN SAFDI

A simulation of axion dark matter in the early universe developed by Safdi and his team. The image shows axions strings, which are energetic structures thought to have formed after the big bang. As the network evolves, it emits axions that go on to become the dark matter.

Safdi has been involved with, including DM Radio and ABRACADABRA, have propelled the axion candidate. These lab bench experiments use resonators to amplify the faint electromagnetic field or photon produced when a low mass axion transforms itself in the presence of a strong magnetic field.

"In my group, we think about a variety of different astrophysical probes of axions using data from many different instruments," Safdi says. "We haven't found an axion yet, but I think we're really getting close. There's really a feeling that a discovery could happen any day."

> **"There's really a feeling that a discovery could happen any day."**

Fueling the excitement is research Safdi published in Physical Review Letters in late 2024. Those results stem from an analysis of data concerning the nearby supernova 1987a. They suggest that direct evidence for dark matter in the form of axions might erupt from supernova events and be detected if researchers are lucky enough to have their instruments pointed in the right direction at the exact time such a star explodes.

In a supernova, Safdi explains, stars develop iron cores at their centers towards the end of their lives. The iron core eventually collapses under the weight of its own gravity until it can't collapse anymore. A shockwave emerges and explodes the now extremely hot star. In that very hot environment, axions can be produced in abundance. But it's not the axions that would be observed, rather their conversion to gamma rays in the magnetic field surrounding the star.

"And so that's what we have pointed out," Safdi says. "This is a unique aspect of axions—that this hypothetical particle, in the presence of very strong magnetic fields, has a small probability that they will spontaneously convert from being an axion to being an observable gamma ray or photon."

The likely place to find a close-by-enough supernova where any gamma ray emissions could be detected is the star-filled center of the Milky Way galaxy. "Statistically speaking, we expect the next supernova in our galaxy to come generally in that direction," Safdi says. However, supernova 1987a was the most recent example of a near-by supernova and it came from a completely different direction. "You can describe statistically where you expect the next event to be, but in reality you're drawing from a statistical distribution and you could get unlucky, and the event could be somewhere else."

Some existing space-based telescopes are capable of detecting these gamma ray bursts, but because they do not offer full-sky coverage odds are long that one of them would detect the next supernova event—in fact, they would likely miss supernova events 90% of the time. "If we miss it because we gambled on a specific sky location that would be unfortunate," he says of a future supernova event. "That's a big source of my own anxiety—that the event could come tomorrow, and we're not prepared for it at all."

What axion dark-matter detectives really want is something akin to supernova surveillance cameras. Safdi is collaborating with colleagues at the UC Berkeley Space Sciences Laboratory on a proposal to build a constellation of cube satellites, or cubesat telescopes. "Our idea is to design a very cheap, basic detector that you can launch many small versions of. The hope is that we can launch 30 or 40 of these little gamma ray telescopes to give us complete sky coverage."

The Fermi Gamma-ray Space Telescope is what Safdi and colleagues have for now, to possibly detect gamma rays from a supernova event, and it is reaching the end of its lifetime. Like other large space telescopes, it's a complex singular device that is costly and not easily replaced. It was designed and built with many redundancies and also made rugged to survive launch and the space environment over the long haul.

"The advantage of what we're trying to do with cubesats," Safdi says, "is that if you lose one, it doesn't matter so much. It's these small, individual pieces that collectively make something much larger for our science application." This should make the cost lower and should make a lot of the headaches associated with large space-based instruments lower, too.

The Safdi group takes a broad approach to the search for dark matter. "I think axions are one of the best-motivated models at the moment, but we truly don't know. It could be something completely different. I also spend a lot of time thinking about the WIMP dark matter model."

To that end, he mentions another ground-based experiment soon to come online called the Cherenkov Telescope Array Observatory (CTAO), being built and operated as an international science consortium. It will be spread across two sites in the northern and southern hemispheres with a total of about 60 telescopes operating in harmony to survey the sky. CTAO will be well suited to looking for WIMP dark matter that would be picked up as very high energy gamma rays—much higher energy than those from a supernova explosion, Safdi explains.

"They're carrying so much energy that they induce this shower radiation that you can observe directly on Earth," he says of theorized WIMP-sourced gamma rays. He calls CTAO a game changer that will either detect WIMP dark matter "or just close the window on it forever. We're doing a lot of work in my group preparing for these data. I am very excited about the next few years."

Research **Highlights**

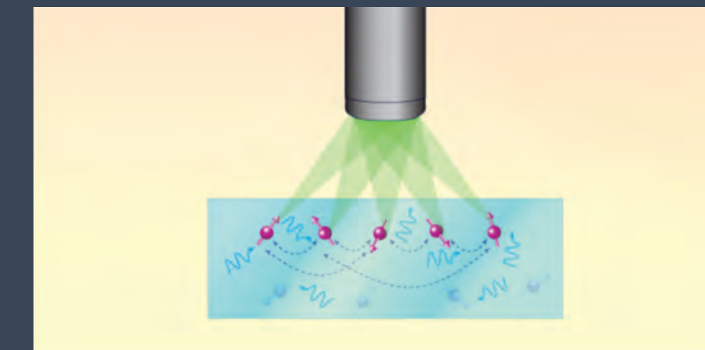


IMAGE: COURTESY SHIMON KOLKOWITZ

Right: Nitrogen vacancy (NV) centers (shown here as pink arrows) are naturally occurring atom-scale defects in diamonds (blue rectangle) that can be used as sensitive nanoscale quantum sensors. The Kolkowitz lab demonstrated a novel approach that enables scalable control and measurement of hundreds of individual NV centers in parallel (green laser beams).

Toward Better Quantum Sensors

Quantum sensors offer a kind of measuring stick for the nanoworld. Quantum sensors that rely on nitrogen vacancy (NV) centers in diamond show great promise for wider application, for example, in biology and microelectronics—if key challenges involving spatial resolution and parallel processing can be met.

As naturally occurring atom-scale defects in diamond, NV centers are useful for quantum sensing because photoluminescence reveals their electron spin state, which is sensitive to the surrounding environment. At room temperature, the spin state can be preserved by investigators for millisecond durations, a long time in the quantum realm. Applications today include research in condensed matter physics, biology, chemistry, and electronics.

Experiments with NV centers typically involve interrogating one spatially resolved NV center at a time, or alternatively, interrogating ensembles of millions of unresolved NV centers. The one-at-a time approach offers nanoscale spatial resolution; however, it can be prohibitively slow and makes information about the spatial correlations in fluctuating signals inaccessible. By comparison, measurements with ensembles of many NV centers can be fast, but spatial resolution is limited by optical diffraction, and information is lost when averaging results over the ensemble.

Now, Professor Shimon Kolkowitz and co-authors present a platform for the simultaneous parallel interrogation of many spatially resolved NV centers with high signal-to-noise ratios, in a scalable manner. They published their work July 14 in Physical Review X.

Kolkowitz' team used NV center-selective charge-state manipulations and single-shot charge-state readout recorded under patterned optical illumination onto an electron-multiplying CCD camera to conduct parallel charge- and spin-state experiments with 108 NV centers. They also demonstrated measurement of pairwise correlations between all NV-center spin states simultaneously, yielding 5,778 unique correlation coefficients. The results show that quantum sensing with single NV centers can be performed in a scalable manner, with potential applications including single-molecule nuclear magnetic resonance (NMR) and characterization of integrated circuits.

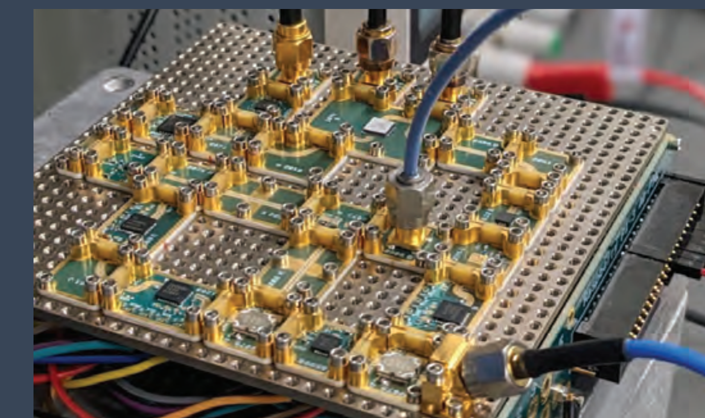


PHOTO: COURTESY ERIC MA

Right: A prototype microwave impedance microscopy (MIM) circuit based on digitally-controlled surface-mount microwave components.

Extending Microwave Microscopy

Probing the electromagnetic properties and behaviors of materials at the nanoscale has become increasingly essential across diverse fields, from condensed matter physics and neuroscience to semiconductor technology and MEMs (micro-electromechanical systems).

One of the newer methods to carry out such nanoscale characterizations in a non-invasive manner is called microwave impedance microscopy (MIM).

Assistant Professor Eric Y. Ma is working to advance MIM using near-field microwaves emanating from a sharp scanning probe tip. At gigahertz (GHz) frequencies, MIM can measure the local electrical properties of materials, including those underneath the surface. Central to MIM is an ultrasensitive reflectometer that detects minute variations in microwave reflections caused by tip-sample interactions. These variations can be related quantitatively to properties such as resistivity, dielectric loss, permittivity, and dispersion.

Ma's team recently extended MIM into nonlinear regimes by employing higher microwave power levels, as highlighted in Applied Physics Letters. According to Ma, the nonlinear interaction manifests as multi-harmonic generation, and his team has developed a quantitative framework for interpreting the signals.

"Existing literature has focused exclusively on linear MIM," Ma explains, noting that traditional methods lack the ability to probe local electrical nonlinearity widely present in dielectrics, semiconductors, and superconductors, for example. "Elucidating such nonlinearity with nanoscale spatial resolution can provide critical insights into semiconductor processing and diagnostics as well as fundamental phenomena like local symmetry breaking and phase separation," the team notes.

Reflecting his longstanding fascination with imaging and instrumentation, Ma's team is now constructing a nonlinear MIM prototype. The idea first took shape as part of a Berkeley Pi2 Summer Scholarship research effort, highlighting Ma's commitment to undergraduate researchers and to embedding them in the frontiers of experimental physics. "This innovative approach to imaging not only pushes beyond current limitations," Ma says, "but it promises to unlock entirely new frontiers—much like the transformative leap from linear to nonlinear optics."

2025 At A Glance

PHYSICS MAJORS 369
- Intended Majors: **400**
- Transfer Students: **192**
- BA Degrees Awarded in 2024-2025: **117**

BPIE: Berkeley Physics International Education 80

GRADUATE STUDENTS 247
- Countries: **24**
- Ph.D. Degrees Awarded in 24-25: **42**

ACTIVE FACULTY 66
- Emeritus Faculty: **28**
- Nobel Laureates: **4**
- National Academy of Sciences Members: **20**

Four New Hires Tackle Becoming Assistant Professors Together

Berkeley Physics is excited to welcome four talented early-career experimentalists as assistant professors, who will explore new frontiers of physics using various quantum systems as sensitive detectors. These new hires share what it is like to navigate their new faculty positions as a cohort.

PHOTOS PROVIDED BY THE INDIVIDUALS FEATURED

Harry Levine

Harry Levine joined the department with Aziza Suleymanzade in July, but they already knew each other from having both worked in the same research group at Harvard at different times. That is coming in handy as they set up new labs with similar equipment, coordinating purchasing so they can share if something breaks. "There's a lot to figure out to build a lab, teach, and mentor students. It's been awesome to be able to group text each other questions to prepare and navigate these things together, even before arriving," he says. "I'm really excited to build a research lab and team of enthusiastic students to harness the power of exotic quantum effects for studying nature and for developing new technologies—in ways that 100 years ago sounded absurd but we're now developing to bring into real life."

Aziza Suleymanzade

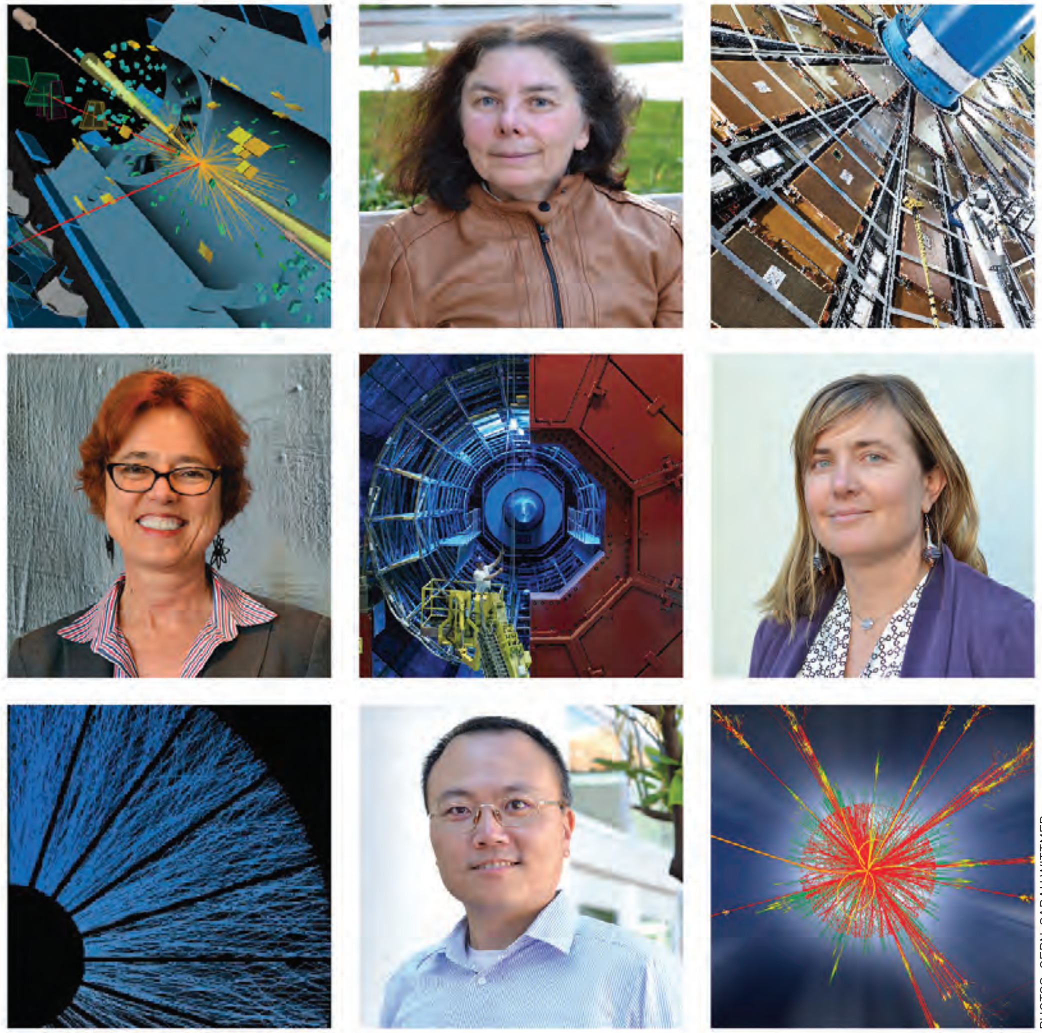
Aziza Suleymanzade viewed their new faculty cohort as a selling point when considering her job options. She is eager to give students a glimpse of why quantum mechanics is so exciting and to work with talented students in her lab. "UC Berkeley is a fantastic place to attract high-quality students. And having a cohort of new experimentalist faculty means the students starting in our labs will also have a super unique cohort. I love that," she says. "My dream research goal is to demonstrate a quantum technology using distributed entanglement, which can be used on a large scale for quantum computing."

Chiara Salemi

Chiara Salemi and Victoria Xu started in January. They quickly bonded by co-teaching the undergraduate Physics 111A instrumentation lab this spring, leveraging Xu's experience as a teaching assistant for this class when she was a Berkeley Physics graduate student. Now that the entire cohort is in town, Salemi appreciates having in-person get-togethers to discuss how to deal with tariffs and other challenges in these turbulent times. "It's really exciting to start my own research group, which is small now but has gotten an impressive amount done already," she says. "My ultimate goal is to discover dark matter, preferably an axion. But along the way of answering big questions, we get to develop very practical things like superconducting qubit sensors."

Victoria Xu

Victoria Xu interacts a lot with the others, having adjoining lab and office space with Levine and Salemi and having earned her PhD in the same Holger Müller lab that Suleymanzade is moving into now. Xu is excited about continuing her work "squeezing light" to improve detection of gravitational waves, as part of the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration. "I think big scientific collaborations like LIGO are a cool example of how people from a lot of different places can work together, united by a common goal, to do something that nobody ever thought was possible."



PHOTOS: CERN, SARAH WITTMER

Breakthrough Prize 'Cast of Thousands' Includes Berkeley Physics Researchers

Left: Images from the ALPHA and ALICE experiments at the Large Hadron Collider at CERN interspersed with photos of the Berkeley Physics Investigators who are collaborators. Clockwize from top: Professor Marjorie Shapiro, Associate Professor Heather Gray, Associate Professor Haichen Wang, and Professor Barbara Jacak

Big awards in science don't often go to a cast of thousands. But that was the case this year for the Breakthrough Prize in Fundamental Physics, awarded to more than 13,000 scientists from around the world, including Berkeley Physics investigators, who worked on four collaborations at CERN's Large Hadron Collider (LHC): ALICE (a large ion collider experiment), ATLAS (a toroidal LHC apparatus), CMS (compact muon solenoid), and LHCb (LHC beauty experiment).

The Breakthrough Prizes are known as the "Oscars of Science." The experiments at CERN are cited for testing with high precision the Standard Model in physics and other theories describing physics that might lie beyond. This includes precisely measuring properties of the Higgs boson and elucidating the mechanism by which the Higgs field gives mass to elementary particles, as well as probing extremely rare particle interactions, and exotic states of matter that existed in the first moments of the Universe.

Berkeley Physics researchers Professor Marjorie Shapiro and Associate Professors Heather Gray and Haichen Wang made major contributions to the ATLAS collaboration that discovered the Higgs Boson; and Professor Barbara Jacak made major contributions to the ALICE program's studies of the quark-gluon plasma that existed in the first milliseconds after the Big Bang.

The ATLAS group at Berkeley Physics includes Shapiro, Gray, and Wang. "We've played very important roles, particularly in the Higgs boson discovery, including the characterization of the Higgs boson, and then searches for new physics and measurements," says Gray. She says the group's contributions have been essential to the collaboration's success.

Shapiro says an important aspect of this year's physics Breakthrough Prize is not only recognition that the science that has emerged from the LHC represents a major contribution to physics, but also that the science must be done in large teams. Also, Berkeley Physics has a "significant interaction" with Lawrence Berkeley National Laboratory, she notes, and that this strong coupling lends unique capabilities and strengths. For example, Berkeley Lab has contributed to designing and developing a new hybrid pixel readout chip with improved functionality for upgraded detectors that are in the works for the upgrade to the LHC, the high-luminosity LHC.

Jacak says Berkeley Physics' major contributions to the ALICE collaboration include building two silicon pixel tracking layers "central to a lot of the physics of ALICE." She adds, "Analyzing jets of particles exiting heavy ion collisions is a really great opportunity for our students—undergrad as well as graduate students—to work on huge data sets. Even if they don't continue as scientists in nuclear or particle physics, they learn a lot of great skills." LHC experiments, she continues, "are dependent on having collisions at the Large Hadron Collider but also having the large teams who build, field, and analyze data from large detectors."

In agreement with the leaders of the four collaborations, The Breakthrough Prize Foundation will donate 100 percent of the $3 million in prize money to the CERN & Society Foundation. The money will be used to offer grants for graduate students to spend research time at CERN, giving students experience working at the forefront of science and new expertise they can bring back to their home countries and regions.

Shining Lights Fellowship Program Promotes Gender Equity in Science

Right: Associate Professor Gabriel Orebi Gann addresses participants of the Berkeley Physics Shining Lights Fellowship program at the kickoff event

PHOTO: A. J. GUBSER

Shining lights are everywhere in physics, from the interactions of subatomic particles to the myriad lights of stars and galaxies scattered across the cosmos. These days, the Shining Lights Fellowship program at UC Berkeley refers to a new and unique effort to support the professional development of postdocs and grad students interested in gender representation in science under the direction of Associate Professor Gabriel Orebi Gann.

The first year of the two-year program ran from January to May and included 16 participants who were senior graduate students or postdoctoral fellows in the Mathematical and Physical Sciences Division. The program has a three-fold focus: building community, building confidence, and training in skills that are not typically part of the science graduate/post-graduate experience such as communications, networking, and leadership.

Through a series of workshops held at regular intervals throughout the semester, Orebi Gann says the group tackled issues like self-confidence in a male-dominated field, handling challenges like bullying, and developing community. "It was shocking to me how many of the women don't interact with another woman in the day-to-day course of their research, and they needed a community of other women," she says.

Shining Lights centered on a series of workshops that ranged from hour- to hour-and-a-half-long talks, which included a meal with the speaker to encourage more informal mixing, to an intensive two-day, in-person workshop. Every participant received six months of unlimited executive coaching, as well as formal headshots participants can use moving forward. "We also provided all sorts of books, as topics came up during the workshops that it was clear resonated with people," Orebi Gann says.

Workshop highlights, she says, ranged from a trained stage actor discussing presentation skills and audience engagement, to sessions on managing fear, toxic perfectionism, and burnout. One workshop centered on establishing a safe space to talk about issues relating to the current political climate, including visa issues for foreign researchers. Now, Orebi Gann says, "They've got a network of people to call."

Asked about metrics for success, Orebi Gann says, participants were surveyed at the beginning and the end of this year's program. What's more, participants were also surveyed after individual events. Given that 2025 is the first year of what she hopes will become an annual event, she told the group, "We really want to continue to improve. Give us your feedback. Be constructively critical."

Orebi Gann came to the program by way of invitation from Dean of Mathematical and Physical Sciences, Steven Kahn. She had previously sat on the Dean's Committee for Faculty Diversity. With donor support for a professional development program that addresses issues of gender representation, "he pulled me in and said, 'would you be willing to run with his?' And it was one of those fantastic opportunities." She was given a budget, and a directive no more prescriptive than to make a program that would be useful for women in science.

"The very first thing I did was put together an advisory board," Orebi Gann says. The board is a mix of very senior scientists, both male and female, and includes people with training in professional development. She says Angela Stopper of UC Berkeley People and Culture "was a rock for me. We met any number of times to talk through ideas, and she put me in touch with some of the people we brought in to do workshops."

At the culmination of this year's program, Shining Lights held a graduation ceremony at Lawrence Hall of Science that included a half-day workshop and an evening reception. Asked about the naming of the program, Orebi Gann says "Shining Lights" was what one of her students named his thesis on solar neutrinos. "I said, Max, can I steal that for my new program? He said, 'Sure! Go for it!'"

PHOTO: A. J. GUBSER

Leinweber Foundation Gives Over $100 Million for Theoretical Physics Research

PHOTO: THE LEINWEBER FOUNDATION

Larry Leinweber has been intrigued by science ever since he was a young child growing up on a farm in rural Michigan. After success as a software entrepreneur, he founded the Leinweber Foundation to support impactful research and expand STEM education access to students from underserved areas.

The Leinweber Foundation just made a transformative gift of over $100 million for theoretical physics research across seven top institutions: University of California, Berkeley, University of Michigan, University of Chicago, Massachusetts Institute of Technology, California Institute of Technology, Stanford University, and Princeton's Institute for Advanced Study.

"I've had a lifelong fascination with theoretical physics. It fuels our understanding of how the world works and opens doors to groundbreaking discoveries," says Larry Leinweber. "We wanted to provide a gift with heft to help keep the U.S. at the forefront of physics research."

These funds will foster independent research at each institution, while also creating a network for cross-institutional collaboration among faculty, postdoctoral fellows, and students.

The Berkeley Center for Theoretical Physics will be renamed the Leinweber Institute for Theoretical Physics at Berkeley and will include four new postdoctoral Leinweber Physics Fellows.

"As the future of research and innovation, postdocs provide a lot of enthusiasm and new ideas. Our endowed fellowships will allow Berkeley to attract top young talent and give them the 'free-range' autonomy to pursue bold, long-term research," says Larry Leinweber.

In addition, the gift supports a new kind of collaboration between the theoretical physicists at the seven institutions in the Leinweber network, who will meet periodically to tackle fundamental questions and identify emerging research ideas.

"Each individual research program may be solving one piece of a problem, but increased collaboration will allow them to see the bigger picture and accelerate discovery," says Ashley Leinweber, Vice President of the Leinweber Foundation.

"We wanted to provide a gift with heft to help keep the U.S. at the forefront of physics research."
— Larry Leinweber

Alum Mike Garland Shines A Light On Future Leaders

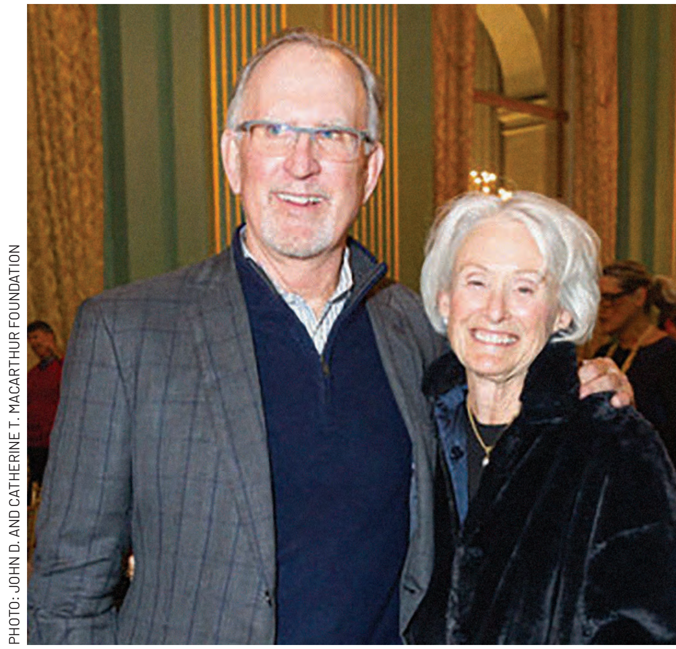


PHOTO: JOHN D. AND CATHERINE T. MACARTHUR FOUNDATION

Mike Garland (BA '72) donates to Berkeley Physics to give back to the university that helped change his life. In addition to supporting the Michael M. Garland Chair in Physics since 2008, he and his wife, Gigi Coe, recently founded the Shining Lights Program—providing leadership training to women-identifying graduate students and postdoctoral scholars in Berkeley's mathematical and physical sciences.

"I've always felt women are equally capable, if not more so, than men. But there aren't enough of them in leadership positions, especially in the physical sciences," Garland says. "We wanted to elevate women to become more successful leaders by providing diverse leadership coaching and networking."

Garland and Coe initiated and funded the program, with the enthusiastic support of Dean of Mathematical and Physical Sciences Steve Kahn and Assistant Dean of Development Maria Hjelm. However, Shining Lights was run by Berkeley Physics Associate Professor Gabriel Orebi Gann.

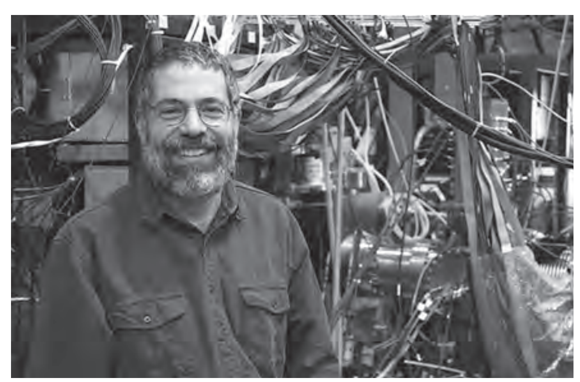
"All the credit goes to Gabriel. She grabbed the idea and ran with it. And she understands better than us what content these women need, including critical soft skills like working with an actor to learn a power stance," says Garland.

The success of the program was clear at the graduation this spring. One thrilled graduate's mother flew out for the ceremony. Former Chancellor Carol Christ came back to give an inspiring speech. And several graduates spoke about how the program had already made a difference in their lives.

"I was amazed at the level of camaraderie and enthusiasm at the graduation. They really lit up about the relationships they've developed with each other," says Garland. "The joyful, formal celebration really showed that Berkeley was the right place for Shining Lights."

"As far as we are concerned, the first year of Shining Lights was an enormous success. We hope to see it build and grow, maybe into other areas in science," adds Coe. "And we may need to add additional training for young scientists to navigate these turbulent times."

In Memory



Joel Fajans (right, 1958-2024), Berkeley Physics Professor, died on November 17, 2024. He was internationally known for his pioneering contributions to nonneutral plasma physics and antimatter research, particularly as a founding member of the Antihydrogen Laser Physics Apparatus (ALPHA) collaboration. More locally, he was also famous as a generous mentor, a devoted instructor of the Physics 111A instrumentation lab, and an avid cyclist.

Robert Dynes (lower left, 1943-2025), UC President Emeritus, former Chancellor of UC San Diego, and former Berkeley Physics Professor, died on June 30, 2025. He was an experimental condensed matter physicist who made seminal contributions to the study of electronic transport properties in various materials, most notably superconductors. He was also a lifelong champion of world-class education for students from all backgrounds, who oversaw the opening of the first new research university in a generation at UC Merced.

William "Bill" Frazer (lower right, 1936-2025), UC Senior Vice President Emeritus and Berkeley Physics Professor Emeritus, died on February 2, 2025. He began studying elementary particle physics theory at Berkeley Physics as a graduate student and faculty before becoming faculty at UC San Diego. He then acted in various leadership roles, including overseeing the scientific programs of the Los Alamos, Livermore, and Berkeley National Laboratories as provost of the UC's nine-campus system.

PHOTO: EMILIO SEGRÈ VISUAL ARCHIVES

Mary K Gaillard (left, 1939-2025), a pioneering theoretical physicist and esteemed educator, died on May 23, 2025. In 1981, she became the first woman to join the Berkeley Physics faculty and was appointed as a Berkeley Lab senior staff member. By predicting the mass of the charm quark (with Benjamin W. Lee), 3-jet events (with John Ellis and G.G. Ross), and b-quark mass (with Mike Chanowitz and John Ellis), she blazed a trail of research and discovery.

Richard Packard (lower left, 1943-2024), Berkeley Physics Professor Emeritus, died in November, 2024. One of his many research accomplishments was the first visualization of quantum vortices. He is also known for discovering Josephson oscillations in superfluids and then using related effects to build the first quantum gyroscope. His work was immortalized by "The Big Bang Theory" show, where the TV characters had their idea of a "superfluid helium gyroscope" stolen by the Army.

Herbert Steiner (lower right, 1928-2025), Berkeley Physics Professor Emeritus and former Chair, died on January 15, 2025. His 77-year career at Berkeley focused on performing high-energy physics experiments at CERN, Fermilab, and SLAC— spanning from being a Berkeley Physics undergraduate to emeritus faculty, while also a research physicist at Berkeley Lab. He made important contributions to the Nobel-prize winning Chamberlain-Segrè experiment that discovered the antiproton and to George Charpak's Nobel-prize winning invention of multiwire proportional chambers.

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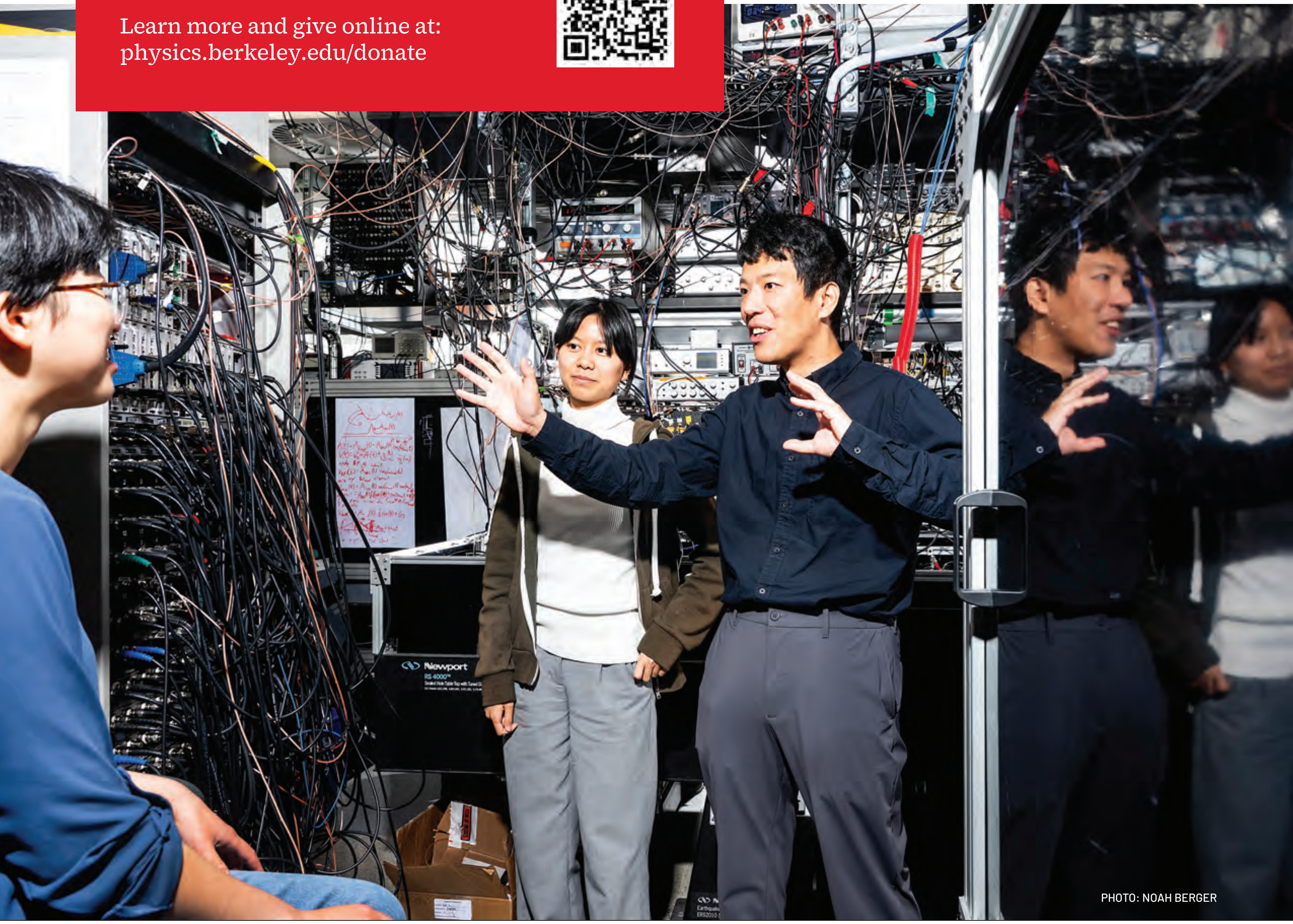

PHOTO: NOAH BERGER