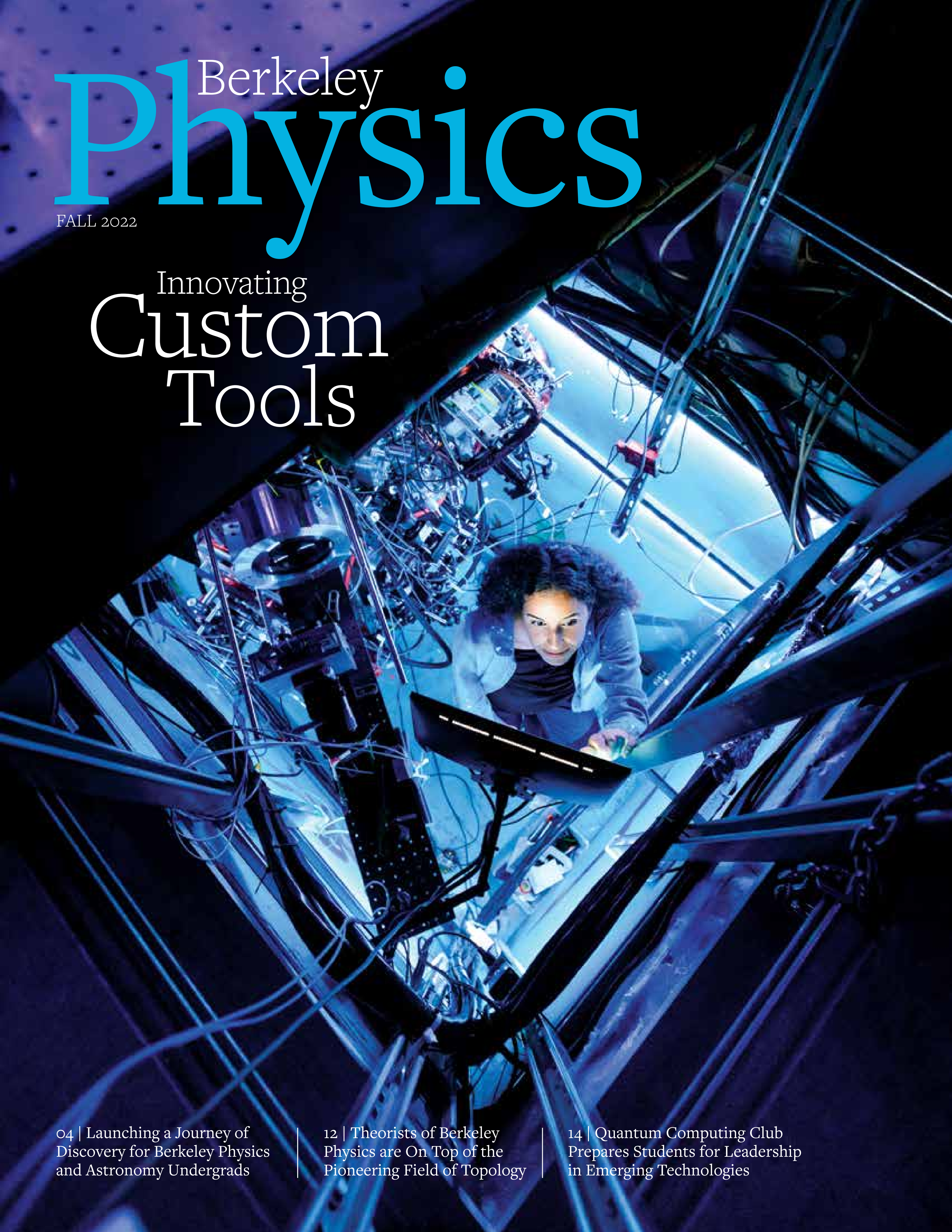
Berkeley Physics

FALL 2022

Innovating Custom Tools



Berkeley
Physics

ON THE COVER:
Graduate student Madeline Bernstein testing the standard model with a precision atom interferometer.

OPPOSITE PAGE:
Inside the machine shop and a tool drawer in the Holger Müller Lab.

BACK COVER:
Graduate student Andrew Neely adjusts customized laser equipment in the Holger Müller Lab.

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CHAIR'S LETTER

We began the academic year 2022-23 with renewed vigor, hopeful that the pandemic was in large part behind us so we could turn our full attention to the teaching, mentorship and ground-breaking research that inspires us. While masks are still part of the every-day routine, the students are back to playing frisbee on the meadow and we once again enjoy hearing their presence in our hallways and classrooms. It feels good to put the last two years behind us.

In this issue of Berkeley Physics, you will learn about how the 1971 experiment by a Berkeley Physics graduate student and a postdoctoral fellow was foundational to this year's Nobel Prize in Physics, follow the discovery of black hole formations with Prof. Raffaella Margutti, and the implementation of innovative storage solutions for neutrino data with Prof. Gabriel Orebi Gann. You will read how we're building our own tools for discovery in physics research, as well as exploring the emerging and complex theoretical realm of topological quantum mechanics that may also impact the development of quantum technologies. Berkeley researchers are driving physics that will change the way we see, and live in, our universe.

We hope you've had the opportunity to check out our new physics website which went live on September 6th. The new site features expanded pages supporting undergraduate research and highlighting the work of our postdoctoral scholars. Our efforts to provide more opportunities for hands-on learning for undergraduates will culminate in a new Physics Innovation Lab which we hope to break ground on in 2023. Programs like the new Math and Physical Sciences (MPS) Scholars program which launched this past semester and the Discovery Arc program (see page 4) provide peer advising, group mentoring and expanded opportunities for students to explore the field of physics.

I hope you'll decide to pay a visit to the blue and gold sometime soon (perhaps at CalDay 2023!), and if you do, please don't hesitate to stop in to say hello.

James G. Analytis, Chair

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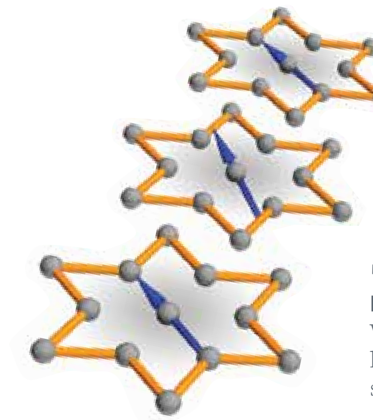


Research Highlights

Berkeley Physicist Zeroes in on Black Hole Formation From Merger of Neutron Stars

An analysis of the X-ray afterglow of two neutron stars that have collided and merged to form a black hole concludes that the black hole didn't form immediately. Instead, says UC Berkeley Professor of Physics and Astronomy, Raffaella Margutti, evidence from the orbiting Chandra X-ray Observatory suggests an intermediate step.

Such a long-standing X-ray afterglow from the merged neutron stars would not be expected if they had collapsed immediately to form a black hole, Margutti says. The afterglow can be explained as a rebound of material off the merged neutron stars, which heated everything around them. The hot material has kept the remnant glowing steadily more than four years after Chandra detected X-ray emissions from a jet of the material.

"If the merged neutron stars were to collapse directly to a black hole with no intermediate stage, it would be very hard to explain this X-ray excess that we see," Margutti says. "It would just fall in. Done."

Margutti and her co-authors of the study, published in The Astrophysical Journal Letters, say the research suggests that the excess X-rays are produced by a shock wave distinct from the jets produced by the merger. This shock was a result of the delayed collapse of the merged neutron stars, likely because its rapid spin very briefly counteracted the gravitational collapse.

"The true reason why I'm excited scientifically is the possibility that we are seeing something more than the jet," Margutti says. "We might finally get some information about the new compact object."

Above left: X-ray analysis suggests a delay occurred before two colliding neutron stars collapsed to form a black hole.

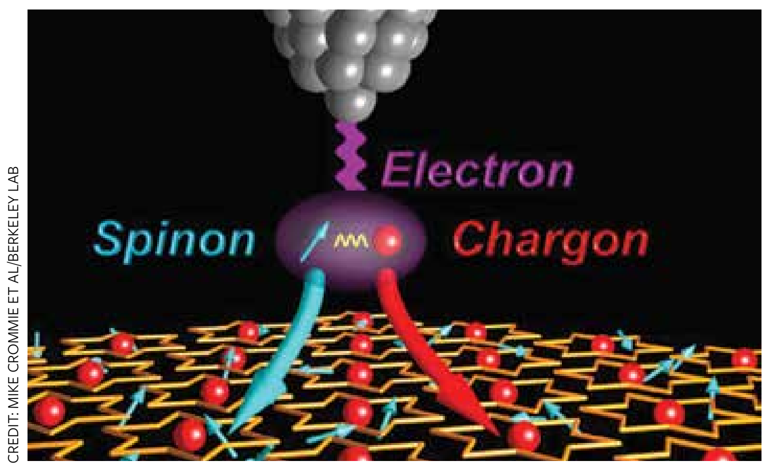
Above right: Illustration of an electron breaking apart into spinon ghost particles and chargons inside a quantum spin liquid.

Opposite page: Stuart Freedman with the experimental apparatus he and John Clauser used to test "spooky action at a distance."

Imaging Exotic Particles Called Spinons Could Aid Quantum Computing

Scientists have taken the clearest picture yet of electronic particles that make up a mysterious magnetic state called a quantum spin liquid (QSL). The achievement, says study leader and UC Berkeley Professor of Physics Mike Crommie, could facilitate the development of superfast quantum computers and energy-efficient superconductors.

The scientists, who include Sung-Kwan Mo at Lawrence Berkeley National Laboratory (Berkeley Lab), are the first to capture an image of how electrons in a QSL decompose into spin-like particles called spinons and charge-like particles called chargons.

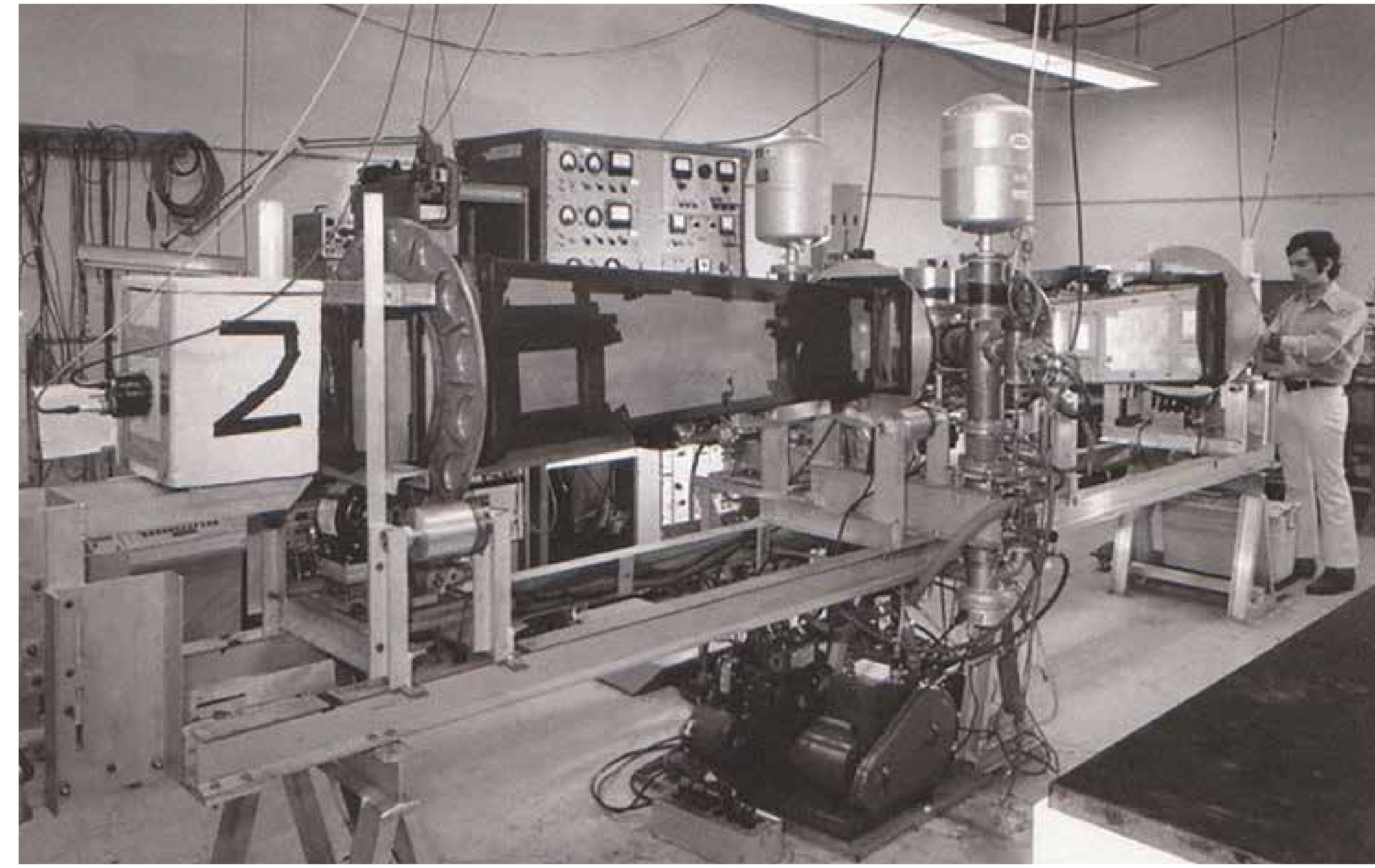


CREDIT: MIKE CROMMIE ET AL/BERKELEY LAB

"Other studies have seen various footprints of this phenomenon, but we have an actual picture of the state in which the spinon lives. This is something new," says Crommie.

As reported in Nature Physics, Crommie and colleagues discovered that when an electron is injected into a QSL—in this case, a 3-atom-thin layer of tantalum diselenide—with the tip of a scanning tunneling microscope (STM) it will break apart into spinons and chargons. Due to the peculiar way in which spin and charge in a QSL interact with each other, the spinons end up carrying the spin while the chargons separately bear the electrical charge. They were able to image this behavior using a technique called scanning tunneling spectroscopy.

Because of their unusual characteristics, Crommie says QSLs could one day form the basis of robust quantum bits, or qubits, used for quantum computing. Another motivation for understanding the inner workings of QSLs is that they have been predicted to be a precursor to exotic superconductivity. Crommie plans to test that prediction with Mo's help at Berkeley Lab.



CREDIT: UC BERKELEY

2022 Nobel Prize in Physics Cites Early Experiment at Berkeley Physics

An experiment by a graduate student and a postdoctoral fellow at Berkeley Physics in the early 1970s was honored and cited as foundational to the work of one of this year's Physics Nobel Laureates, John Clauser.

In 1971, Berkeley Physics grad student Stuart Freedman and postdoc Clauser took over room B219 in Birge Hall to test one of the most enduring puzzles of quantum mechanics, what Albert Einstein called "spooky action at a distance."

The experiment involved the decay of excited calcium atoms to produce two photons of light which, because of the law of conservation of the angular momentum, must have opposite polarizations to make the net angular momentum zero.

Since the photons are emitted simultaneously, they are entangled. According to quantum mechanics, measuring the polarization of one should give the polarization of the other, even though, in the experiment, the measurements were taken 10 feet apart.

Freedman and Clausen's experiment was the first to show that two particles once linked quantum mechanically, or entangled, can be separated by large distances — even the diameter of the universe — and still "know" what happens to one another.

The work was Freedman's Ph.D. dissertation in 1972. He went on to a distinguished career, studying neutrinos and the weak interaction, and eventually returned to UC Berkeley in 1991 to become a professor of physics and a faculty scientist at Lawrence Berkeley National Laboratory. He died tragically in 2012. The Nobel Academy acknowledged Freedman's role in the quantum mechanics research honored by this year's Physics Prize.

Clauser continued to refine the experiment to provide more convincing proof that the quantum mechanical description of entangled particles is correct. Today, entangled particles are at the core of quantum computers and other quantum technologies being developed. He shares the 2022 Nobel Prize in Physics with Alain Aspect of the Université Paris-Saclay and École Polytechnique in Palaiseau, France, and Anton Zeilinger of the University of Vienna, Austria.

Nobel Prizes are not awarded posthumously, though, "I am 100 percent sure Stuart would have received the prize if only he was still with us," said Freedman's longtime friend and colleague Dmitry Budker, now a UC Berkeley Professor of the Graduate School in the Department of Physics.

A Journey of Discovery

New approach to undergraduate education aims to give students a rich tapestry of experience

PHOTOS BY KEEGAN HOUSER

Gazing at stars during nighttime parties, dinners with "family," getting creative in a machine shop, and long philosophical discussions with peers might not seem like the expected stuff of an undergraduate education in science, but it is all part of a new plan for student-led discovery unfolding in the UC Berkeley Physics and Astronomy (PA) Departments.

Faculty members in both departments—along with their enthusiastic students—are reaching beyond just the pursuit of scientific knowledge—as central as that is—to foster, in a deliberate way, a concept and practice of discovery that is more expansive, open-ended, creative, and collaborative.

This approach to undergraduate education, say two PA faculty members, Austin Hedeman and Eugene Chiang, is meant to continually engage and connect students throughout their time at Berkeley in both academic and social activities that revolve around their physics and astronomy education.

For PA students it means a rich tapestry of experiences including lively discussions of science ethics, opportunities to conceptualize and build experimental devices, work out 'back of the envelope' solutions to problems, tutor their peers, operate telescopes at "star parties," and more.

It is part of a broader, campus-wide effort known as the Berkeley Discover Initiative in which students are "invited into an immersive and inquiry-driven learning that culminates with a personalized discovery project, whether original research, artistic production, entrepreneurial initiative, or community-engaged service."

The aim is to instill a life-long ethos of engaging with grand challenges, fostering creativity, and journeying toward innovation.

Hedeman and Chiang's particular vision for the PA departments won a five-year Departmental Innovation Award to support the changes underway. Their plan includes a "Discovery Arc" of experience, tools, curriculum, and mentoring that begins the moment students first arrive on campus.

Hedeman and Chiang say they felt a specific urgency to use the Discovery Arc concept to address what seemed like a troubling disconnect between PA undergraduates and how their education relates to the wider world. They heard it in tough questions posed by PA majors, for example:

"I majored in physics to understand how the universe works. Why is this class just about math?"

"I want to do research. But where do I start? There do not seem to be enough openings."

"None of my family or my friends studies science. Who can I look to for help?"

Left: A group of Discovery students meets on the terrace of Campbell Hall. Elena Vasquez (center) has had a pivotal role in helping to form scholar families for the program.

Above: Physics undergrad Sarah Kwon has an informal meeting with Professor Eugene Chiang and Austin Hedeman, who are faculty leads in the Physics Astronomy Discovery program.

They say the questions helped outline main challenges for the PA departments, including how to build a Discovery Arc that would weave creative agency and curiosity-driven learning into the curriculum. Other challenges include how to mentor at scale hundreds of undergraduate students, and how to recruit and retain underrepresented students.

The Discovery Arc has three main parts: connect, immerse, and culminate.

To foster connections, each undergraduate can opt into the PA Scholars Program and be assigned a "scholar family" that consists of six to eight undergraduates from diverse backgrounds as well as senior family members to include faculty and staff, postdocs, and graduate students. Connections and introductions begin the first day students arrive on campus, via a Golden Bears Orientation.

The PA Scholars program is what is known as a near-peer mentoring system to connect undergraduates from all education and socioeconomic backgrounds, especially minorities who are severely underrepresented in the physical sciences. Any student in the department with a willingness to learn from and serve the PA communities can participate.

For graduating senior Elena Vasquez, the PA Scholars Program has included her involvement with the Berkeley Society of Physics Students (SPS) as the club's chair of equity, diversity, and inclusion (EDI).

"I helped create [scholar] families and paired upper and lower division students to help them navigate their way through the physics department," Vazquez says of her SPS service. "In physics specifically, we talk about ways to make others feel included because sometimes it can feel like it's not all inclusive." She says SPS has worked with the department to "create a community such that everyone from every background from any situation feels like they can be here that they can do physics at Berkeley."

Vasquez says the SPS mentorship program helps many students. "We pair upper division students with first and second years or transfer students. There are usually two to three mentors in each group and four to six mentees.

We pair them up based on academic interests, whether that be research or classes they are taking or fields of physics they are interested in."

She says mentors and mentees might pair off according to gender or pronoun preferences and that mentors receive help in learning how to be to be a successful mentor and, and how to ensure that a community is being built. Twice monthly meetings are required, Vasquez says, though typically they meet more often.

Asked about her personal experience with EDI, Vasquez says, "I came out of high school knowing that physics was something I wanted to pursue. And so, I took my first physics class, and I was not necessarily prepared for the rigor and for the feeling of being a minority, being different than everyone else." She says the turning point came when "I found a little community of women who were in the class with me, and we pushed through together."

"They come in—they get to talk face to face in an informal way with the professors. It has really been lowering the barrier.

For undergraduate Angela Cheng, the PA Scholars program meant an opportunity to help fellow students in the Physics Department Student Machine Shop.

For 10 hours each week, "I help out with maintaining the machines, or if students need help when they come in, I can give them a few pointers," she says.

Equipment in the shop includes familiar tools like a bandsaw and a drill press as well as more advanced equipment like a computer numerically controlled (CNC) mill and a CNC lathe, machines programmed by the operator.

Cheng says when she works with fellow students who might be new to the shop, "We always start out by reviewing a machine's manual so there is a better understanding of how it works. Then, Jesse [Jesse Lopez], the shop manager, will show the student how to write code for the CNC machine."

Typical student projects in the shop, she says, involve a piece of equipment in a professor's lab—say an optics component—that breaks but a replacement from the manufacturer would take too long or cost too much to obtain.

Instead, "It can be straightforward for the student to come in the shop and make the replacement part themselves. It can be something like a piece of glass for a lens, metal pieces to align the glass—or some weird part that needs to be fixed," Cheng says.

And while Cheng enjoys helping fellow students in the machine shop, there is a personal benefit, too:

"I am in a rocketry club on campus called Space Enterprise Berkeley. We are trying to develop a liquid-propellant rocket engine. Some parts we design ourselves and it would be too expensive to ask a professional machinist to make it, so I can use some of my time at the shop to make those components."

Cheng's experience tutoring fellow undergraduates in the machine shop while applying that experience to other pursuits like the rocketry club exemplifies the immersion component of the Discovery Arc.

The idea, Hedeman and Chiang say, is a curriculum that cultivates universally useful skills—back of the envelope estimation, hardware and software know how—that will take students from a level of "knowing that" to "knowing how."

For course work, Hedeman and Chiang have developed a new cross-listed course and modules for Physics and Astronomy on how to sketch solutions on the fly using intuition and simple arithmetic. They use the example of Enrico Fermi, who estimated the yield of the Trinity atomic test by observing how scraps of paper moved in the wake of the blast.

Chiang's Physics/Astronomy C101 "Order-of-Magnitude Physics" course challenges students to grapple with real-world problems like the power requirements of a helicopter on Mars or the odds that they carry the genes for certain diseases. The students use their physics knowledge to work out answers without the aid of the Internet.

"Armed with a few physical first principles and the courage to put pencil to paper, anyone can leverage their life experience to compute a surprisingly wide variety of quantities," Chiang says of the class. "We want students to get into the habit of deciding what is important and what can be ignored in any given situation by being quantitative."

Classes under the Discover initiative include student-led courses in a facet of the program called "hidden intersections."

Physics undergraduate student Ana Lyons has designed and led a seminar course for discussion of topics like the history of systemic bias in the physical sciences.

"I like being a woman in physics," Lyons says. "Most of the people I was reading about did not really look like me. So that kind of pushed me to want to seek out more information about female physicists."

In her hidden intersections course, she says, "We have also discussed ethical issues like the recent controversy surrounding the building of the 30-meter Telescope on Mauna Kea [in Hawaii]." That situation has pitted astronomers' desire for a new telescope against the interests of native Hawaiians who say building the telescope facility will disrupt territory of deep cultural and spiritual importance.

Other topics discussed, Lyons says, include ethical responsibilities for the end results of physics research, for example, weapons programs, or examining the sources of research funding.

Through an ongoing partnership with the MPS Dean and the Student Learning Center, Chiang says, the PA departments have assembled a squadron of peer tutors for the breadth of Physics and Astronomy core curricula. Peer tutors are chosen by Berkeley Discover staff, trained in pedagogical best practices—and they get paid.

The program is "good for the students and for the tutors," Chiang says. "[Tutors] learn the subjects better than they might otherwise... as the saying goes, 'the best way to learn a subject is teach it!'"

Along with these innovative class experiences, the Discover initiative includes a series of labs, each of which ends in a "capstone project" where students design, conduct, and analyze their own experiment. Hedeman notes that the Discover grant has aided the effort by providing funds for supplemental equipment to expand the range of project possibilities.

"Previously, we relied on borrowing pieces of equipment from lecture demos," Hedeman says. "We are also planning on integrating a new 'Student Maker Space' in the student machine shop. This will give PA students access to equipment like a laser cutter and 3D printer. Altogether we hope that this opens a new world of possibilities for in-class projects students might devise, as well as supporting work like the Space Enterprise Berkeley rocketry club."

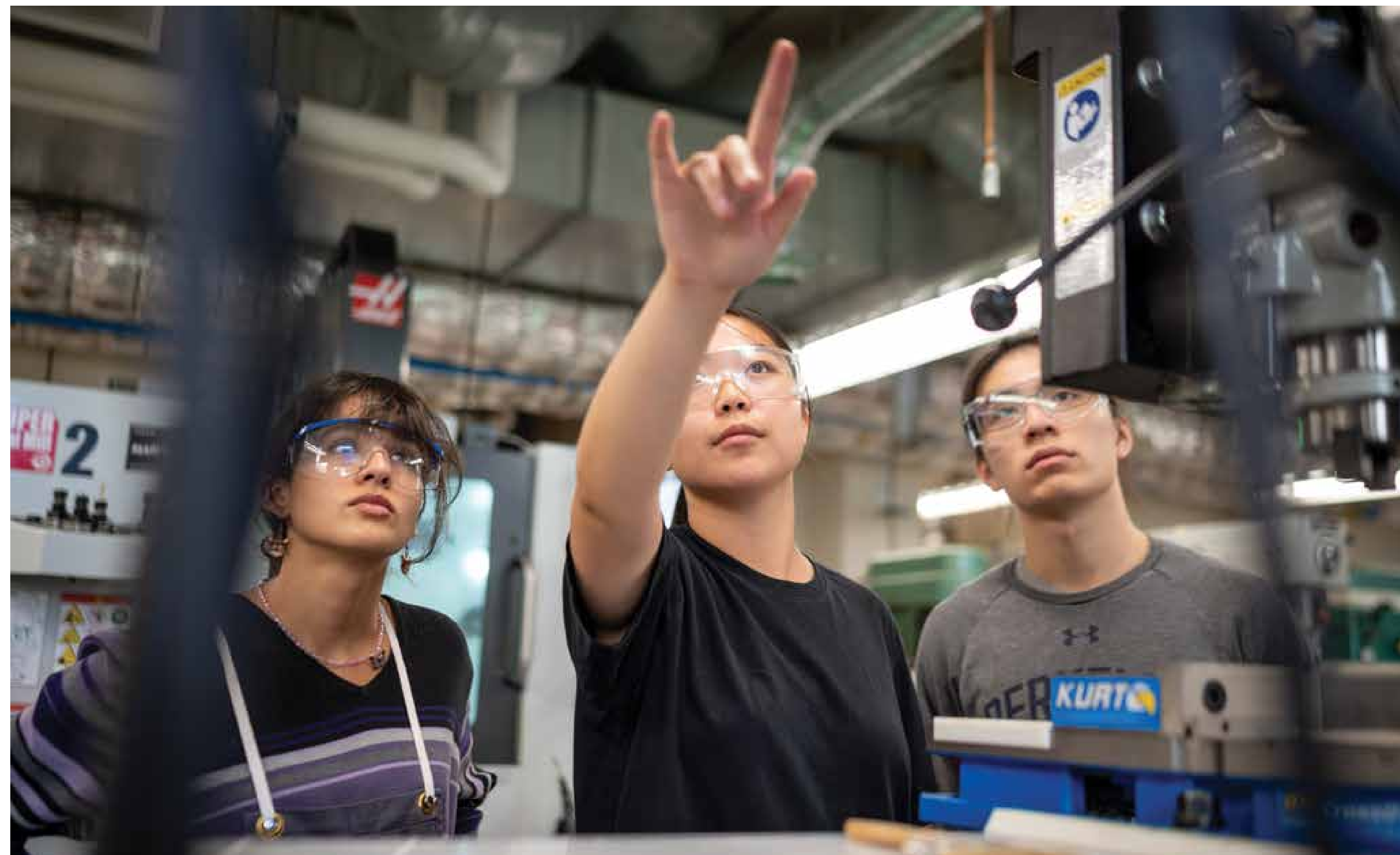
Other investments have included new telescopes for the Undergraduate Astronomy Society, which hosts popular star parties, in which students can socialize and gaze skyward, experiencing the collegiality and fun of science.

Chiang says Berkeley Discover has also helped to sponsor individual research projects during the semester through the Berkeley Physics-and-Astronomy Undergraduate Research Stipend. The program this year included a Spring Fair in which faculty were on hand to share about their research and possible research positions available in their labs. After the event, students could apply to available research positions.

"We wanted to build a space where students in a very low-pressure environment can learn about the research in the department and what opportunities there are for undergraduates. Twelve to fifteen principal investigators or their representatives come to the research fair and to meet with some 80 to 100 undergraduates," Hedeman says. "They come in--they get to talk face to face in an informal way with the professors. It has really been lowering the barrier. Even students who are in their first year who might not be ready to dive into research, start to understand what's involved in physics research, what it looks like, and begin to make those connections."

Left: Physics undergrad Vivian Frisk working in the Student Machine Shop.

Below: Angela Cheng (center) shows fellow undergraduate students how to use the Kent KTM-4VKF-E Vertical Knee Mill, which is capable of both manual and CNC operations.



Innovating Custom Tools

Professor Holger Müller with the atom interferometer, a custom-built instrument for probing fundamental laws of physics.

Crafting Custom Tools Keeps Berkeley Physics at the Forefront of Discovery

PHOTOS BY NOAH BERGER

Whether looking out in space to the early universe, obtaining sharper images of biological macromolecules, detecting elusive dark matter, or measuring the physical "constants" that form nature's backbone, UC Berkeley physicists rely on a wide array of sophisticated experimental probes to achieve their research goals.

But oftentimes, these detectors, microscopes, and other instruments are not off-the-shelf devices, or at least not entirely. Instead, the work requires a special kind of creativity in which scientists figure out what type of devices they need to make for the discoveries they envision, and then set out to build those custom tools.

"Why do we do this? Why do we need to make these extremely small things?" Physics Professor Adrian Lee asks referring to his group's "lithograph detectors" for use on telescopes high up in the mountains of Chile's Atacama Desert. They are searching for evidence of a so-called inflationary event, sometime after the Big Bang but before the formation of galaxies, when the universe underwent an abrupt period of expansion, much like sudden inflation of a balloon.

Lee notes that there is good evidence for the Big Bang, a widely accepted theory for the origins of the universe. But knowing when inflation occurred could help solve open questions like why the whole universe is at one temperature—2.7 degrees Kelvin. As the universe continued to cool and expand after the inflationary period, he says, it began to emit light called the white cosmic background. "And with our telescopes, we look back at that searching for a signature radiation pattern that would tell us inflation occurred."

Fifteen years ago, Lee says, astrophysicists were using tens of detectors, individually machined, for placement at the focal plane of a telescope. But with advances in electronics and the demands of the research, his group pioneered mass production of micron-scale detectors etched—that is, lithographed—onto silicon wafers using ultraviolet light at UC Berkeley's Marvell Nanolab.

"And we have made ones that are closer to 10,000 [detectors] at this point," Lee says of the palm-sized detector arrays all made by his graduate students. "We're not as small as computer chips these days but, you know, we're not Intel either."

He says it is "fairly unique to our university group to be doing this [fabricating detectors on silicon wafers], but I did this kind of stuff as a graduate student, and I wanted to bring it into my research group's culture."

The Lee Group purchases telescopes from outside companies, but many smaller parts are fabricated at the Physics Department's professional machine shop. "There's no way we could do all this stuff without them," Lee says of the modifications to the instrument necessary for the work. "They're not just a parts shop. Often, we need them to make things that are new and different, or out of exotic materials and to a level of precision that would be difficult to achieve anywhere else."

While Lee's detectors are gathering signals from the far reaches of the cosmos, Assistant Professor of Physics Matt Pyle is making detectors and detector housings that he hopes will one day find a particle of dark matter— an elusive goal in experimental physics.

Unseen, because it does not emit, absorb, or scatter light, dark matter's presence and gravitational pull are nonetheless fundamental to our understanding of the universe. For example, the presence of dark matter, estimated to be about 85 percent of the total mass of the universe, shapes the form and movement of galaxies, and researchers invoke it to explain what is known about the large-scale structure and expansion of the universe.

> "Often, we need them to make things that are new and different, or out of exotic materials and to a level of precision that would be difficult to achieve anywhere else."

There are several ways physicists might find direct evidence of dark matter, for example, using particle accelerators, multi-ton tanks of liquid xenon, or looking for dark matter waves instead of particles. These typically look to detect high-mass particles via detectable interactions with other matter. However, big detectors are necessary because, in theory, there are fewer high-mass dark matter particles to detect at any given time.

Pyle's approach is to look for low-mass dark energy particles that weigh anywhere from 1 to 11 orders of magnitude below the mass of a proton. Just as there should be fewer high-mass dark matter particles to find via interactions with other matter, he explains, there should be more of the lighter dark matter particles per volume of space zipping around bumping into things like electrons, neutrons, and protons.

"But then the sensitivity one needs becomes way more daunting, because the smaller the dark matter particle, the smaller the interaction signal," Pyle says of finding the extremely faint signals of these interactions. "And that's really the core trade off." It meant that he needed to create the world's most sensitive dark matter detectors to stay in the game.

Pyle and co-workers have been designing, fabricating, and testing a series of small devices known as low-temperature calorimeters. When a dark matter particle bumps into a silicon crystal on the detector—they look like small computer chips--it should leave behind a very small but detectable amount of energy. But to do so the detectors must be kept at cryogenic temperatures and shielded from vibrations such as people walking around,

electromagnetic interference like cell phones, cosmic background radiation, and the calorimeters can't be glued or fixed to any substrate that could crack and interfere with dark-matter signals.

Each new iteration of the detectors relies on the same basic idea of capturing the energy of a dark matter particle in a crystal. The puzzle for Pyle and his team is to figure out all of the ways to best shield the detectors from any interference—vacuum chambers, Faraday cages to block electromagnetic signals, and more. The plan, he says, is to put the most recent iteration of these detectors some 2,500 feet underground in re-purposed mines where all the "noise" of the world above can be better kept at bay.

Some custom tools are modifications of off-the-shelf equipment that deliver entirely new capabilities. Professor Holger Müller, for example, has introduced high power lasers to transmission electron microscopy (TEM) of complex biomolecules, pushing the instrument to unprecedented contrast resolution.

Müller explains that in TEM, proteins don't absorb electrons which means a low contrast in the images produced. However, the proteins do cause the waves of electrons to go either a little bit faster or slower as they move through the protein, a phenomenon known as phase shifting.

With the help of a high-power laser beam, phase shifting of the electron beam can be manipulated by researchers to produce higher-contrast imaging.

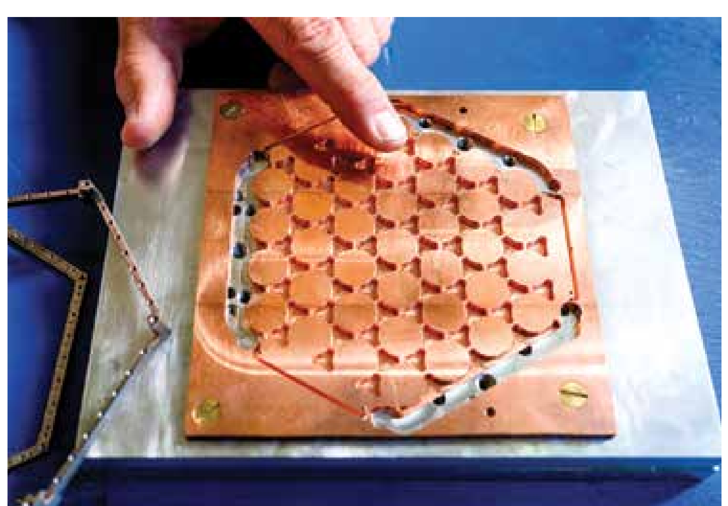
"The key is that the laser beam needs to be incredibly bright," Müller says. "In fact, it's the most concentrated continuous laser beam ever made—an intensity of 450 billion watts per centimeter squared. How do you get that strong? You take a pair of extremely good mirrors and bounce the beam back and forth 10,000 times."

To outfit the electron microscope with the lasers, mirrors, and other equipment needed to achieve the phase contrast, many custom parts were built by the Physics Department machine shop. "The nice thing about the machine shop," Müller says, "is that they don't just take your drawings, they give you feedback. You bounce an idea back and forth until you have something better than the original."

In other work, Müller is using lasers to measure with greater precision the so-called fine-structure constant, which defines the strength of the electromagnetic interaction between charged elementary particles, and is one of the four known forces—electromagnetic, strong, weak, and gravity.

With the help of the department's machine shop, he combines the lasers with an about 12-foot-tall cylindrical vacuum chamber to probe a cloud of cesium atoms. The lasers are used to move the atoms around and to measure the velocity of photons being absorbed by the atoms. "I can use that as input information to calculate the fine structure constant," Müller says.

From exploring the far reaches of the universe, to revealing elusive particles and forces, the culture and resources to "build your own" tools of discovery have been serving Berkeley Physics well.



Above: Professor Holger Müller discusses a mechanical drawing with Principle Mechanician Gordon Long.

Below: A custom-made part for one of Professor Adrian Lee's detectors.

2022 AT A GLANCE

Berkeley Physics Students and Faculty

284 Undergraduate Majors

203 ♂
77 ♀
4 prefer not to say

75 transfer students
102 BA degrees awarded in 2021-2022
19 BPIE (Berkeley Physics International Education)

262 Graduate Students

192 ♂
63 ♀
7 prefer not to say

26 countries
34 Ph.D. degrees awarded in 2021-2022

Phyiscs Faculty

62 Active faculty members
4 Active Nobel Laureates
34 Emeritus faculty
25 Members of National Academy of Sciences

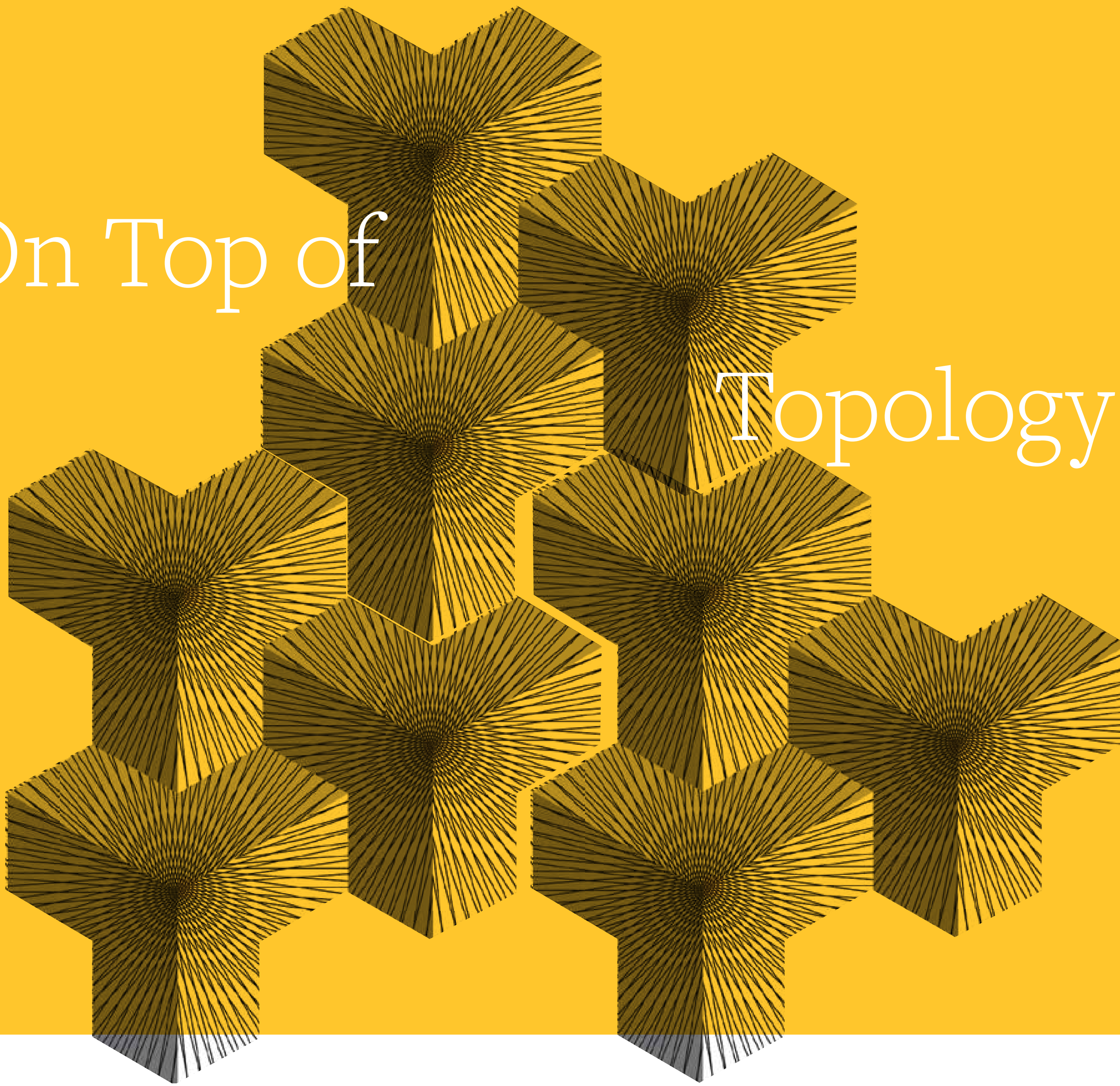
Berkeley Physics Alumni Nobel Prize Winners

1955: Willis Lamb (BS '34, PhD '38)
1997: Steven Chu (PhD '76)
1998: Robert Laughlin (BA '72)
2000 in Chemistry: Alan J. Heeger (PhD '61)
2004: David Gross (PhD '66)
2006: John C. Mather (PhD '74)
2011: Saul Perlmutter (PhD '86)
2012: David J. Wineland (BA '65)
2017: Barry C. Barish (BA '57, PhD '62)

Berkeley Phyiscs Nobel Laureates

1939 Ernest O. Lawrence
1951 Edwin McMillan
1959 Owen Chamberlain, Emilio Segrè
1960 Donald Glaser
1964 Charles Townes
1968 Luis Alvarez
2006 George Smoot
2011 Saul Perlmutter
2014 Eric Betzig
2020 Reinhard Genzel

On Top of Topology



Theoretical physicists, working alone or in conjunction with experimentalists, have long had a home at the UC Berkeley Department of Physics, where they have made foundational contributions to science.

Today, the theorists of Berkeley Physics continue to work at the cutting edge, including in a rapidly evolving area of investigation known as topological quantum mechanics. It is a mashup of topology—a branch of pure mathematics that, in simplest terms, describes mathematical spaces—with the world of quantum mechanics.

Unlike classical physics, we don't experience quantum phenomena in our everyday lives, but it has become the bedrock of physics understanding. Our world of cell phones and the global internet would not exist without these theoretical underpinnings.

Topology can be partly understood through a simple analogy. Consider the hole in the handle of a coffee cup and the hole of a donut. While the holes might look different to us, the mathematics that describes these two spaces—that is, their topology—is the same.

What's more, the coffee cup and donut holes will stay the same, topologically, no matter how they might be bent, stretched, or otherwise re-shaped—just as long as they are never cut or broken. In this way, topology is said to be robust.

In quantum mechanics, on the other hand, states of matter are fragile and fleeting. This is a major limitation for applications like quantum computing. The quantum bits or qubits at the heart of quantum computing, can never be directly measured, interact with one other, or be disturbed by the surrounding environment—for example, other parts of the computer—lest the quantum state collapse, taking information with it. Maintaining qubits in their proper quantum state for useful periods in larger machines is one of the biggest hurdles quantum computing has yet to overcome.

Researchers have reason to believe, however, that topology can be brought into the picture to provide new materials and devices that will help solve this and other problems when trying to lasso quantum phenomena for useful applications. As a broad area of research in physics, the work of many Berkeley Physics faculty members touches on some aspect of topology and topological quantum mechanics.

"One can say 'well, there is no chance that we'll ever be able to create a quantum computer because it's not scalable. It becomes exponentially more fragile as you make it larger and larger," notes Professor **Ehud Altman**. But, he adds, studies of topology and topological phases of matter have enabled new ideas. For example, researchers now believe that topological materials with certain electronic properties might be used to corral and protect qubits, enabling larger and more practical machines.

A beautiful proposal for how to accomplish this was put forward recently by other theorists, says assistant professor **Mike Zaletel**. "When a particle is confined to move in a 2D sheet like graphene its trajectory traces out a string in 3-dimensional spacetime," he says. "In certain rare materials, controlling the motion of the particles so as to trace out knots in spacetime—for example a trefoil or bowline knot—could be used perform the operations of a quantum computer.

"The operation is robust because it depends only on the type of the knot which is drawn, rather than the precise trajectory," Zaletel continues. "The material we're going to use is graphene in a regime called the quantum Hall effect. You take graphene, you cool it down to 100 milli Kelvin or so, and then apply a huge magnetic field perpendicular to the graphene layer. This causes the electrons to enter into a delicate correlated dance called the fractional quantum Hall effect. People have actually known since the 1990s that this dance had the right properties with which to build a quantum computer. But the challenge has been realizing this in practice, and a big part of my research is working with experimentalists to make it happen." Altman is currently exploring alternative approaches for realizing topological protection of quantum information by generating the state dynamically in a quantum circuit, rather than as the ground state of a material.

In fact, "topological materials are sort of a holy grail for quantum computing," says Professor **Joel Moore**. He is co-author of a recent book, "Topological Phases of Matter," an authoritative review of the state of the science. He describes it as an exceptionally dynamic field of research that has generated new, topological notions of order, interactions, and excitations in physics. Moore's research interests include topological insulators, semimetals, and semiconductors—all of which could give rise to a new generation of materials and devices. He recently collaborated with Berkeley experimentalist **Joe Orenstein** and others on the first observation of how nonlinear optical properties, which measure how a material responds to intense light, can be governed by topology.

But topological quantum mechanics isn't just about creating new things. The field is providing fundamental insights applicable in other areas of pure research. That is certainly the case for assistant professor **Geoff Penington**. His research focuses on using ideas from quantum computing/quantum information in hopes of improving scientists' understanding of the quantum mechanics of gravity. It's work that leads him to search for answers about how information that falls into a black hole ends up being encoded in the Hawking radiation left behind after the black hole evaporates.

About working at Berkeley Physics, Penington says, "There's an atmosphere that I really like. It's a very collaborative and energetic environment, with a willingness to be ambitious, but without any sense of people competing against each other. We're all just feeding off each other's energy, trying to think about big problems, and getting excited about research progress. Berkeley is amazing for that."

Berkeley Quantum Computing Club Prepares Students for Leadership in Emerging Technology

FOR SUCH A COMPLICATED SUBJECT, the leaders of the Quantum Computing at Berkeley (QCB) club articulate a very straightforward mission:

"Our goal is to promote quantum computing in a diverse population of students—different majors, different people—and also to educate the campus community about what quantum computing is and how it will affect the future of technology and life," says 2022 QCB President Andris Huang.

"This year, one of our primary goals to promote education as much as possible. As a starter we updated our website (https://qcb.berkeley.edu) to incorporate a resource library, as well as a collection of tutorials and courseware," says QCB Co-President Elias Lehman. He says additional materials are planned, including a student-led course on Full Stack Quantum Computing.

Last year's QCB President, Emilia Dyrenkova, says the club provides an opportunity for undergraduate students to approach an otherwise daunting subject—she mentions the necessity for high-level understanding of mathematics—but to still get involved and demonstrate interest as they are learning.

As undergraduate leaders, she says, "We realize how hard it is to immediately start getting involved in something so high science, high tech as quantum computing. The entrance bar is quite high."

Lehman says his case is something of an example: "Last year I was browsing Berkeley's research programs when I came across Quantum Computing. Intrigued by the subject but having very little knowledge I needed to begin self-studying. That's when I joined QCB. It was my first extracurricular organization here at Berkeley so naturally I was shy to meet so many new faces, but my fellow members warmly took me in, quickly sharing the academic resources that helped them navigate the space effectively."

Members of QCB meet every Friday, and Huang says there are three main branches: education, a project group, and a reading group. Huang says for education, the group's student led course will be for "total beginners who don't know anything about quantum computing. The project group, he says, is based on online tutorials and research so that undergrads might get some hands-on experience. The reading group, he says, tackles advanced research papers for group discussion and probably requires greater familiarity and understanding of the subject matter.

Another highlight of the club, says Dyrenkova, is the opportunity to hear invited talks by industry speakers. Such as Denise Ruffner, Chief Business Officer at Atom Computing; Terry Rudolph, a founder of PsiQuantum; and Jack Hidary, CEO of Sandbox AQ.

As Berkeley students, Dyrenkova says, "I think it's really important that we invite speakers with different backgrounds."

There's a joke among fans of quantum computing that "you need a PhD even for marketing roles," says Huang. As a junior, he says he thinks he is headed in the direction of graduate school.

Dyrenkova, a senior who spent a summer semester at Canada's Waterloo University participating in quantum research, says she will be applying to graduate schools soon and would like to to work on quantum simulations research. "The club helped me a lot in getting here," she says, particularly her work with QCB's advisor and Berkeley Physics Associate Professor **Hartmut Haeffner**.

> "We realize how hard it is to immediately start getting involved in something so high science, high tech as quantum computing. The entrance bar is quite high."

"What I'm most excited to see is how the investment we put into education today will pay off in the form of accomplished research in just a few semesters," Lehman says of students who participate in QCB. "Next semester, we're launching our Quantum Undergraduate Opportunities in Research program as an intermediate step between education and advanced research. There is so much more to explore in this field. I can't wait to see our generation lead the way."

QCB Leaders (L to R): Sidharth Duthaluru, Riley Peterlinz, Samyak Surti, Elias Lehman, Emiliia Dyrenkova, and Andris Huang.

DEPARTMENTNEWS

Orebi Gann Group Partners with Seal Storage Technology

NEUTRINOS ORIGINATE FROM SOME OF THE MOST MIND-BENDING ELEMENTS of the universe: black holes, exploding stars, and the big bang. Researchers such as Professor **Gabriel Orebi Gann** and her group at UC Berkeley are creating a detector to trap these mysterious "ghost particles" to uncover mysteries of the universe. Web3 decentralized cloud storage provider, Seal Storage Technology, is partnering with the Berkeley Orebi Gann Group to provide secure and immutable storage for the neutrino data. The groundbreaking research is not possible without a reliable place to house the data.

This new detector will be four tons and a couple of meters in scale— a prototype for a larger detector, Theia, that will weigh 25 to 100 kilotons and be several tens of meters in scale. Such a detector can give clues about the origins of the universe and push the boundaries of research ranging from high-energy to particle and nuclear astrophysics. Since these detectors are enormous, they create a large amount of data that needs secure storage.

"Nuclear and particle physics experiments have an ever-increasing need to store and access large amounts of critical, unique data," says Orebi Gann. Our team is developing novel technologies that will be used to address fundamental mysteries about the nature and formation of our universe and for applications such as nuclear nonproliferation activities. We are excited to work with the Seal team to address the challenge of data handling for the exponentially increasing data sets produced by next-generation experiments."

Above: Professor Gabriel Orebi Gann

Post-Pandemic, the Berkeley Physics International Education Program is Picking Up Steam

WITH COVID-19 RESTRICTIONS ON TRAVEL AND IN-PERSON ACTIVITIES NOW BEING RELAXED, the Berkeley Physics department is seeing a resurgence in its Berkeley Physics International Education (BPIE) program. The program partners with universities around the world to provide undergraduate international students an opportunity to study abroad at Berkeley for a semester or an entire year without the need to go through the university's normal admissions process.

The students are first nominated by their home universities—most are from mainland China, but the program is expanding—and then they apply. "They're selected by us once we have reviewed their applications, entrance exam scores, and language proficiency tests," says Berkeley Physics Director of Student Services **Claudia Trujillo.** "Berkeley Physics is ranked top in the world and so we have a lot of demand for students."

Academic opportunities through BPIE include studying physics with some of the world's best students and most distinguished faculty, courses that include quantum mechanics, atomic physics, solid state physics, biophysics, string theory, cosmology, and more; and Berkeley courses count toward credit at students' home universities.

What's more, Trujillo says, BPIE students enjoy opportunities to meet with faculty, tour research labs, and attend workshops on applying to graduate school at Berkeley as international students. She says extracurricular activities include hiking trips near campus, movie outings, as well as access to UC Berkeley libraries and recreations sports facilities. What's more, the program includes field trips to nearby places of interest like the Lawrence Hall of Science, visits to San Francisco, and scenic tours of the Pacific coastline.

Trujillo says past participants have commented positively on the rigor and structure of the program. "They highlight how much they like the approach to teaching, the faculty/student lunches that facilitate conversation with researchers, and the opportunity to do research with Berkeley faculty. And they appreciate the life experience—to be somewhere else and challenge themselves."

But the pandemic, of course, changed everything at least for a time.

"We ran the program with great success for a year and one semester before the pandemic," Trujillo says. "We had 45 students in the first year." When the pandemic and pandemic-related shutdowns and restrictions came into play in March 2020, the program took a huge hit. But starting with the 2021-22 academic year, BPIE had 11 students for the first semester and then 15 more in the second. Administrators expect to return to pre-pandemic levels of participation, Trujillo says, and the program will still have room to grow.

"We're slowly starting to pick up momentum again," Trujillo says. "Students are coming back and they're extremely happy." She says program administrators have begun coordinating and partnering with student organizations to make this year's program rewarding for BPIE students.

"They're an important part of our community," Trujillo says of program participants. "It's a lot of work, as you can imagine, but it's really rewarding to know that our efforts make for a good academic and life experience. "

Alumni Stories

Exciting Research at Berkeley Physics Inspired Astrophysicist Danielle Speller

It's year three of Danielle H. Speller's search for answers to questions behind the so-called matter-antimatter asymmetry of the universe, as well as the search for dark matter. The Johns Hopkins University Assistant Professor of Physics explains that, based on the laws of physics, particles of matter and antimatter should be created in equal amounts.

Speller working at Yale University's HAYSTAC experiment.

Should be.

"So, if you had the same amount of matter and antimatter created in the same area of the universe, early on, you would have expected them to annihilate each other and what you'd be left with is energy," Speller explains. Instead, our world is made of protons, neutrons, and electrons rather than positrons, anti-neutrons, and anti-protons.

"Pretty much everything is made out of matter," says Speller, an experimental nuclear and particle astrophysicist who received her PhD degree in 2017 in the Berkeley Physics Department. "We observe very little antimatter naturally in the nearby observable universe and so one of the questions we have is why that might be the case."

Toward that end, Speller is a collaborator on such international physics research projects as Italy's Cryogenic Underground Observatory for Rare Events (CUORE) and Yale University's HAYSTAC (Haloscope at Yale Sensitive to Axion Cold dark matter) experiment, which is looking for a dark matter candidate called the axion. Her related graduate work at Berkeley included the Super Cryogenic Dark Matter Search (SuperCDMS) experiment.

Speller says one of the reasons she chose Berkeley Physics for her graduate studies was her familiarity with the campus and the department's research as an undergraduate intern at Lawrence Berkeley National Laboratory.

"When I applied to graduate school, I tried to apply to places that I knew were doing really exciting research," she says. "The Berkeley graduate students I met seemed to be in a good place in terms of their interests and excitement about what they were doing. "

And it was also a matter of prayer, Speller says. "I was really trying to figure out what direction I wanted to follow for research coming out of undergrad [at North Carolina State University]." She found her way at Berkeley Physics.

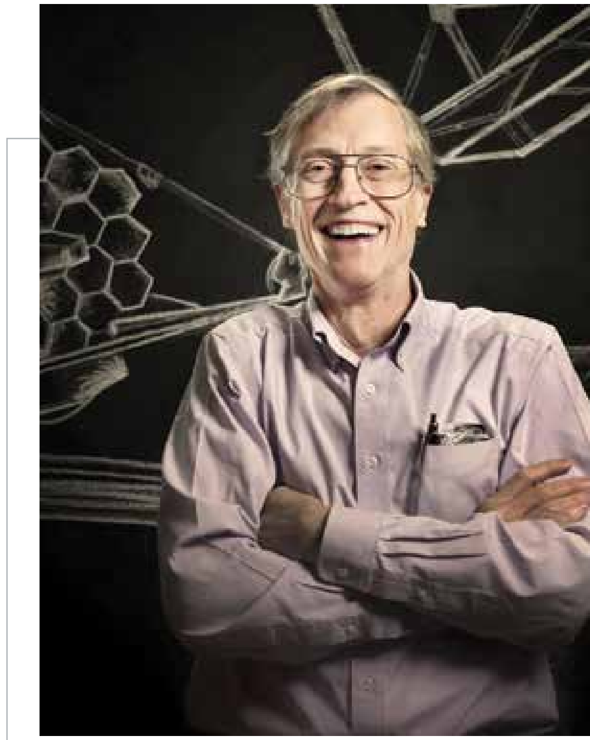
Alum David Klein Finds Inspiration from Life's Unique Moments

Inspiration can arise from many unique moments in life, but for David Klein, founder of Gener8, LLC in Sunnyvale, California, the idea for his company popped up during a trip in the early 2000s with the Berkeley Hang Gliding Club.

At the time, "a fair number of Berkeley physicists and engineers were in that group," Klein recalls. He mentioned to a fellow Berkeley PhD, who was looking to start his own company, Klein's idea for an engineering services firm that would focus on commercializing complex instrumentation. About two months later, Klein says, his colleague approached and asked, "'are you actually going to do that company because I will be your first customer.'"

Klein says the experience is part of the frothy entrepreneurial spirit of the Berkeley area, including nearby Silicon Valley, that he first encountered as a Berkeley Physics PhD candidate in 1992. He credits his graduate education with helping him build a "unique perspective on system design. The thing about physics is that you have to know a little bit about everything." Being a maker of precision instruments, he says, can be akin to putting together a group of musicians/specialists. "It's not about having a great first violinist but a very good one, coupled with a very good clarinet player, trumpet player, and so on. It's about being able to take all of those talents and make them work together in harmony."

PHOTO COURTESSY OF DAVID KLEIN



CREDIT: CHRIS GUNN

As NASA's James Webb Space Telescope Looks Back in Time, UC Berkeley Alum John Mather Explains How

The James Webb Space Telescope awed the world on July 12 with the unveiling of its first pictures of the universe. For John Mather, UC Berkeley Physics alum and senior project scientist for the National Aeronautics and Space Administration's new telescope, it was another important milestone in 25 years of work aimed at unraveling the secrets of the cosmos. His previous work on the Cosmic Background Explorer satellite culminated in Mather being named co-recipient, with George F. Smoot, of the 2006 Nobel Prize in Physics for discoveries supporting the big bang model for the beginning of the expanding universe.

When asked what discoveries can be expected with the Webb, Mather explains, "Well, the telescope does look back in time by looking at things that are far away. Light takes a long time to get here from there. So we can look back not quite all the way towards the beginning. But if nature gave us an object to look at, then we should be able to see it as soon as 50 or 100 million years after the expansion started up. So those primordial objects are purely predicted at the moment. Nobody's ever seen them. But we built the Webb telescope so that we could see if they are there." On what the project might answer, he added, "Basically everything from here in the solar system all the way out as far back as you can possibly go in time to tell the story of the universe: How did it go from the big bang to people?"

Pulitzer Prize Winning Alum Natalie Wolchover Tells Her Story

One sleepless night during her time as a graduate student in the Berkeley Physics Department helped place alum, Natalie Wolchover, on a path to winning one of journalism's highest honors: the 2022 Pulitzer Prize for explanatory reporting, for an article on NASA's James Webb Space Telescope (JWST).

Wolchover explains that, even though she had always wanted to be a physicist, "I suddenly realized I wanted to be a physics writer instead." She stayed up all night mulling over the decision, "realizing that physics writing sort of brought all my interests together in a perfect way."

More than personally pursuing answers to any of the puzzles modern physics researchers confront, Wolchover says, "I am kind of drawn to developing the big picture, understanding how the pieces fit together into an overall narrative. I love the ideas, but I love to crystallize them both for myself and for readers as well."

She left Berkeley in 2010 to pursue a science writing career in New York. After working at a couple of science publications, she went to work for the Simons Foundation that would launch, in 2013, a new online publication today known as Quanta Magazine.

About six months before JWST's launch, Wolchover and her editor decided that she should tell the story about the 30-year development of the telescope, the development of telescopes generally, "and how so much of what we know about the universe comes from the work that goes into building these instruments."

The story included the history of exoplanet science and how JWST would advance it by searching for biosignature gases and atmospheres on other worlds, as well as cosmology and astrophysics. She says it all added up to "this kind of epic narrative" in which she fell in love with many of the characters who had a hand in building the telescope, the success of which was far from certain.

Wolchover saw the story as a "way to give people an understanding of what science is, how it works, and how it's ultimately this beautiful enterprise that humans are engaged in."

Above: Wolchover giving a talk at New York University's Arthur L. Carter Journalism Institute.

Editor's note: Natalie Wolchover will be the Berkeley Physics 2023 Commencement speaker.

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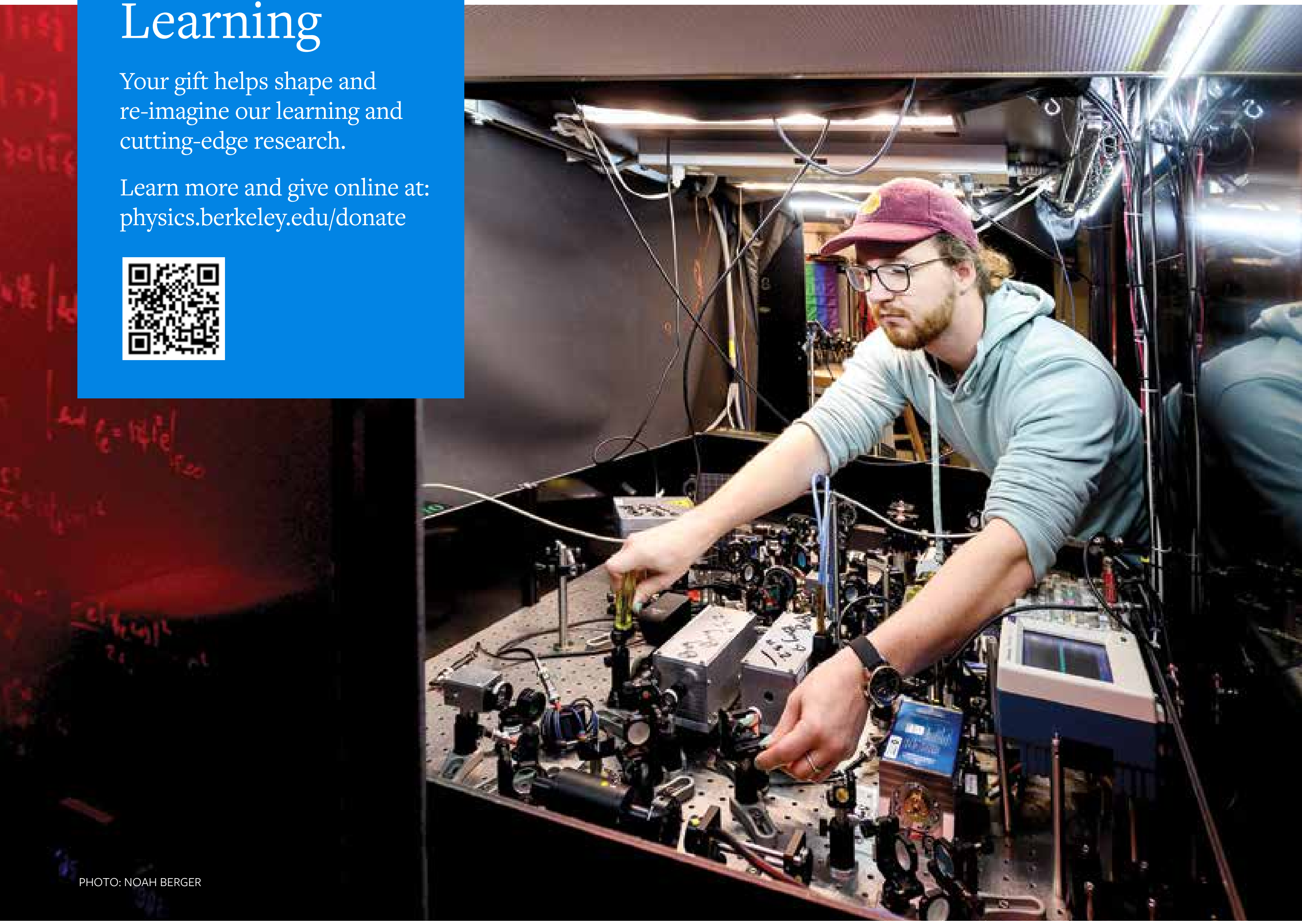

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