DIVISION OF

Mathematical & Physical Sciences

FALL 2024

UC Berkeley College of Letters & Science

ASTRONOMY | EARTH & PLANETARY SCIENCE | MATHEMATICS | PHYSICS

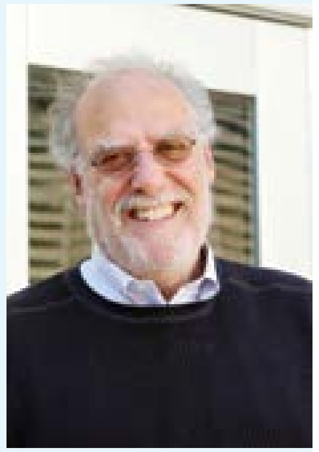

Photo: Sarah Wittmer

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Cover photo: Lava fountain erupts in 2023 from a vent at Kilauea, Hawai'i, a site studied by volcanologist Penny Wieser. (See page 6.)

Photo credit: M. Patrick/USGS.

Letter from Dean Steven Kahn

Reflecting on the past year in Mathematical & Physical Sciences, I am proudest of our recruitment of exceptional faculty across all our departments. We are pleased to welcome Dan Stark in astronomy, Francis Macdonald and Kristel Chanard in earth & planetary science, Christian Gaetz in mathematics, and, notably, four quantum experimentalists: Chiara Pancaldo Salemi, Aziza Suleymanzade, Victoria Xu, and Harry Levine in physics. Each is top-ranked in their field, and they will invigorate our division with stimulating ideas. We continue to maintain the excellence of our departments, which rank among the best globally.

While this has been a year of great success and innovation, we are still faced with challenges. The university's budget constraints, exacerbated by limited state support, remain an area of concern for the division. Our building and laboratory infrastructure suffers from serious deferred maintenance and is in desperate need of refurbishment. We have decided on a path forward, which includes a new building for math and a revitalization of the physics building. As quantum information science has become a fast-growing and important field in which Berkeley is a leader, it is vitally important that our students and researchers have access to state-of-the-art facilities where they can advance this area of study. We look forward to updating our physics space to accommodate that goal. We have an understanding of the cost of these projects, and while there is a long road ahead, this remains a top priority.

Looking ahead, there is much that I am optimistic about. Our division's priorities align with the university's broader goals under our new Chancellor, Rich Lyons. We are committed to maintaining our historic strength in curiosity-driven research; our scientists are motivated by asking blue sky, fundamental questions about the phenomena in the world around us, and uncovering new understandings that shift our future in unimaginable ways. We are also motivated to emphasize growing areas of research, like quantum information science and AI, and are embracing the opportunities for entrepreneurship that they provide. The integration of AI into our research practices is transforming our approach to science, and our faculty are at the forefront of these exciting developments.

I want to conclude by thanking you, our friends and supporters, for being a part of our vibrant scientific community. The impact of your support was made clear in our successful recruitment of top-notch faculty, and for this, we are incredibly grateful. I look forward to continuing to engage with you this year through events and opportunities on and off campus.

Thank you for your continued support.

Fiat Lux,

Steve Kahn
Dean, Division of Mathematical & Physical Sciences

Astronomy undergraduate students / Photo: Johnny Gan Chong

Donors see astronomy students as real stars

ELLIN AND **NED PURDOM** GREW TO APPRECIATE ASTRONOMY later in life. Neither took astronomy courses in the 1970s while at UC Berkeley, where the two met. Now, they look forward to the Department of Astronomy's Evening with the Stars lecture every year, and in February, the couple pledged $500,000 and a portion of their estate to advance student access and diversity in astronomy.

"I don't think we ever thought about ourselves as philanthropists," said Ned Purdom. "If you told us we were going to give to the Astronomy Department, I would have thought you were kidding. I couldn't even tell you where Campbell Hall was, having walked by it 10,000 times!"

The catalyst for this change was Ned's father, Paul, who would take long, solo drives to the desert in Nevada and Utah just to gaze up in awe at the clear night sky. He didn't own a telescope, but he could access the knowledge he gained from dozens of astronomy books and weekend UC Berkeley Extension courses to decipher the vast starscapes above him.

Despite Paul's stargazing pastime, Ned and his brother, Charlie, were surprised when their father left a substantial gift in his will to help Berkeley recruit and retain excellent faculty in astronomy. As Ned and Ellin met professors and became more involved with the department, their interest in the field grew.

Ned and Ellin Purdom

"Paul's legacy has been fascinating and has opened up astronomy to both Ned and I," said Ellin Purdom. "Then, when it came time for our estate plan, we came to create our own fund in the same department. It just felt right. The department was small enough that whatever contribution we made would make a difference, and in the meantime, we're both becoming astronomy nuts."

In focusing their philanthropy on diversity, Ellin drew on her social welfare degree and Ned on his background as an Albany High School teacher. Ned noticed the demographic disparity between students in honors and advanced placement classes and those making up work during summer school. He worried that society was relegating many kids to a secondary status by inadequately addressing education and underlying issues like poverty.

"Everybody has the right to understand our cosmological background," said Ned. "We were all formed from that explosion. It's an equal opportunity, life-creating event, but access to understanding it is certainly unequal. So why not help create an opportunity to expand on that?"

Astronomy has long been a gateway to spark students' interest in the sciences. Ellin recalled a conversation with Steven Kahn where the dean of the Division of Mathematical & Physical Sciences contended that every child is born interested in the stars and the galaxies. They learn their planets in kindergarten. They have stickers on their ceilings. Astronomy is a friendly way to continue that quest for knowledge.

"We just looked at each other and said we need to do this," said Ellin regarding their gift. "It feels genuinely great."

For more, please visit ASTRO.BERKELEY.EDU

Colliding neutron stars emit multi-messenger signals from photons (wavy lines), neutrinos (dashed lines), and gravitational waves (radiating bands) toward Earth.

Illustration credit: RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/P.Marenfeld

New Center to Decipher Messages in Cosmic Explosions

A FUNNY MEME ON #ADULTING COMPLAINS "Nobody wants to know your favorite dinosaur." Professor **Raffaella Margutti** isn't having it. She named her new research project Multi-RAPTOR, i.e., the UC Berkeley Center for Multi-messenger Research on AstroPhysical Transients and OutReach. Margutti joined the Astronomy Department in 2021, 15 years after earning a magna cum laude astrophysics bachelor's degree back in the old country (Milan, Italy), but her obsession with dinosaurs remains strong.

Even stronger is her hunger to hunt down a more coherent physical picture of our universe using the newest instruments and methods that astronomers can deploy. The first time ever that gravitational waves (GW) and light emissions from the same event were caught by cosmologists in 2017, Margutti was there to tear into them and other emissions that shot out of the merger of two neutron stars. "A new era of investigations" began, she beamed.

The gravitational wave was coming from the constellation Hydra, 130 million light-years away, and lasted only two minutes. But it was followed by a short gamma ray burst (GRB). Over the next few days, weeks, and months, astronomers observed a range of signals, including X-rays, ultraviolet, visible light, infrared, and radio waves. Margutti's research helped confirm theoretical predictions about neutron star mergers and their connection to GRBs.

The study of this cosmological combination of sources has been dubbed the new subfield of "multi-messenger" astronomy. It represents a paradigm shift in how astronomers and astrophysicists acquire, analyze, and infer from their data. Margutti said, "The frontier now resides in the capability to synthesize" information that is "inhomogeneous" and electronic-brain-bogglingly complex — what data scientists and theoretical physicists call high-dimensional problems. As you might already be guessing, this is where artificial intelligence (AI) enters the picture.

The Multi-RAPTOR Center will build "strong partnerships with data science and AI-based approaches." Astrophysicists will bring the hardware: new instruments coming online in the next few years, including the Legacy Survey of Space and Time (LSST) on the Vera C. Rubin Observatory, the La Silla Schmidt Southern Survey (LS4) and the UltraViolet EXplorer (UVEX), plus new gravitational wave instrumentation in development. Data science researchers will devise tactics to tease out the significant events from the information collected, and theorists will adjust their strategies for comprehending everything.

Margutti pulls no punches in describing stellar explosions, neutron star mergers, and black hole collisions as "the most violent transient astrophysical phenomena in the universe." Now, as a point person for modern interdisciplinary astrophysics — where combining data from diverse types of observations leads to a more complete understanding of the universe — she is eager to pursue the immense scientific potential of this new era of discoveries at Berkeley.

AstroTech 2024: an instrumental immersion

This summer, UC Berkeley once again hosted the annual week-long AstroTech Summer School, an opportunity for young astronomers from universities across the country to come together to learn the basics of astronomical instrumentation. A collaboration between the University of California Observatories and the Keck Observatory, and made possible by a generous grant from the Heising-Simons Foundation, the intensive program offers undergraduate and graduate students alike the chance to delve deeply into the world of instrumentation, network and collaborate with their peers and leaders in the field, and gain hands-on lab experience that will be crucial in their studies and research.

During AstroTech, students are charged with building a spectrograph — an instrument that splits the light from an object into its component wavelengths to be analyzed — in just one week. They do this by working together in teams, made up of students who generally have little to no experience building instruments but are eager to dive in and get their hands dirty. It's an intense experience that exposes students to all aspects of astronomical instrumentation, from optics principles to the practicalities of designing, building, and testing their instrument. Students gain valuable experience working collaboratively, learning not only the technical skills needed to develop astronomical tools, but also the importance of inclusive teamwork.

"We're hoping that this program helps revitalize and bring about the next generation of astronomical instrumentalists," says AstroTech Program Co-director and Chair of the Astronomy Department **Jessica Lu**. "We bring people in, especially from underrepresented groups, who may not think that they want to build instruments, and in one week they have to build a spectrograph. And they do it. It's pretty astonishing!"

For more, please visit ASTRO.BERKELEY.EDU

Forecasting Volcanic Flows

Penny Wieser at Mt. Jefferson, Oregon

SINCE MOUNTAINS MOVE AT A GEOLOGICAL PACE, are geologists ever in much of a rush? Maybe that depends on the scientist. Out of the 1980 Mount St. Helens eruption, modern volcanology was born. Governments provided funding to develop forecasts for eruptions. Igneous petrology, the specialization focused on rock that began as molten lava, was about to come to a boil.

Big pockets of magma churn up close to a thin spot in the Earth's crust, resulting in an occasional leak or blowout of lava and gases. Samples of igneous rock have tiny pockets of those gases, which can be examined through a variety of techniques, analyzed, and compared so that geoscientists can form models for forecasting hotspot activity.

In 2022, Berkeley's Department of Earth & Planetary Science (EPS) welcomed an igneous petrology expert, Assistant Professor **Penny Wieser**. In her EPS 80 class, Wieser demystifies the processes in the Earth that shape our environment. "Everyone," she warned, "should be aware of what is going on" under our feet. If current students aren't aware that the Hayward fault runs right through Memorial Stadium, how can they be informed citizens?

Wieser's future took shape when she saw the movie "Dante's Peak," starring Pierce Brosnan as a volcanologist. The possibility of "doing volcanoes as a job"? Wieser was off and running. She dove into the earth sciences major at Oxford and has barely paused for breath since. At Cambridge for graduate school, she kept up a fast pace. "Being on the university sailing team meant I was constantly taking time off my studies for fun stuff!"

EPS approached Wieser in 2020 with an invitation to apply, and she successfully competed with a pool of over 300 candidates. She spent the pandemic as a postdoc at the University of Oregon with Adam Kent, one of the new cadre of geologists using advanced imaging and analysis methods from chemical engineering to examine igneous rocks towards improving our understanding of volcanic systems.

The primary way to get a snapshot of the composition of a magma pocket has been melt inclusion studies. They are useful for analyzing trace elements and volatile components like water, carbon dioxide, and sulfur. Geoscientists can reconstruct the sequence of magmatic events, such as magma mixing, crystallization, and ascent. Melt inclusions yield insights, but they come with technical and interpretive challenges. Doing them is tricky, slow, and expensive. Wieser and others are turning to Raman spectroscopy of fluid inclusions instead. For many of these measurements, it is easier, faster, much cheaper, and gives comparable results.

Advances in Raman spectroscopy make it a favorite technique from electrical engineering to polymer chemistry and even forensic analysis and art conservation. It's relatively simple to prepare samples, and the samples aren't burned up by the testing. Chemical compounds have a signature or a fingerprint that can be detected even in samples that are as small as a single molecule. Professor Wieser is proving that, when applied to fluid inclusions, it gets results just as reliable as those of melt inclusion. "Raman spectroscopy measurements are robust and require only a fraction of the time and resources of melt inclusion studies," she said.

So, volcanologists are closer to being able to forecast lava flows and volcanic eruptions. Eventually, civil authorities and residents will have enough time to respond wisely to emergencies. During the eruption of Kilauea in 2018, no lives were lost and the spots where magma rose were where the hazard maps predicted, but the size of the flow took geologists by surprise. It was the largest leak in two hundred years. Wieser's research shows that Raman analyses of fluid inclusions from the eruption could have given nearly real-time information as solid as that from "postmortem" samples. The day may come when igneous petrologists like Wieser are more like volcano cardiologists than coroners.

Fluid inclusion slides are easier to prepare but still demand day after day of examining tiny bubbles in slices of lava. To find their chemical fingerprints she often polishes away her own. The data painstakingly gathered at the Raman microscope are wrung well and hung up to dry into reliable evidence. Imagine a day not long off when magma's potential danger might not be tamed, exactly, but could be dealt with calmly, with foresight. Where to next? The Cascade Mountains, thanks to her recently awarded Heising-Simons Faculty Fellowship. Wieser will be applying her techniques to the highest threat volcanoes in that range, uncovering their history of past eruptions and discovering the warning signs of future hazards.

Wieser with Raman microscope

Logical Additions to the Mathematics Faculty

MATHEMATICAL LOGIC, WHICH CONSIDERS CONCEPTS SUCH AS PROVABILITY AND DEFINABILITY, has a deep tradition at Berkeley. In 1957, the Department of Mathematics launched a graduate group in Logic and the Methodology of Science. Among that group's core areas of study is set theory, involving collections of objects or elements that can be grouped according to shared properties. The department recently had four set theorists on its active faculty, but those members have since retired.

Two new faculty recruits are continuing to keep Berkeley at the center of set theory. After conducting postdoctoral research in the department, Assistant Professor **Gabriel Goldberg** joined the faculty in 2022. Last year, Professor **Andrew Marks**, a department doctoral alum who has taught at Caltech and UCLA, returned to Berkeley.

"There was a great group of grad students that it was energizing to be a part of," recalled Marks, who earned his Ph.D. under Theodore Slaman in 2012. Now, he said, "It's nice to be able to see and talk directly with my advisor" along with other colleagues in mathematical logic. He's become a specialist in the subfield of descriptive set theory. "That particular area hadn't ever been something people at Berkeley did, but now I'm here," he said. It's also of growing interest, in part due to its connections with theoretical computer science.

Set theory provides basic hypotheses and a clarifying, unifying framework that formalizes all of mathematics. The standard axioms of set theory are known as Zermelo-Fraenkel axioms plus the Axiom of Choice, or ZFC for short. Descriptive set theory studies those sets that can be explicitly defined, in contrast to sets whose existence is shown using non-constructive methods, such as the Axiom of Choice. Said Marks, "Our understanding of definable sets, especially as they get more complicated, needs a lot of complicated set theoretical machinery," like that used in Goldberg's work.

Mathematicians use the term "cardinality" when referring to the size of sets, and Goldberg contemplates some infinitely large ones. "I work on large cardinal axioms, which are a proposal for extending the ZFC axioms in order to settle more of the undecided questions [in set theory]," he said. "There are many questions you can ask of the universe of sets where it just seems impossible to get an answer."

Using inner model theory, Goldberg seeks canonical models of large cardinal axioms that can answer such questions. For his doctoral dissertation at Harvard under W. Hugh Woodin, who was on Berkeley's mathematics faculty from 1988–2015, Goldberg developed a principle he calls the Ultrapower Axiom to address an open problem in set theory: whether there can be a canonical model for a particular type of large cardinal, a supercompact cardinal.

Not only is Goldberg's axiom compatible with the existence of supercompact cardinals, it also seems to hold for any other known canonical model. In the realm of set theory, however, there is plenty more terra incognita for scholars like Marks and Goldberg to explore and reveal.

Math Major is Most Distinguished Graduate

2024 University Medalist Chris Ying

Mathematics alum **Christopher Ying '24** was awarded the 2024 University Medal — the highest student honor that Berkeley bestows.

While maintaining a 3.98 GPA as a double major in math and history, the San Francisco native managed to participate in courtroom simulations with Cal Mock Trial, report and edit for the *Daily Californian*, and to volunteer at California's oldest prison, San Quentin Rehabilitation Center, where he edited stories for the newspaper and taught algebra and general math.

As the top graduating senior, Ying spoke at spring Commencement. He described his experience as a math instructor for Mount Tamalpais College, an independent liberal arts college whose campus is inside San Quentin: "My students asked nonstop questions, never shy to admit what they did not know. Students from rival gangs helped each other factor quadratic expressions."

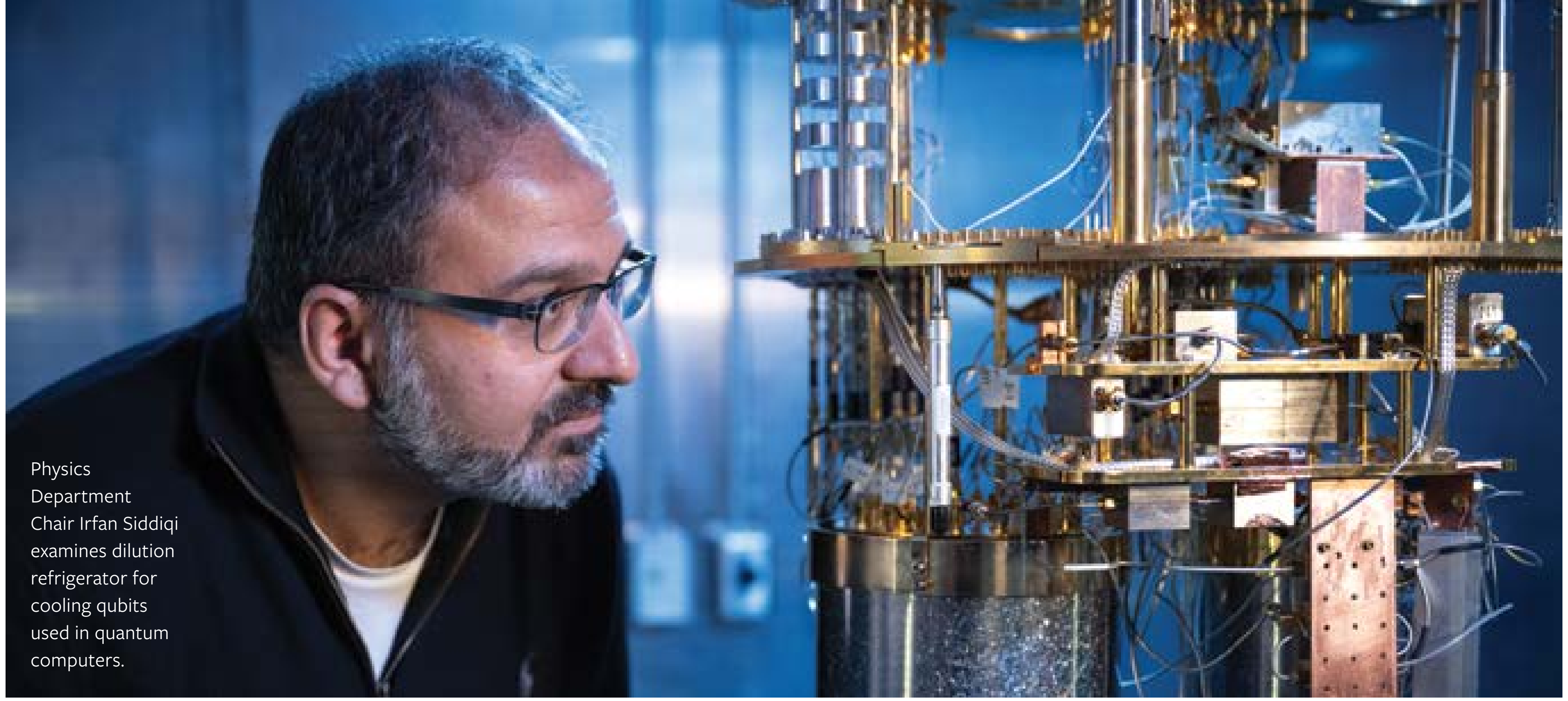
As Ying grew to see his San Quentin students as individuals rather than inmates, he became more acutely aware of the need for criminal justice reform. Studying law, which had previously been one of many interests, became his next goal.

"Math and law are sort of kindred subjects as they both try to create order out of nothing," said Ying. Both disciplines demand logical reasoning and critical thinking. "As you get to higher levels of pure mathematics, it's all about can you make a logical argument?"

After completing his undergraduate studies last December, Ying prepared for the LSAT exam, on which he scored in the upper 99th percentile. Soon to apply to law schools, Ying still works with San Quentin's news program and will be there teaching algebra in the fall.

For more, please visit MATH.BERKELEY.EDU

Physics Continues Quantum Commitment



Physics Department Chair Irfan Siddiqi examines dilution refrigerator for cooling qubits used in quantum computers.

THE UNIVERSITY HAS EXPANDED ITS REACH INTO THE FRONTIER OF QUANTUM SYSTEMS RESEARCH with the recent hires by the Department of Physics of four early-career faculty, who will augment the array of quantum exploration already underway across three colleges. These new assistant professors — **Harry Levine**, **Chiara Pancaldo Salemi**, **Aziza Suleymanzade**, and **Victoria Xu** — leverage the bizarre quantum properties of light and atoms to make sensitive detectors and improve quantum computing.

Professor and Chair of Physics Irfan Siddiqi said about his new colleagues, "They bridge traditional fields of physics with more modern notions of quantum information science. What's wonderful is, not only are they pushing a particular discipline forward, but they're also seeing how harnessing the quantum nature of light and matter can push the limits of quantum sensors and the power of quantum computers."

Research in campus labs has long explored the quantum properties of new materials, clusters of cold atoms, excited single atoms, and chemical interactions. Others take advantage of quantum properties of matter to make sensitive detectors for magnetic fields or gravity. Berkeley scientists are also utilizing the strange phenomenon of entanglement — first demonstrated in a 1972 experiment conducted in the bowels of Birge Hall — to build quantum computers. Entanglement links the fates of one or more particles such that what happens to one instantly affects what happens to the others, regardless of the distance between them. Quantum computers manipulate entangled quantum bits, or qubits, to solve problems that would take classical supercomputers an eternity.

Now, these four experimentalists will bring their new ideas and approaches to complement Berkeley's existing strengths in quantum information science and technology. Salemi and Xu will join Berkeley's faculty in January, while Levine and Suleymanzade arrive next July. Here is a snapshot of each of their research programs.

Harry Levine explores new types of qubits in an effort to reduce the noise in quantum computers that can cause less entanglement and more computational error. Levine comes to Berkeley from the Amazon Web Services Center for Quantum Computing, based at Caltech, where his qubit of choice is solid state circuits cooled to cryogenic temperatures. At Berkeley, Levine plans to continue working with another type of qubit, single atoms levitated in vacuum chambers, that he studied for his Ph.D. at Harvard.

Chiara Pancaldo Salemi employs quantum properties of superconducting circuits as detectors in a search for axions — theoretical particles that may be key to the mystery of dark matter, the predominant missing mass of the universe. Now a postdoctoral researcher at Stanford, Salemi helped build a tabletop axion detector as part of her Ph.D. thesis at MIT. The superconducting circuits used as qubits in quantum computers make ideal quantum sensors, which Salemi will use to look for tiny cumulative effects of axions acting in an electromagnetic field.

Aziza Suleymanzade uses entangled photons of light in optical fibers to interconnect quantum computers, like the way that digital computers are linked through the internet. Current challenges to this goal include the fact that quantum computers operate on different systems for qubits, and the process of linking them can disrupt the entanglement that enables them to compute so powerfully. Now a postdoctoral fellow at Harvard, Suleymanzade aims to develop a hybrid qubit system at Berkeley and envisions a future where quantum computers exist in a network of nodes distributed over vast distances.

Victoria Xu squeezes laser light to significantly improve the sensitivity of gravitational wave detectors, specifically the Advanced Laser Interferometer Gravitational Wave Observatory (LIGO). During the past decade, LIGO successfully made the first detections of gravitational waves, ripples in the fabric of spacetime generated by mergers of black holes and neutron stars.

Currently a postdoctoral researcher at MIT, Xu intends to further apply quantum technologies at Berkeley to maximize detections of merging massive objects in the universe. It will be an academic homecoming for Xu, who earned her Ph.D. in physics with Holger Müller.

"These are the best young people in this super-exciting field," said Dean of Mathematical & Physical Sciences Steven Kahn. "Each of them had multiple offers from competing institutions. The new directions their research will take us could be revolutionary."

For more, please visit PHYSICS.BERKELEY.EDU

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Basic Science Lights the Way *Goes Live*

During Homecoming weekend, "Basic Science LIVE! It's Getting Hot in Here: Insights on a Warming World" brought together series alums Bill Boos, Caroline Williams, David Romps, and Dipti Nayak for an on-campus discussion about climate change — specifically the effects of a warming world on microbial systems, plants, animals, and humans. Our faculty represented the departments of Earth & Planetary Science, Integrative Biology, and Molecular & Cell Biology, and shared perspectives from their respective fields. The hour-long moderated discussion was an insightful success, allowing the audience to ask questions and addressing some of the most pressing environmental issues of our time. We look forward to continuing to bring this series in front of new audiences.

This fall we hosted our ninth consecutive season of "Basic Science Lights the Way," continuing to bring our community of alums and friends together over Zoom to learn about foundational research happening on campus. Our virtual lineup this season covered topics from California's ancient fossil record to fluid dynamics to the connections between music, physics, and neuroscience. The appeal of this series keeps expanding, and we reached a milestone this semester by hosting our first live session.

You can watch recordings of all Basic Science Lights the Way events, and sign up for future events, at basicscience.berkeley.edu

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