# Berkeley Physics

FALL 2023



## Leading the Search for Dark Matter

# Berkeley Physics

**ON THE COVER:**
Postdoctoral researcher Junsong Lin and graduate student Yue Wang install a prototype HeRALD dark matter detector on the base of a dilution refrigerator.

**BACK COVER:**
Postdoctoral scholar Lucas Schneider and graduate students Emma Berger and Michael Arumainayagam in the Michael Crommie Lab.

**CHAIR**
Irfan Siddiqi

**DIRECTOR OF ADMINISTRATION**
Roia Ferrazares

**CONTRIBUTING EDITOR & SCIENCE WRITER**
Jennifer Huber

**MANAGING EDITOR, ART DIRECTOR**
Sarah Wittmer

**CONTRIBUTORS**
Noah Goss
Gabriela Felipe Spirandelli

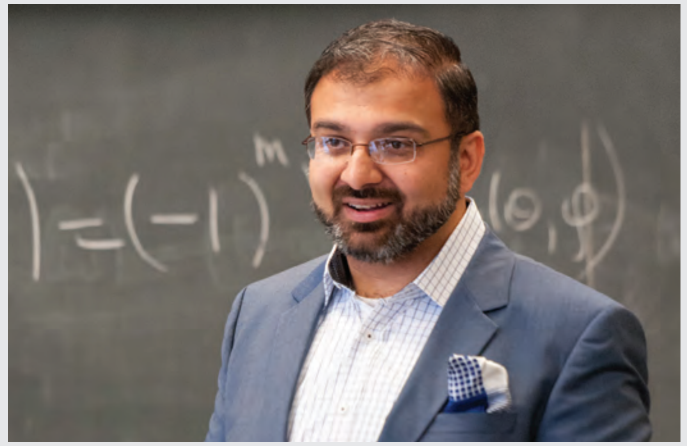
**COVER PHOTO**
Noah Berger

Send comments, alumni updates, and changes of address or email to:
physicsalum@berkeley.edu

Published annually by the Department of Physics, Division of Mathematical and Physical Sciences, University of California, Berkeley
366 Physics North
Berkeley, CA 94720-7300
Phone: 510-642-3355



## CHAIR'S LETTER



Physics is thriving at Berkeley with research milestones galore. In this issue of Berkeley Physics, you'll get the inside scoop on a quantum materials cookbook from master chefs Professors Crommie, Lanzara, and Wang. They outline three ways to prepare a designer 2D material from atomically-thin films: stack and rotate films, regulate the population of electrons, and engineer composite excitations. They also describe their custom tools used to probe the materials' exotic properties. These atomic pancakes may be the transistor of this generation, driving quantum technologies that promise to revolutionize computation, communication, and sensing.

Teams of researchers at Berkeley are also employing cutting-edge instruments in their quest to illuminate the vast majority of matter in the universe which is, well, ... dark! For example, Professors McKinsey and Pyle look for WIMPs, which, contrary to their name, are comparatively massive. And Assistant Professor Safdi looks on the lighter side for axions, which may also hold the key to other mysteries of the universe involving gravity and quantum mechanics.

You'll also find some of the latest research highlights from the Department, including advances in atomic-clock-based metrology and quantum computing with ternary logic. Not only can the proverbial cat be asleep and awake at the same time, it may simultaneously be in a third state where it sleepwalks.

We celebrate our alumni by sharing their stories. What they have in common is the problem-solving acumen of a physicist—a gift that allows our graduates to make a profound impact in whichever field they pursue. Berkeley Physics alum and Nobel Laureate John Mather was honored as Cal's Alumnus of the Year for his many contributions including work on the James Webb Space Telescope, which continues to dazzle us with spectacular images of outer space. Alum Gina Quan, now a professor at San Jose State University, was active in the Compass Project while at Berkeley. She has now seeded new efforts to promote equity and inclusion in STEM fields, including spearheading studies recently commissioned by the National Science Foundation.

Please accept my well wishes for a productive year and don't forget to stay connected! Together we can usher in the next genre of scientific excellence at Berkeley.

Irfan Siddiqi, Chair

## CONTENTS

# Berkeley Physics




# Exploring the Mysteries of Exotic 2D Materials

Berkeley faculty build novel tools to understand the fundamental properties of materials

**BERKELEY PHYSICS FACULTY ARE DRIVEN** to understand the fundamental physics of materials. Theorists hypothesize the existence of new forms of matter and behaviors, and their experimentalist colleagues develop novel materials and tools to observe these exotic properties.

"We can now control parameters to systematically study how a material goes from one quantum phase to another quantum phase," says Berkeley Physics Professor Feng Wang, the Williams H. McAdams Chair in Physics. "Instead of solving equations in a computer, we can design model systems in our lab to test and understand the underlying mechanisms of phase formation and the properties of different phases."

The community of condensed matter physicists researching exotic materials includes experimentalists Mike Crommie, Alessandra Lanzara, and Wang, who are physics professors at Berkeley and senior faculty scientists at Lawrence Berkeley National Lab.

Although understanding the fundamental physics is what most excites Berkeley physicists, they also expect exotic materials to lead to important applications.

"People talk about using these new materials for future quantum technology—either in quantum sensing or quantum computation—where switching is done by alternating between quantum states," says Wang. "People are also exploring whether they can replace silicon, allowing transistors and electronics to become even more miniaturized."

## BUILDING EXOTIC 2D MATERIALS

How to create exotic 2D materials is not obvious, but Crommie offers some guidance.

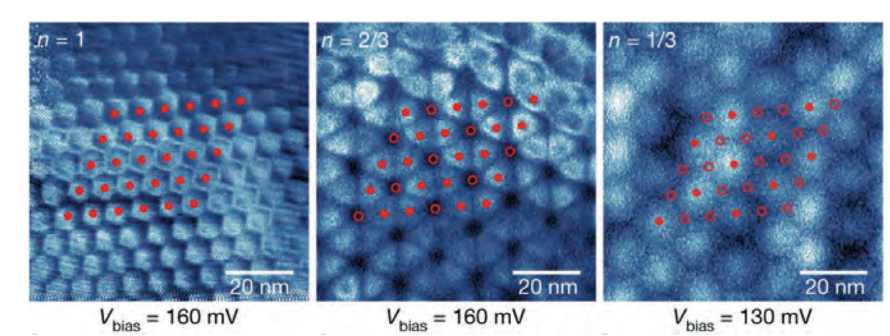
"In most conventional materials, the periodicity—the distance between the atoms and how they're arranged in the lattice—determines the behavior. Electron-electron interactions and topology don't play a big role," says Crommie. "We make so-called exotic 2D materials by modifying these properties using techniques developed in recent years, using three general approaches."

In the first approach, the researchers stack and rotate atomically-thin layers of different materials to create what is called a 2D moiré superlattice. Strong covalent bonds provide in-plane stability, whereas relatively weak van der Waals forces hold the layers together. And a small mismatch in the spacing of the atoms between the layers produces an interference pattern—like when you put two screens together and rotate one—thus creating a new superlattice periodicity.

"Moiré superlattices allow us to engineer new lattices for electrons and to control their correlation behavior," says Wang. "We're building quantum materials by design with an unprecedented control that doesn't exist in nature."

In the second approach, the scientists induce exotic behavior from conventional 2D materials by very carefully controlling the electron density and screening environment.

"For example, if we take a single layer of a transition metal dichalcogenide (TMD) and put electrons in it at a very low density, then the electrons crystallize into a pattern called a Wigner crystal," says Crommie. "That's a very exotic behavior where the electrons freeze like ice




Opposite page: Graduate student Jingxu Xie climbs a ladder to align the optics atop the millikelvin cryostat in the Feng Wang Lab.

Below: A diagram showing two-dimensional generalized Wigner crystals: the crystalline phase of electrons stabilized at low electron density.

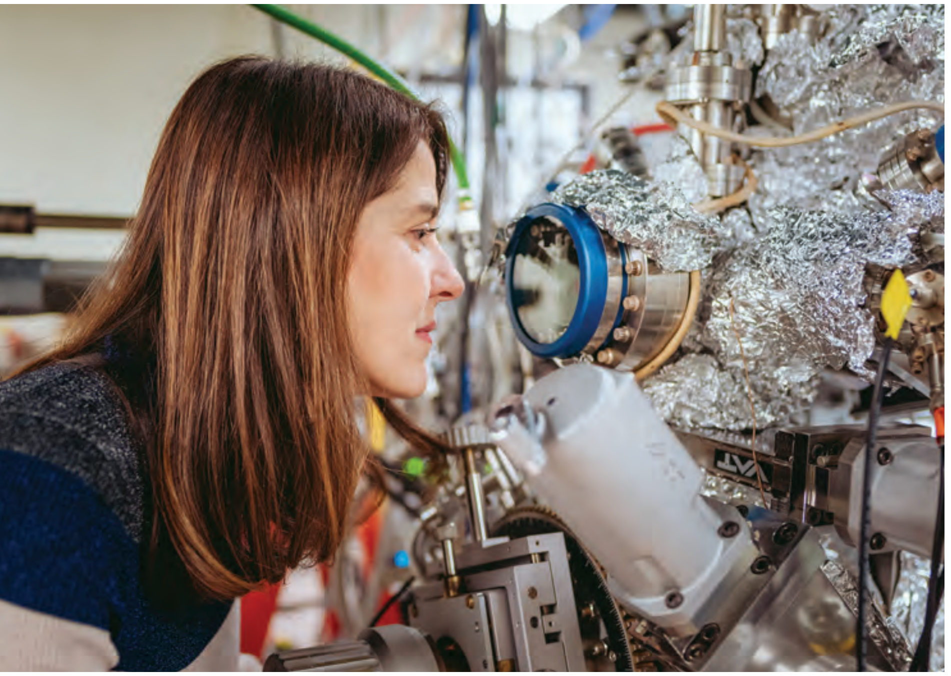


PHOTO: MARK JOSEPH HANSON

“Having access to higher resolution tools and new ways of probing materials is how we make new discoveries. It’s a must if you want to lead the way to new science.”

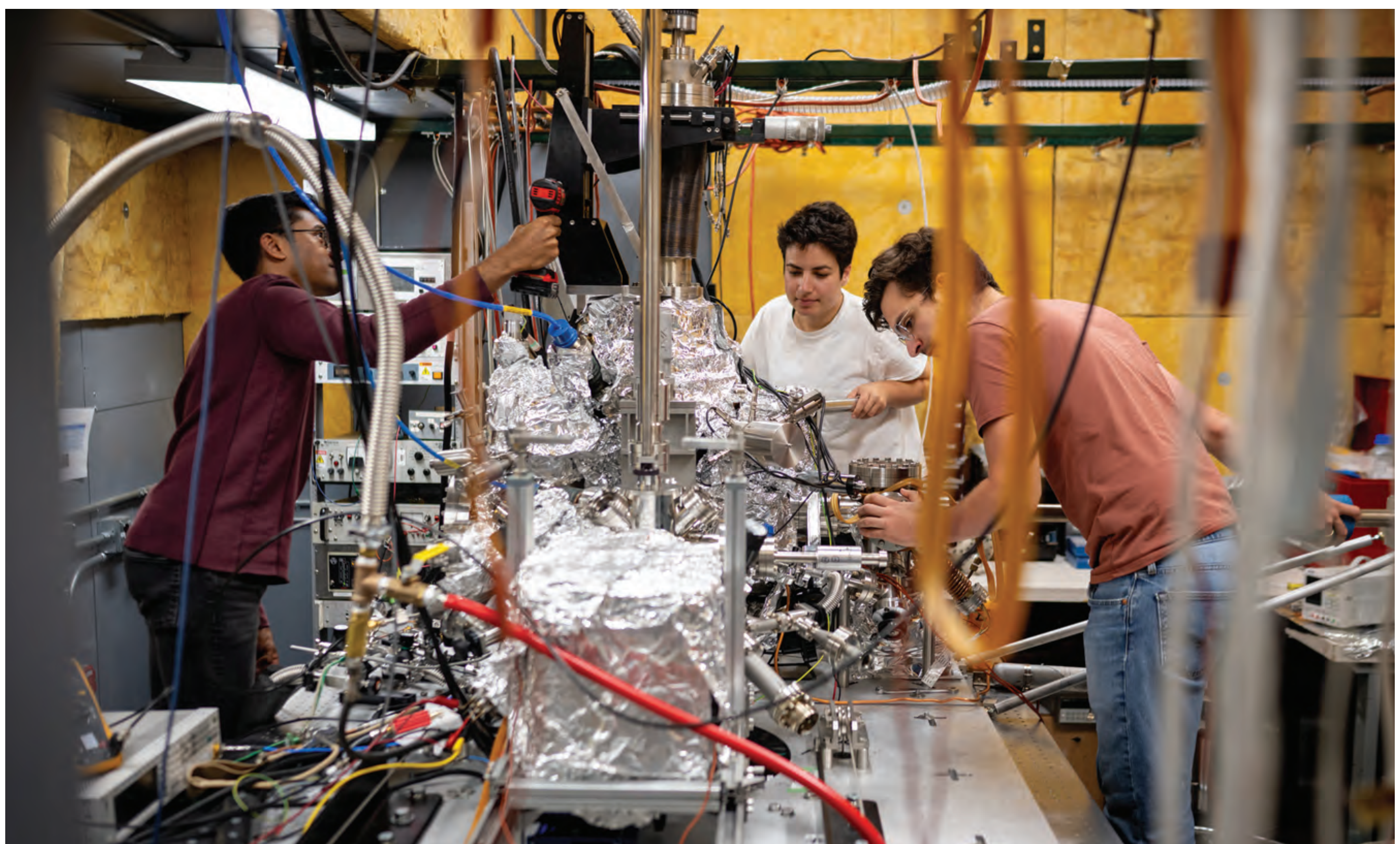


PHOTO: KEEGAN HOUSER

Right: Graduate student Dhanvanth (Danny) Balakrishnan fabricating air-sensitive 2D material nanodevices in the glove box.

Opposite page, top: Professor Alessandra Lanzara uses custom-built state-of-the-art equipment to study the formation of a topological exciton state in a 2D material.

Below: In the Michael Crommie Lab, graduate students Michael Arumainayagam and Emma Berger and postdoc Lucas Schneider prepare 2D heterostructure devices for study in their scanning tunneling microscope.

PHOTO: KEEGAN HOUSER

into a new crystalline phase, because the potential energy dominates over the kinetic energy. Wigner crystals were predicted almost 90 years ago, but we can image them now in new 2D materials.”

In the third approach, they create novel excitonic states in topological insulators, materials that behave like an insulator in their interior but conduct electricity along their surfaces.

“On the surface of a topological insulator, it’s like there are two freeways for electrons. Electrons with one spin move in one direction, and electrons with the other spin move in the opposite direction,” says Lanzara, the Charles Kittel Chair in Physics. “Our goal is to use optical pulses and leverage the topology and bulk/surface properties of these materials to engineer new quasiparticles.

## DEVELOPING NOVEL TOOLS

To build and investigate a diverse range of exotic 2D materials, Berkeley physicists are pioneering new techniques. “Having access to higher resolution tools and new ways of probing materials is how we make new discoveries. It’s a must if you want to lead the way to new science,” Lanzara says.

These experimentalists have favorite tools; for example, Wang specializes in studying how light interacts with materials.

“We use optical photons from near microwave to UV,” says Wang. “The combination of optical modalities depends on the material and the specific questions we’re trying to answer.”

Optical spectroscopy is Wang’s primary technique. But his group also uses scanning tunneling microscopy (STM), including a novel non-invasive spectroscopy technique he developed with Berkeley Physics Professors Alex Zettl and Michael Crommie.

Together they built a moiré superlattice from single layers of tungsten diselenide and tungsten disulfide and then added a spacer layer of boron nitride capped by a top layer of graphene. The graphene layer enabled them to sense a delicate crystal of electrons within the TMD moiré structure without destroying it with the STM tip. The spacer layer prevented electrical shorting and permitted independent doping for the TMD and graphene layers.

“We made the first real-space images of 2D Wigner crystals in our moiré superlattice by actually imaging a lattice formed by electrons. We were able to see the correlated ground state and interesting excited state properties,” Wang says.

This approach could also be used to image electron lattices in other materials, rather than relying on a “magic angle” between the layers to control the correlations. “Our TMD moiré superlattices exist even at zero twist angle due to the lattice mismatch, and the correlation effects remain strong,” says Wang.

Berkeley physicists are also directly measuring electrons and spin in momentum space using novel spin-, time-, and angle-resolved photoemission spectroscopy pioneered by Lanzara and her coworkers. In this technique, a material is irradiated with a beam of ultrafast photons and the spin, speed, and direction of the ejected photoelectrons are measured with incredible sensitivity to figure out what’s happening inside the material. Lanzara’s latest instrument, named the momentum nanoscope, can also look at real space.

Lanzara recently used her state-of-the-art system on the topological insulator bismuth telluride to search for novel types of excitons, which are charge-neutral quasiparticles created when light is absorbed in a semiconductor. Her team discovered and characterized the first spatially indirect topological exciton state. “The electron trapped on the surface is coupled to a hole confined in the bulk, generating a long-lasting spatially-separated exciton that retains the special spin properties inherent to topological states,” she says.

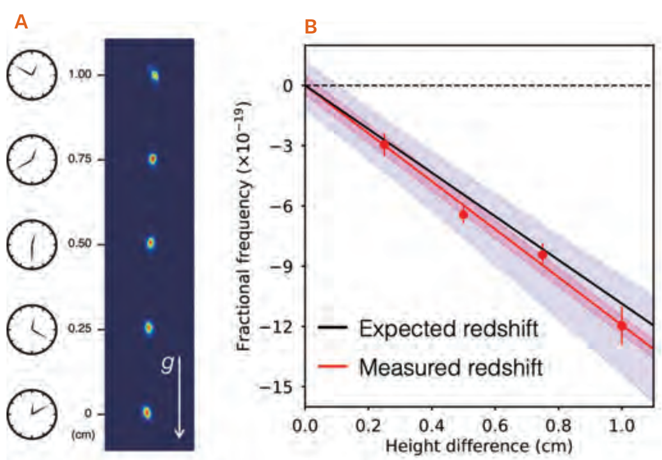
One potential application of exotic materials is sustainable electronics that stays cool. “Your cell phone and computer heat up because charges bounce into each other as they move,” explains Lanzara. “Some of these new 2D and topological materials allow information to be transported instead through spin, minimizing interactions and eliminating heating issues. Moreover, they can be combined as Lego-like blocks, enabling easy assembly of materials on demand that are reusable and recyclable.”

Just think, you might have an exotic 2D material in your pocket someday.

# Research Highlights

## Testing Gravitational Time Dilation with Array of Miniature Clocks

**Einstein's theory of general relativity predicts that gravity causes time to pass more rapidly for a clock higher off the ground than an otherwise identical lower clock. Correcting for this relativistic effect is vital to the location accuracy of global positioning systems (GPS) because it causes the clocks in satellites to tick faster than their counterparts on the ground. But gravitational time dilation is also important to theoretical physics.**



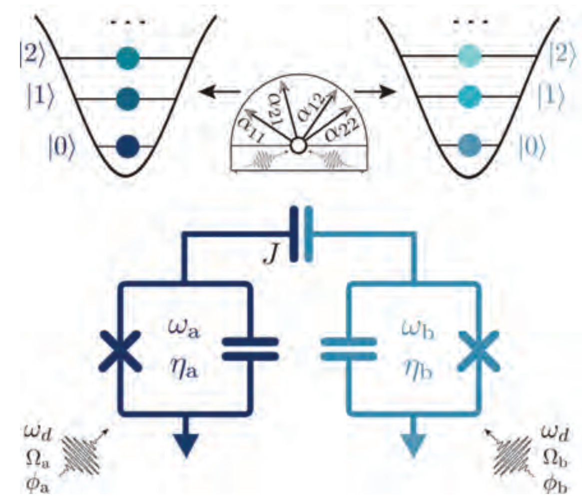

Above: (A) Camera image of 5 strontium atomic clocks spaced 2.5 mm apart. (B) Clock frequency difference as a function of height difference, showing the measured rate difference between clocks (red line) agrees with the theoretical prediction one (black line).

"We're still trying to understand how general relatively and quantum mechanics fit together. They're both incredibly successful theories whose predictions have thus far always proven to be true, but they're fundamentally at odds with each other," says Shimon Kolkowitz, Berkeley Physics associate professor and the Roger Herst Professor in Physics. "So, we're exploring the interface between quantum systems and relativity."

Kolkowitz recently tested gravitational time dilation in his lab using a novel quantum clock network—comprised of five evenly-spaced ensembles of ultracold $^{87}Sr$ atoms trapped in a vertical 1D optical lattice that spanned a total height difference of 1 cm. Using an array of clocks with the same atomic resonance, optical lattice, vacuum chamber, and apparatus allowed his team to measure the rates the clocks were ticking with respective to each other with 19 decimal places of precision and accuracy.

"When we corrected for all the systematic shifts using pairwise comparisons and we unblinded our data, our more precise and accurate results confirmed time passes more rapidly for a clock 2.5 mm higher off the ground in a way that's entirely consistent with the predicted gravitational time dilation," says Kolkowitz.

"We have a whole new playground for exploring relativity and quantum mechanics. For example, what happens when the atoms are experiencing different heights simultaneously?" he says. "We're also developing new applications for these clocks, including searching for dark matter."




Right: Technical illustration of two-qutrit entangling gates at fixed frequency and coupling.

## Generating Two-Qutrit Entangling Gates for Quantum Computing

**Like Schrödinger's famous cat, a quantum bit (or qubit) can exist in a simultaneous superposition of two states. Quantum computers entangle many qubits together, causing them to become correlated at a quantum level and no longer describable as individual systems.**

By exploiting large-scale entanglement, researchers can generate increasingly complex quantum states. Ultimately, their goal is to build quantum computers capable of quickly solving problems too complex for even the most powerful conventional supercomputer.

Most research on the design and control of quantum processors currently focuses on two-level qubit systems. But a collaboration of researchers at UC Berkeley's Quantum Nanoelectronics Laboratory and Berkeley Lab's Advanced Quantum Testbed are now using three-level (qutrit) systems to develop a superconducting quantum processor.

"Ternary quantum information processors potentially offer significant advantages in quantum simulations, error corrections, and algorithms," explains Noah Goss, a Berkeley Physics graduate student involved in the work. "Entangling two-qutrits, however, is challenging because the quantum system is more complex, so we had to introduce a new approach."

Recently, the Berkeley team achieved a breakthrough by implementing a faster, flexible, and tunable entanglement between two qutrits. They then used their approach to engineer two types of two-qutrit logic gates.

"We successfully entangled two qutrits on a superconducting quantum processor with gate fidelities significantly higher than in previously reported works," says Goss. "This represents a significant step towards enabling qutrit-based quantum computing."

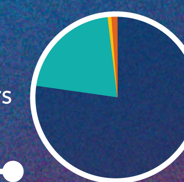


# 2023 AT A GLANCE

## Berkeley Physics Students and Faculty

### Undergraduate Majors 333

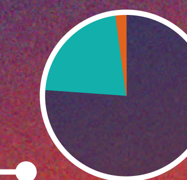
257 male physics majors
71 female physics majors
2 nonbinary physics majors
3 prefer not to say



122 transfer students
110 BA degrees awarded in 2022-2023
35 BPIE (Berkeley Physics International Education) cohort

### Graduate Students 259

198 male physics grads
56 female physics grads
5 prefer not to say



20 countries
45 Ph.D. degrees awarded in 2022-2023

### Physics Faculty

62 active faculty members
34 emeritus faculty
4 Nobel Laureates
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 Physics 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

# Leading the Search for Dark Matter

PHOTO: NOAH BERGER

CREDIT: MALTE BUSCHMANN, PRINCETON UNIVERSITY.

## Berkeley experimentalists and theorists hunt for the missing mass

Left: Postdoctoral researcher Ibles Olcina Samblas and graduate student Yue Wang install a prototype HeRALD dark matter detector on the base of a dilution refrigerator.

Above: In a simulation of the early universe, shortly after the Big Bang, tornado-like strings (dark blue loop) throw off axion particles. These axions should still be around today and they could be the dark matter that astrophysicists have been searching for.

**SCIENTISTS HAVE BEEN STUDYING THE COSMOS** for centuries, but we still don't know what makes up 85% of all matter in the universe. Unlike ordinary matter that we can see and feel, dark matter hasn't been observed directly by even our most advanced scientific instruments. These invisible particles may be zipping through us all the time without interacting.

But scientists believe our world wouldn't exist without dark matter. Its gravitational pull holds galaxies together, gathers them into clusters, bends light around them, and affects how they rotate. Dark matter also played a crucial role as galaxies initially formed.

"Lots of observational data show us that dark matter is a real particle, but we don't know what kind. Its possible mass has a huge range, and there might be multiple types of dark matter particles," says Berkeley Physics Professor Dan McKinsey, the Georgia Lee Chair in Physics. "We're working hard to detect dark matter in the lab to open a window into new physics. It's the only particle we know to exist outside the standard model."

Berkeley Physics is one of the top places in the world to study dark matter. Experimental and theoretical physicists at Berkeley are leading far-reaching searches—hunting for dark matter candidates ranging from 1 TeV weakly interactive massive particles (WIMPs) to 1 MeV light dark matter particles down to 10 µeV axions.

Berkeley faculty are conducting, building, and designing next-generation dark matter experiments, including the LZ, SuperCDMS, TESSERACT, and ALPHA plasma haloscope. These innovative experiments are guided by models developed by Berkeley Physics theorists, including professors Hitoshi Murayama, Lawrence Hall, and Ben Safdi. We highlight only a few of these comprehensive efforts here.

### HUNTING FOR WIMPS WITH LZ

One promising candidate is WIMPs, weakly interacting but heavy dark matter particles with a predicted mass of about 10 GeV to 100 TeV. A GeV is roughly the mass of a proton.

Hunting for WIMPs over 9 GeV is the aim of LZ, the larger and more sensitive successor of the LUX experiment. After 60 days of running, LZ recently became the most sensitive dark matter detector in the world. Berkeley Physics Professor and Berkeley Lab Director Mike Witherell, Emeritus Professor Bob Jacobsen, and McKinsey contributed to this success.

Because dark matter particles rarely interact with ordinary matter, their signal is easily drowned out by background noise. To shield from cosmic rays, LZ is located nearly a mile underground at the Sanford Underground Research Facility (SURF) in South Dakota. To reduce radioactive contamination, it uses ultra-clean detector materials. And to lower environmental backgrounds, it is built in several layers like an onion.

At the center of LZ is a time projection chamber (TPC)—a tank filled with seven tons of highly-purified liquid xenon. If a dark matter particle strikes a xenon nucleus, a flash of light and an electric charge are produced as the nucleus recoils. A strong electric field drifts the charge to the top surface of the TPC, where the electrons create a much larger flash of light that is measured by photomultiplier tubes on top and bottom.

The pattern and timing of the two flashes pinpoint the position and energy of the event. And the ratio of the two scintillation signals determines if the event was caused by a nuclear or electron recoil.

Outside the TPC are two veto detectors—a "skin" holding three tons of liquid xenon and then an "outer detector" of gadolinium-loaded liquid scintillator—which are used to reject signals from gamma rays and neutrons, respectively. The whole thing lives inside a massive tank of water.

LZ is 25 times larger than the previous generation LUX experiment, which helps suppress backgrounds. But this increase also created a major challenge for McKinsey: designing and building a much higher high-voltage system to get the correct drift electric field, without the xenon lighting up like a neon lamp.

McKinsey also led the data analysis effort to reduce "accidental backgrounds" with support on backgrounds from Berkeley Physics postdoc Ibles Olcina and graduate students Jose Soria, Yue Wang, Ryan Gibbons, Ryan Smith, and James "Reed" Watson. "Occasionally, isolated first and second scintillation pulses randomly pair up to look like a dark matter event," explains McKinsey. "My group combed through data, produced a statistical model, and developed cuts to reduce these accidentals without cutting into our dark matter acceptance."

So far, LZ has found no evidence of WIMPs, but it set the most stringent limits on WIMP cross-sections and masses to date. And the second 1000-day run is underway.

"LZ is performing to specification, which is a big deal since we've been working on it for a decade," says McKinsey. "We're now poised to push through more dark matter parameter space over the next few years."

McKinsey is also helping to design the next-generation of LZ, a scaled-up 80-ton xenon experiment called XLZD.

## SEARCHING FOR LOW-MASS WIMPS WITH SUPERCDMS

SuperCDMS, the next-generation of the CDMS experiment, is located deep underground at SNOLAB near Sudbury, Canada. It plans to detect dark matter particles with a mass between 10 GeV and 0.5 GeV. Berkeley Physics Professor Emeritus Bernard Sadoulet led the NSF-funded part of its construction.

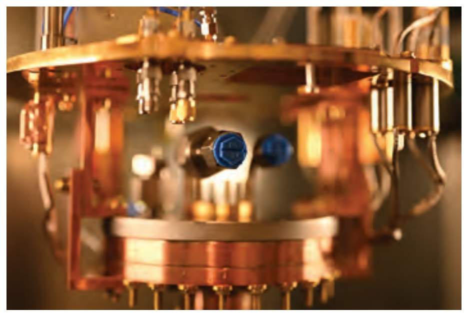
Searching for dark matter with lower mass requires more sensitive detectors. SuperCDMS uses germanium or silicon crystals attached to sensors on both faces. When a dark matter particle interacts with either semiconductor, its nucleus recoils and creates minute crystal vibrations (phonons) and ionization (charge). An electric field causes the charge to drift and shed lots of phonons.

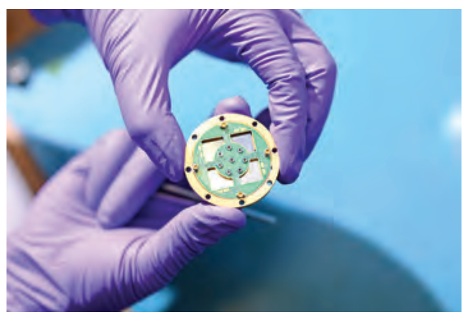
"Measuring both phonons and ionization gives us discrimination capability against backgrounds. And drifting the charges in the high-voltage detector increases our energy sensitivity by a factor of 100, allowing us to search for lower masses," says Sadoulet.

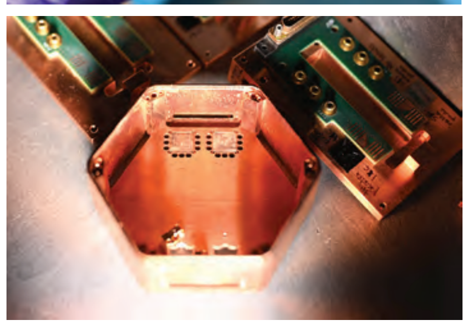
However, measuring these phonon signals is challenging. Berkeley Physics Assistant Professor Matt Pyle played a major role in developing this unique sensor technology with the help of Berkeley's associate research physicist Bruno Serfass and former postdoctoral fellow William Page.

At its core are transition-edge sensors (TES)—materials stabilized in the middle of their superconducting transition—attached to aluminum fin antennas. The fin absorbs the energy of the vibrations, concentrates it, and pushes it into the TES. The resulting increase in TES temperature changes its resistance, which is measured by cryogenic electronics.

"These phonon sensors need to be small to reduce their heat capacity. But if they're attached directly to a giant crystal, an athermal phonon bounces around for a long time before it interacts with the TES. By using fins, we increase the interaction probability and area coverage," says Pyle, the Michael M. Garland Chair in Physics.







PHOTOS: NOAH BERGER

Top: A prototype HeRALD detector mounted to a dilution refrigerator.

Middle: A calorimeter array (2 X 2) with transition-edge-sensor (TES) readout for the HeRALD experiment.

Bottom: Shown here as semi-transparent squares, sapphire dark matter detectors held within a larger hexagonal copper mount are used by the Matt Pyle Lab as part of the the SPICE experiment.

He adds, "Only about 30% of the energy is transferred to the TES using the fins, but that's more than made up for by collecting the phonons quickly before they thermalize."

The collaboration is currently installing the experiment at SNOLAB. Meanwhile, they have been commissioning the SuperCDMS detectors, software, and operations at CUTE, a nearby cryogenic underground test facility at SNOLAB.

Sadoulet notes that Berkeley Physics collaborations encourage technology and data analysis transfer between various groups. The core athermal phonon sensor technology and discrimination methods are being used in multiple experiments, including SuperCDMS and TESSERACT.

"We're giving a single solution that will hopefully be employed many times by many different experiments, all searching for slightly different things," says Pyle.

## SEEKING LIGHT DARK MATTER WITH TESSERACT

TESSERACT intends to take the dark matter search a step further. This umbrella of two experiments is being designed to detect light dark matter particles from both nuclear and electron recoils, in the mass range of the proton to the electron—1 GeV down to 1 keV.

The entire project will use identical Berkeley Physics next-generation sensors, readout technology, and operations—and no electric field for signal amplification.

"What makes TESSERACT unique is that every detector is designed to have multiple signal channels that have to be in coincidence for dark matter events. That's the secret idea sauce of TESSERACT," says Pyle. "We're also eliminating a whole class of backgrounds by going to zero field, which means we need very highly sensitive detectors."

McKinsey's group is helping develop TESSERACT's HeRALD experiment with assistance from Assistant Project Scientist Junsong Lin and graduate students Roger Romani, Will Matava, and Wang. HeRALD uses purified liquid helium as the target for nuclear recoil dark matter. Its silicon athermal phonon detectors are submerged in the vat of liquid helium and suspended in a vacuum above it.

"Using helium provides excellent background discrimination. If a dark matter event occurs in the helium, it lights up multiple pixels in coincidence, whereas a background event or microfracture in the silicon only lights up one pixel." Helium is also cheap, easy to purify, easy to scale up, and naturally immune to some backgrounds. HeRALD will initially be sensitive to dark matter particles from 1 GeV to 100 MeV, but the scientists hope to reach the keV scale in the future.

Pyle's group is helping develop TESSERACT's SPICE experiment. It uses polar crystals—either gallium arsenide (GaAs) or sapphire ($Al_2O_3$)—as the target for both nuclear and electron recoil dark matter. A polar crystal has two types of ions with opposite charges. Some dark matter candidates may transform themselves, with low probability, into photons, which then nudge the different ions in opposite directions. This produces phonons that can be detected by the TES.

For the GaAs part of SPICE, the photons and phonons are collected in separate detectors, enabling photon-phonon coincidence to tag the unique dark matter signature, says Pyle. This scheme is designed to detect dark matter between 1 GeV to 1 MeV, caused primarily by electron scattering.

To detect dark matter with even lower mass, the second part of SPICE measures only the athermal phonon signal using sapphire detectors with even better energy sensitivity.

Pyle's group is unraveling how to read out and calibrate these sapphire crystalline targets using his latest TES. Currently, the detectors are sensitive to dark matter in the GeV to MeV range, but the team hopes to get down to a keV.

McKinsey and Pyle are both enjoying their tabletop experiments. "If the detector is sensitive enough, then you can in principle detect light dark matter in your lab at the surface. It could happen," McKinsey says. But TESSERACT will be installed underground in the next few years—at SURF or the Modane Underground Laboratory.

## PROBING FOR AXIONS

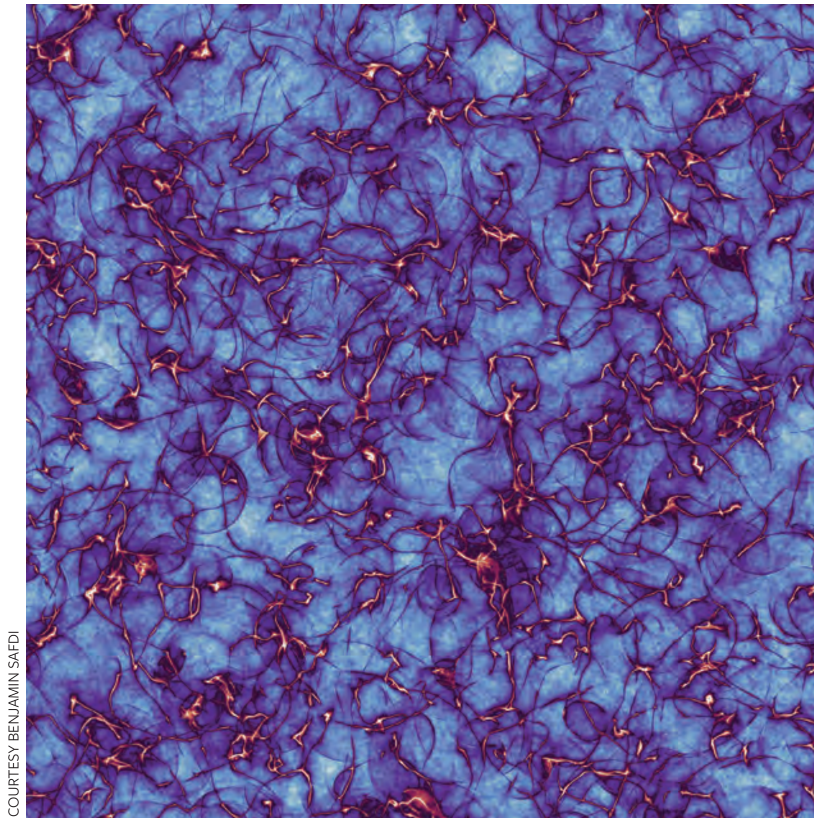
Berkeley Physics Assistant Professor Ben Safdi studies other dark matter candidates, but he finds the ultra-light axions to be the most compelling because they explain more than dark matter. Axions were first theorized to explain the mystery of how neutrons behave in electric fields. And they have deep connections to the consistency of gravity at a quantum level.

"Axions are theoretically very well motivated, and they're almost completely unexplored experimentally," says Safdi, who holds the Henry Shenker Professor in Physics. "In the next decade or so, we'll be able to say definitively whether or not these particles exist in nature."

> "We're working hard to detect dark matter in the lab to open a window into new physics."

Although Safdi is a theoretical physicist, he looks for indirect signatures of dark matter in experimental data with his team, including graduate students Yujin Park and Joshua Benabou. "My work starts theoretically, with pencil and paper and then simulations. For a particular astrophysical system or precision laboratory experiment, we ask how axions would affect it and what data we need to test these predictions. Then, we get and analyze those data sets, determining if we find evidence for axions or not."

Additionally, Safdi spends much of his time simulating how axions were produced shortly after the Big Bang to determine what mass gives the correct abundance of dark matter. For this work, he uses advanced supercomputers at the National Energy Research Scientific Computing Center (NERSC) at Berkeley Lab, which just commissioned its faster and bigger Perlmutter supercomputer. "We have lots of jobs up the hill churning away. It's a game changer for our mass prediction computations," says Safdi.



COURTESY BENJAMIN SAFDI

A zoom-in of axion strings in a simulation of axion dark matter in the early universe. The strings throw off axions that go on to become that dark matter. These simulations are used to predict the properties of the axion, which informs laboratory detection efforts.

One feature he needs to simulate in the early universe is axion strings, which are very violent but narrow regions of space—like tiny tornadoes—that whip around and emit lots of axions.

"During the simulations, a small part of the expanding universe is represented by a 3D grid over which the equations are solved," explains Safdi. "But the axion strings are moving, so we have to dynamically update the grid. Despite running on supercomputers, computer memory is our limiting factor."

Luckily, Safdi teamed up with the AMReX collaboration at Berkeley Lab, adapting their code framework designed to solve multi-scale problems. The key was using an adaptive mesh grid with a fine spatial resolution around the axion strings and sparse resolution elsewhere.

Using the biggest simulation of cosmology to date, they more precisely predicted the axion mass to be between 180 to 40 µeV, higher than expected. This claim implies axions from the early universe can't be detected by the current experiments, which use a microwave resonance chamber to enhance the photon frequency coming from axions. The required chamber would be too small to get a measurable signal.

However, Safdi's prediction excited Berkeley Nuclear Engineering Professor Karl van Bibber. He is building the ALPHA plasmonic haloscope, which creates resonant enhancement using parallel wires in a strong magnetic field. And van Bibber is waiting to tune his experiment using the more precise predictions Safdi is now calculating with the Perlmutter.

Overall, Berkeley Physics' search for dark matter is casting an impressively wide net. "Berkeley might be the best place in the world for dark matter research. I can't think of any place that's stronger overall and better," says McKinsey.


Clockwise from upper Left: Erika Isomura, Jeffrey Hunt, David Brahm, Marc Peters, and Nasreen Gazala Chopra.

PHYSICS

# Thinking Like A Physicist

## Berkeley Physics alumni apply their physics training to non-academic careers

**AS AN UNDERGRADUATE** at UC San Diego, I knew I wanted to work in science or engineering but I wasn't sure what I specifically wanted to do "when I grew up." That's why I majored in physics–it's versatile.

After earning a PhD in physics at UC Santa Barbara, I worked for years as an academic researcher at Lawrence Berkeley National Lab (LBNL). I later veered off this career path, merging my passions for science and writing. On the surface, my physics degrees may seem unnecessary for a science journalist, given that I mostly write about medical research. But my physics training is integral to how I research, interview, and write. So, I was intrigued to speak with several Berkeley Physics alumni doing non-academic jobs to see how they apply their physics degrees.

> "Physics education and training will serve you well in whatever profession you want to pursue."

Marc Peters is an intellectual property attorney at Turner Boyd LLP. He helps clients resolve disputes related to technology, including those involving patents, trade secrets, and copyrights.

According to Peters, "thinking like a physicist" means approaching issues with the right level of abstraction, which helps determine what matters, what does not, and what is "good enough." It also requires the curiosity to always ask "why." These are key skills for a successful litigator.

"I was fortunate to have Professor Marjorie Shapiro as my advisor and to work with the CDF group at LBNL. They taught me how to break down any problem into solvable chunks and how to work with a group of really smart people, which I am fortunate to still do," says Peters. "And my electronics, semiconductor, programming, and teaching experience helps me understand my clients' technology and helps me communicate it to non-technical judges and juries."

Peters offers some advice to current students: "Physics education and training will serve you well in whatever profession you want to pursue. You'll learn how to learn—and that is a huge advantage in any career, inside or outside of science."

Erika Isomura is currently a fifth-grade elementary school teacher at the Hayward Unified School District. Although she initially thought she would teach high school physics, she's spent the last 25 years teaching all grades between second and sixth grade.

When discussing her work, she sounds like an experimental researcher. "In teaching, you don't know in advance how things are going to turn out. So, you think about the variables, potential outcomes, and desired outcomes. And then you try things out with the kids, reflect upon what you learned, refine, and use those modifications the next day," says Isomura. "I tease my kids that I'm a scientist experimenting on them." She also applies this experimental approach to teaching yoga to kids.

Isomura credits her methodical planning skills to her Berkeley Physics training. Teachers need to be able to identify an end goal, as well as break that goal into manageable chunks that help students feel successful, she says.

"My work has also benefited from the classes I took at Cal. I often tell my kids about Professor Clarke, my quantum mechanics professor. His tests were open. He said it was more important that you knew how to apply the concepts than memorize or just blindly derive things. And I've taken that to heart," Isomura says. "I mostly use application-level exams, rather than asking students to memorize and regurgitate something; I think that's benefited my students."

David Brahm recently retired as a financial portfolio manager at Geode Capital Management. As a quantitative analyst, he typically spent his days programming mathematical financial models—using databases of financial statements from several thousand companies—that aimed to maximize stock returns and minimize risk. As he describes this big data optimization problem, he is clearly still thinking like a physicist.

"To a physicist, a stock portfolio is a vector of expected returns. And every stock has some volatility, but there are also strong correlations; for example, within the airline industry. So, risk is basically a covariance matrix. And we can put these together to solve a straightforward quadratic optimization problem, where we maximize the return and minimize the risk," explains Brahm. "Like a physicist, we make simple, useful models. However, these models can fail during an extreme event like the pandemic."

Jefffrey Hunt is a Senior Technical Fellow at the Boeing Company. He is essentially a professor in an international company. He publishes, gets patents, gives talks, and interfaces between the technical and managerial sides of the company—always pushing the forefronts of their technology.

According to Hunt, Berkeley Physics training contributed to his success in industry. "I learned how to see the big picture, be creative, and solve problems," he says. "My training was also very broad—optics, electronics, computer algorithms, and more—which has enabled me to reinvent myself, move around, and advance at Boeing. A physics degree is the liberal arts degree for the new millennium."

Hunt also appreciates that his Berkeley Physics group included students and postdocs from around the world, preparing him for global collaborations.

Nasreen Gazala Chopra is the Vice President of Systems Engineering and Sustainability at Applied Materials. She spends most of her time in meetings, where she relies on the fundamentals that she learned at Berkeley Physics to successfully understand and engage in technical discussions.

"Physics also helped me think more clearly and become a stronger problem solver," she says. "Its generality helped me get an entry ticket to jobs. And I get a lot of respect as a capable person because physics is challenging."

Since getting her PhD in physics at Berkeley, Chopra has worked in various roles, industries, and companies, including a Silicon Valley startup, Apple, the solar industry, and the semiconductor industry. She is now excited to share this industry experience as a new member of Berkeley's College of Letters and Science Advisory Board.

"I'm looking forward to brainstorming with my fellow board members on how we can enrich the students' curricula and experiences," she says. "Berkeley has a reputation for being a leader in change. I'm interested in having a frontline seat to see how that's being implemented."

# Highlighting Rising Stars in Physics

Berkeley Physics was delighted to host the 2023 Rising Stars in Physics Workshop this spring, sponsored by the Heising-Simons Foundation. This event brought together 24 outstanding women physicists and astronomers for two days of scientific talks and informal discussions aimed at helping them navigate the early stage of their academic careers.

The workshop was led by Pablo Jarillo-Herrero, associate professor of physics at MIT and founder of the workshop series, and Alessandra Lanzara, professor and Charles Kittel Chair in Physics at UC Berkeley. Lanzara's personal experiences motivated her to help organize it. "My first years at Berkeley were difficult with too few role models in my department. I often felt lonely and like I didn't belong," says Lanzara. "These types of workshops help create a network for young women to share experiences, challenges, and ideas with their peers and senior colleagues to help them succeed."

> "I also appreciated the participants' talks. I rarely hear about research outside my narrow niche of theoretical particle physics."

The highlight of the workshop for many of the participants was getting to know each other—through workshop sessions and casual interactions over meals or in an airport shuttle. "Meeting my physics peers from different fields was amazing," says Veronika Sunko, Miller Postdoctoral Fellow. "The atmosphere was different with 80% of the people in the room being women. It was fun." Sunko is a condensed matter experimentalist studying quantum materials with Berkeley Physics Professors Joe Orenstein and James Analytis. "We use lasers to learn about the magnetism of materials that exhibit an interesting interplay of magnetic and electronic degrees of freedom, yielding new phenomena that we're working to understand," she says.

Upper Left: Alessandra Lanzara; Above: Veronika Sunko; Upper Right: Weishuang (Linda) Xu; Lower Right: Carolyn Zhang.

Weishuang (Linda) Xu, postdoctoral researcher at the Berkeley Center for Theoretical Physics, enjoyed the keynote speeches by senior investigators. "Very accomplished people talked in-depth about their career trajectory and the massive-scale projects they're overseeing," says Xu. "I also appreciated the participants' talks. I rarely hear about research outside my narrow niche of theoretical particle physics." Xu works on various projects with different collaborators, using astrophysics and cosmology tools to study the particle nature of dark matter. "For example, I collaborate with Berkeley Physics Assistant Professor Ben Safdi. We're analyzing data of gamma rays that come from the middle of our galaxy to search for Higgsino dark matter," explains Xu.

As a new postdoc at the Harvard Society of Fellows, Carolyn Zhang soaked in career tips from workshop panelists on how to apply for faculty positions, build a research group, and balance commitments. "It was helpful to hear about different people's unique journeys to where they are today. And it was cool to see so many women physics professors in one room," she says. As a condensed matter theorist, Zhang studies the quantum phases of matter and the transitions between them. But her interests are broad and her fellowship is not tied to a single department.

Zhang also appreciates the volunteers who devoted time to organize the workshop. "They seemed genuinely passionate about supporting women entering the physics field, which was very encouraging."





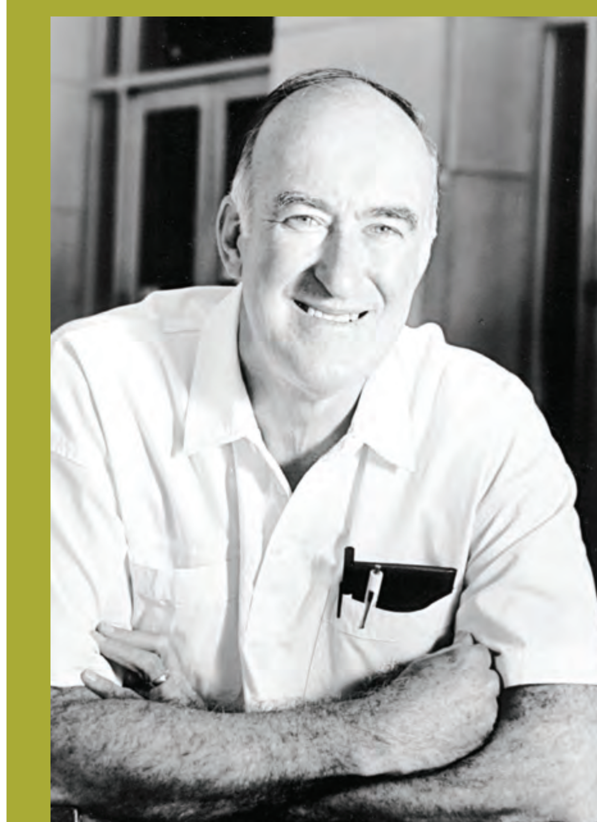
# Berkeley Physics welcomes 2 new faculty members

**RAÚL BRICEÑO**

Raúl Briceño was born and raised in Caracas, Venezuela. In 2013, he received his PhD in physics from the University of Washington. He then joined the Center for Theoretical and Computational Physics at Jefferson Lab as a postdoc. In 2016 he became the Nathan Isgur Research Fellow at Jefferson Lab and in 2017 he started an assistant professor position at Old Dominion University. His research largely focuses on aspects of theoretical nuclear and particle physics. He joined Berkeley Physics as assistant professor in January of 2023 with a joint affiliation in the Nuclear Theory group at Lawrence Berkeley National Lab.

**SHIMON KOLKOWITZ**

Shimon Kolkowitz earned his PhD in experimental physics at Harvard in 2015. He was a postdoctoral fellow at JILA/NIST/CU Boulder. He started a faculty position in the Department of Physics at the University of Wisconsin, Madison in 2018 as an assistant professor, and was promoted to associate professor with tenure in 2022. Shimon's research focuses on quantum sensing, precision measurement, and metrology. He joined Berkeley Physics in July of 2023 as associate professor and is the Roger Herst Professor in Physics.



# Howard Shugart's Continuing Legacy

The late Howard Shugart, Berkeley Physics professor, was a dedicated teacher loved by his students for more than 60 years. His outstanding service to the department and university was recognized by prestigious awards, including the Donald Sterling Noyce Prize for Excellence in Undergraduate Teaching in 1988 and the Berkeley Citation in 1993.

Professor Shugart also shared his passion for physics with the greater Berkeley community through the annual "Fun with Physics" presentation. "He was the face of the department on CAL Day every year. With the help of graduate students and other faculty, he performed physics demonstrations to a standing crowd of visitors," says Peter Yu, Berkeley Physics professor emeritus. "One of these demonstrations involved a piece of superconductor, cooled by liquid nitrogen, floating magically above a magnet in air without any attachment. And it ended with making ice cream using dry ice or liquid nitrogen to the great pleasure of all the kids!"

Professor Shugart passed away in 2016, and his beloved wife Elizabeth (Betty) Shugart passed away in 2022. But their devotion to Berkeley Physics continues on through their estate. "Howard and Betty understood the needs of the department so well. The Shugart Fund supports emerging needs, whether that means student support or furniture for the front office," says Maria Hjelm, Assistant Dean of Development, Mathematical & Physical Sciences. "Their generosity is felt all over, a fitting tribute to their dedication to the Physics Department and its students."

# Alumni Stories

PHOTO: NASA

## Alumnus of the Year John Mather

Berkeley Physics alum John Mather has won many prestigious awards—including the 2006 Nobel Prize in Physics with George Smoot for taking precision cosmic background radiation measurements that supported the Big Bang Theory of the expanding universe. But receiving this year's UC Berkeley Alumnus of the Year award in front of an audience of longtime friends and former Berkeley colleagues was still special. "It was a joy to see my thesis advisor Paul Richards, who set me on the trajectory that got me to Stockholm. And John Hauptman and others, who I shared a house with on Walnut Street that resembled the Big Bang Theory TV show," says Mather. "I also got to share the happiness with my fiancée Cheryl Hoffman."

Mather received the award in part to honor his work as a senior project scientist for the James Webb Space Telescope (JWST), which takes spectacular images of the universe as it appeared billions of years ago. He says the biggest surprise from JWST so far is that the first galaxies appear to be bigger, brighter, hotter, more massive, and faster than expected, and astronomers don't know yet why their predictions were wrong. They look forward to solving this and other mysteries using JWST over the next decade.

"I'm immensely grateful to the people who collectively were able to support and build the most powerful space observatory we could ever hope for," says Mather. "We humans, just 6 feet tall, walking around a small planet, are discovering secrets of the universe. And we can, if we choose, manage the future health of our planet for a long and glorious civilization."

The UC Berkeley Alumnus of the Year award is supported by the UC Berkeley Foundation and the CAL Alumni Association.

## Alum Gina Quan Fosters Student Leaders and Inclusion

Gina Quan moved into her Berkeley dorm two weeks before freshman year in 2008 to participate in the Compass Project's early start program for freshmen interested in physical sciences. "This amazing student-led organization fosters student leadership and inclusion, particularly for students who are underrepresented in physics," says Quan, assistant professor of physics at San José State University. "It was an incredible way to start at Berkeley because I created a support network of core friends. And when you encounter people that you work well with and share values with, you just never let them go."


© 2023 SJSU, PHOTO BY ROBERT C. BAIN, UNIVERSITY PHOTOGRAPHER

Compass Project participants later created similar groups at other universities—including the Equity Constellation co-founded by Quan at the University of Maryland as a graduate student—and connected them by forming the Access Network. Through the Compass Project, she also met Berkeley Physics alum Angie Little, who introduced her to physics education research and who is co-principal investigator on Quan's new project recently funded by the National Science Foundation's Racial Equity in STEM education program.

In partnership with Michigan State University, Quan and Little will soon study how physics departments can better support and retain transfer students of color. "We'll form transfer advocacy groups (TAGs) of students, faculty, and staff who will develop new ways to support transfer students. We don't know what will emerge from these TAGs because students need to be at the forefront of designing any change," she says. The researchers also want to better understand and document the experiences of these understudied students. They plan to disseminate their findings via journal articles and podcasts.

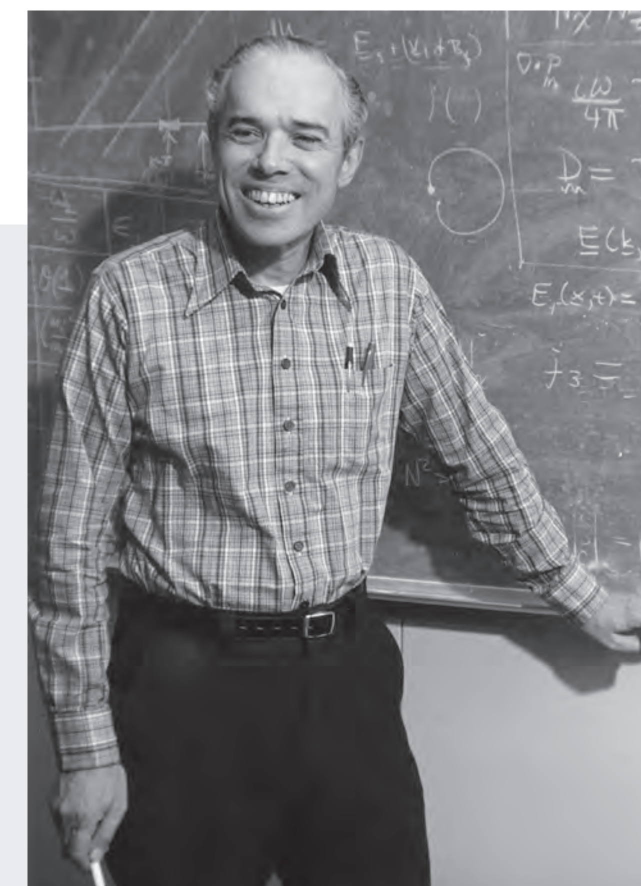
Quan clearly values empowering student leaders on both a professional and personal level. "I learn so much from my incredible and brilliant students at SJSU. I'm excited for the world they're going to create and lead," she says.

## Berkeley Team Hosts Reception for Alumni in Beijing

On July 14, the Division of Mathematical & Physical Sciences hosted an alumni reception in Beijing. About 40 UC Berkeley MPS alumni attended the reception. Dean Steve Kahn shared the latest division updates and had a lively discussion with the alumni. Other attending Berkeley representatives included faculty from Math and Statistics departments, as well as staff members from the Office of Development and College Relations.

From left: Rachel Schafer, Shuyun Zhou, Maria Hjelm, Jinxing Zhang, Jianhao Chen, Fa Wang, Steven Kahn, Pu Yu, and Yi Zhang.

# In Memory



## Alan Kaufman (1927-2022)

Allan Kaufman, a former Berkeley Physics professor, passed away on December 2, 2022. As an undergraduate and graduate student at the University of Chicago, Kaufman worked with numerous great theoretical physicists, including Enrico Fermi, Gregor Wentzel, and Marvin Goldberger. After receiving his PhD in 1953, he took a position at the newly formed Livermore Laboratory where he worked on Project Sherwood—the US program to develop controlled nuclear fusion—and other fundamental research programs. He started teaching at Berkeley in 1959 and joined the faculty in 1965. As a Berkeley Physics professor, he mentored graduate students who went on to become major figures in the field of plasma physics, including Chuan Liu and Ron Davidson. During his long career, he was recognized as an insightful pioneer who made many seminal contributions to theoretical plasma physics. Kaufman became Emeritus in 1998.

Berkeley Physics

University of California, Berkeley
Department of Physics
366 Physics North
Berkeley, CA 94720-7300

**ADDRESS SERVICE REQUESTED**



# Support Our Hands-On Learning

Your gift helps shape and re-imagine our learning and cutting-edge research.

Learn more and give online at:
physics.berkeley.edu/donate

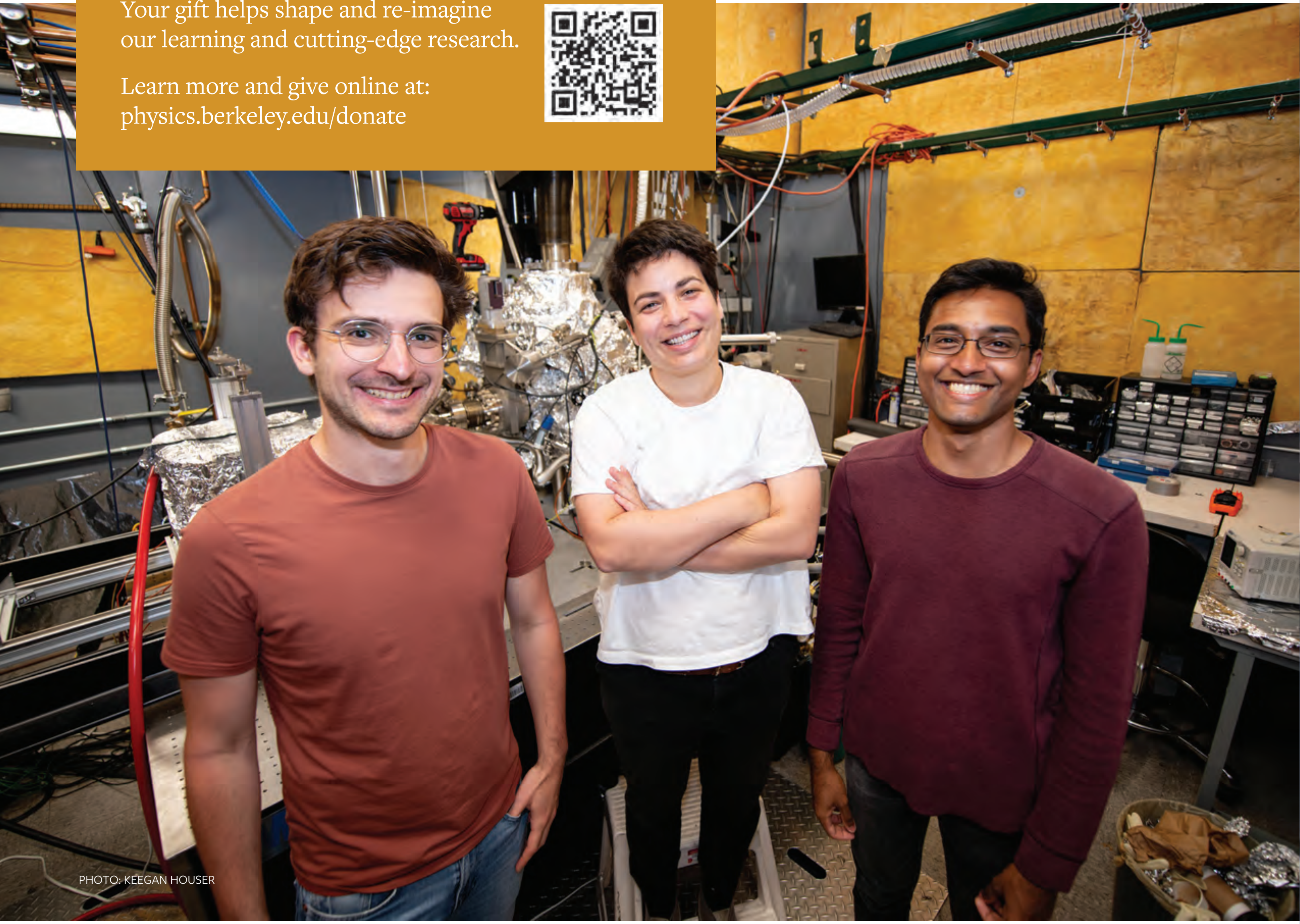


PHOTO: KEEGAN HOUSER

Berkeley
UNIVERSITY OF CALIFORNIA