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ILLINOIS PHYSICS

condensate

THE NEWS MAGAZINE *of the* DEPARTMENT OF PHYSICS

Gammie group contributes to first image of black hole at center of Milky Way

Charge orderings in superconducting cuprates share common origin

Alumna Spencer Hulsey: Spreading the spark of curiosity

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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ILLINOIS PHYSICS CONDENSATE

is a semiannual publication of the Department of Physics at the University of Illinois Urbana-Champaign.

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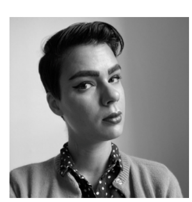

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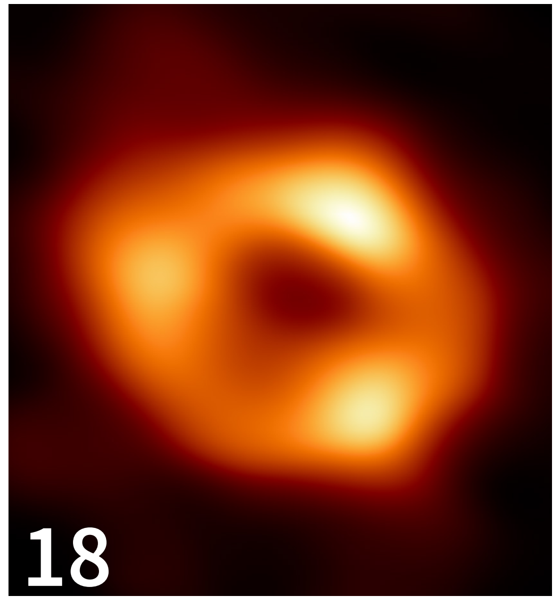

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ILLINOIS
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Cover image: Illinois Physics Professor Charles Gammie and his team pose for a photo at the historic Campus Observatory, constructed in 1896. Pictured left to right are graduate students Ben Prather (sitting on ladder), David Lee, Vedant Ketan Dhruv (sitting at desk), postdoctoral researcher Michi Bauböck, Professor Charles Gammie, Abhishek Vidyadhar Joshi, and Nicholas Conroy.
Credit: Heather Coit, Grainger Engineering, University of Illinois Urbana-Champaign

WELCOME

FROM OUR *Department Head*

MATTHIAS GROSSE PERDEKAMP

Dear Physics Family,

Spring semester 2022 has been a busy one here in the Department of Physics—and one that has provided ample opportunities to celebrate the achievements of our faculty and students. We ended the semester with the investitures of Charles Gammie as the Donald Biggar Willett Chair in Engineering and Nadya Mason as the Rosalyn Sussman Yalow Professor in Physics. Among our guests, Ben Yalow represented his mother's family and entrusted the department with the original doctoral theses of both his mother and father. The Yalow professorship is endowed through a generous gift from the Heising-Simons Foundation, and the foundation's Director of Science Dr. Cyndi Atherton also spoke at the event.

Unified undergraduate degree program

Our incoming class—the class of 2026—will be the first to graduate from our new unified physics undergraduate degree program. It combines the separate programs that had been split between the College of Liberal Arts & Sciences and The Grainger College of Engineering. Over time the degree programs had grown to be nearly identical. By unifying the curricula into a single Bachelor of Science in Physics in Grainger Engineering, we better focus the available resources and further optimize the quality of our instruction. This change also improves cohesion among our students.

Increased research activity catalyzed by recent faculty hires

Our newest faculty members—we hired fourteen over the last 3.5 years—are highly active and successful in their scientific endeavors. Many are working in the new Illinois Quantum Information Science and Technology Center (IQUIST) or in the new Illinois Center for Advanced Studies of the Universe (ICASU). During the past three years, faculty members have increased their external grant support from federal funding agencies, and the annual spending on research has risen from $23M to about $28M. While the number of tenure-track faculty members has remained steady at 60, the number of postdoctoral researchers has risen to over 50 and graduate students, to over 320. Research activities are very high, and we have successfully overcome the limitations imposed during the pandemic.

Our PhD programs rose in rank

The increased research activity may already have impacted our graduate program rankings—three research areas made the top ten in US News & World Report's 2023 rankings. Condensed matter continues to rank number one, and four other specialties rose in rank: nuclear physics, fourth; atomic molecular optical, tenth; quantum, twelfth; and particle physics, fourteenth. As always, our top ranked program in condensed matter attracts the best graduate students from around the world, and our graduate program is now the largest in the country.

The war in Ukraine, our response in Illinois, and the helium supply crisis

Illinois Physics is collaborating with the Scholars at Risk Network to shelter displaced Ukranian physicists at UIUC. We will host up to five graduate students and two research scholars. Faculty, emeriti, students, alumni, and friends have already given more than $110,000 in support of our Ukrainian colleagues. I'm very thankful to all who have contributed.

At home the war has contributed to widespread inflation. Similarly, helium has become a scarce resource, and helium prices have risen by a factor of five. At UIUC, research programs supported by grants totalling over $120M rely on liquid helium. Our researchers are strongly impacted. We are working actively on further improving our helium recovery and on securing a helium contract from a crisis-independent source in Qatar.

Please get in touch if your travels bring you to Central Illinois. You will always be welcomed home at the Department of Physics at the University of Illinois!

Warmly,

ILLINOIS PHYSICS Spectrum

The Department of Physics at the University of Illinois Urbana-Champaign is known for its long history of collaborative research—the "Urbana style of physics"—that frequently reaches across research areas and involves close coordination between theoretical and experimental physicists. Here is an inside glimpse of what some of our leading physicists are working on.

NICO YUNES

ASTROPHYSICS, RELATIVITY, AND COSMOLOGY

My work focuses on studying the most violent and extreme physical phenomena in the universe. Black holes are the densest objects in nature, possessing such strong gravity that not even light can escape their interior. Neutron stars are less dense, but the pressure and densities in their cores are still so extreme that the building blocks of matter—neutrons and protons—may dissolve into a soup of quarks.

Both of these "compact objects" are unavoidable predictions of Einstein's theory of general relativity. When these compact objects collide with each other, their collision releases tremendous amounts of energy in just milliseconds, outshining all the stars in the universe put together for a short moment. How is it then that we don't see these collisions with the naked eye? The reason is that the energy released is not contained in light waves, but rather in gravitational waves—ripples in the very fabric of space and time. The Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors in the United States and the Virgo interferometer detector in Italy have already observed over 90 such gravitational waves—the first detection in 2015 earned the 2017 Nobel Prize in Physics.

My group performs both analytic calculations and computer simulations on high-performance clusters to understand the details of these compact-object collisions and to search for new physics in gravitational wave data. Specifically, we construct models within Einstein's theory and in its quantum gravitational extensions that we then compare to data through Bayesian analysis to pull physics out of the noise. What are the properties of matter in the cores of neutron stars? What are dark matter and dark energy? Does Einstein's theory correctly predict nature when black holes collide and gravity waves? These are but some of the questions that we tackle in the gravity theory group.

Professor Nico Yunes (right) meets with NSF Graduate Research Fellow Kristen Schumacher at Loomis Laboratory of Physics. Photo by L. Brian Stauffer, University of Illinois Urbana-Champaign

Research in the Yunes group is supported by the National Science Foundation (NSF) Windows of the Universe Astrophysics Theory Program under Grant Nos 2009268 and 2007936, the NSF Gravitational Physics Program under Grant No. PHY-2207650; by a NASA Research Opportunities in Space and Earth Sciences, Astrophysics Theory Program Grant No. 80NSSC22K0806; and by a Simons Foundation Targeted Award in MPS Grant No. 896696. The findings presented are those of the researcher and not necessarily those of the funding agencies.

SANGJIN KIM

BIOLOGICAL PHYSICS

My group's research is at the interface of biology and physics. Biology is often perceived as complicated and unpredictable, but we try to discover the generalizable principles underlying the complexity by using physics-inspired methods and analyses. More specifically, we develop advanced instruments that offer higher precision and sensitivity in measurements and make predictable and testable theoretical models.

Illinois Physics Professor Sangjin Kim works with Illinois Physics graduate student Brooke Ramsey in the Kim laboratory at Loomis Laboratory of Physics. Photo by Yu-Huan Wang for Illinois Physics

One of the problems that we are interested in is transcription. Transcription is a process whereby genetic information on DNA is copied into a form of a polymer called messenger RNA, which serves as a template for protein synthesis. Transcription involves many cellular factors, but the primary player is an RNA polymerase, which is a molecular motor that moves along the DNA in one direction. Inside cells, multiple RNAPs run on the DNA, just like cars running on a highway. If the RNAPs were actually like cars, they would influence each other's motion only upon physical collision. However, we found that the RNAPs can influence each other's motion from a far distance, without physical contact, by affecting mechanical stress on the DNA that they share. While we are studying the biological implications of this interaction, we are also looking at the physical properties of DNA that allow for this long-distance "communication" between moving motor proteins. One possibility is that the mechanical stress created by an RNAP is transmitted through DNA, just like electricity on a wire. We are trying to build an instrument that can manipulate DNA's mechanical stress and measure its dynamics. All living cells contain DNA as genetic material, and its sequence (genetic code) has been a primary focus in biology. Our study will help illuminate the hidden nature of DNA and will give us a better understanding of the biological capacity that this fundamental molecule of life carries.

Work in the Kim research group is supported by the Searle Scholars Program and by the National Institutes of Health under Grant No. R35GM143203. The findings presented are those of the researcher and not necessarily those of the funding agencies.

ERIC KUO

PHYSICS EDUCATION RESEARCH

How can we help physics students succeed? Besides the physics topics listed in the course syllabus, successful students learn a wealth of strategies for thinking about and learning physics, such as connecting physical and mathematical reasoning, anchoring one's understanding in a small set of fundamental principles, and building coherence among different ideas. However, other students may struggle to recognize and pick up these ways of thinking in their courses, making succeeding in physics class a challenging prospect. My research group works to formalize our understanding of these strategies that constitute physics expertise and to provide equitable opportunities for learning them in physics class.

Our approach to physics education combines basic research on the fundamental mechanisms of learning with course design and implementation. Our work relies on disciplinary physics knowledge as well as methods and theories from other fields, such as education, psychology, and cognitive science. We build cognitive models of physics expertise by studying the problem-solving and reasoning behaviors of students and experts through interviews, classroom observations, and experiments. My group specializes in developing models of how one's knowledge and epistemological beliefs (or beliefs about what it means to do physics) interact to produce physical reasoning and insights.

Illinois Physics Professor Eric Kuo. Photo by L. Brian Stauffer, University of Illinois Urbana-Champaign

These models of physics expertise motivate the development and testing of new principles for teaching and assessment. In line with the long history of educational innovation at Illinois Physics, these principles get implemented into our courses, where they can be tested and refined. Current efforts focused on helping students build coherence among physical and mathematical ideas are being implemented in PHYS 100, a course developed at UIUC to prepare students for success in the introductory physics course sequence. In this way the research is having a direct and immediate impact on our students' educational experiences.

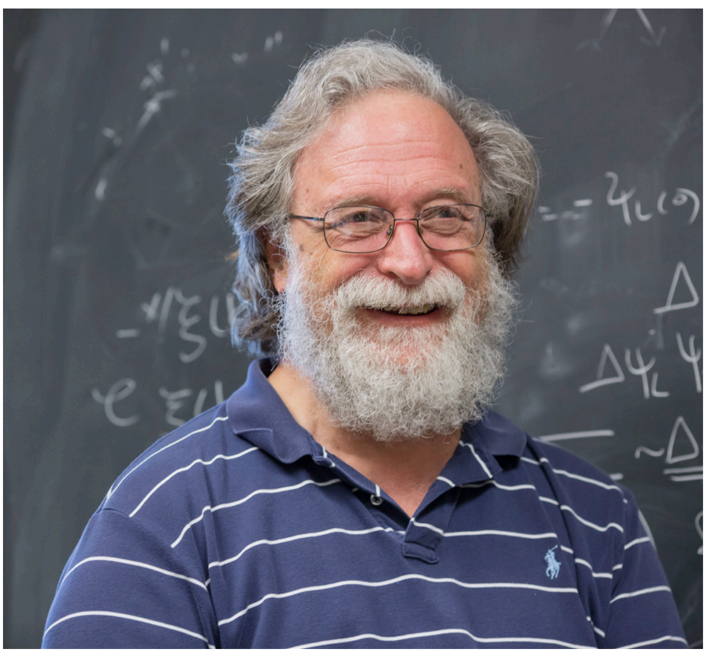
This work in the Kuo research group is supported by the National Science Foundation under Grant No. 2100040 and by the University of Illinois Grainger College of Engineering Strategic Instructional Innovations Program. The findings presented are those of the researcher and not necessarily those of the funding agencies.

EDUARDO FRADKIN

THEORETICAL CONDENSED MATTER PHYSICS

My group works in condensed matter systems involving large numbers of strongly interacting degrees of freedom and having strong effects of quantum mechanics. We use the framework of quantum field theory to study and explain the emergent behavior of high-temperature superconductors and topological phases of matter.

I showed that strongly correlated electronic systems become spontaneously organized into electronic liquid-crystal phases. Three features of these phases, which break spatial symmetries to different degrees and are often superconducting, are that the orders are closely intertwined, have comparable strengths, and have similar critical temperatures. A good example of this is observed in the electron nematic phases in systems ranging from high-temperature superconductors to two-dimensional electron fluids in high magnetic fields.



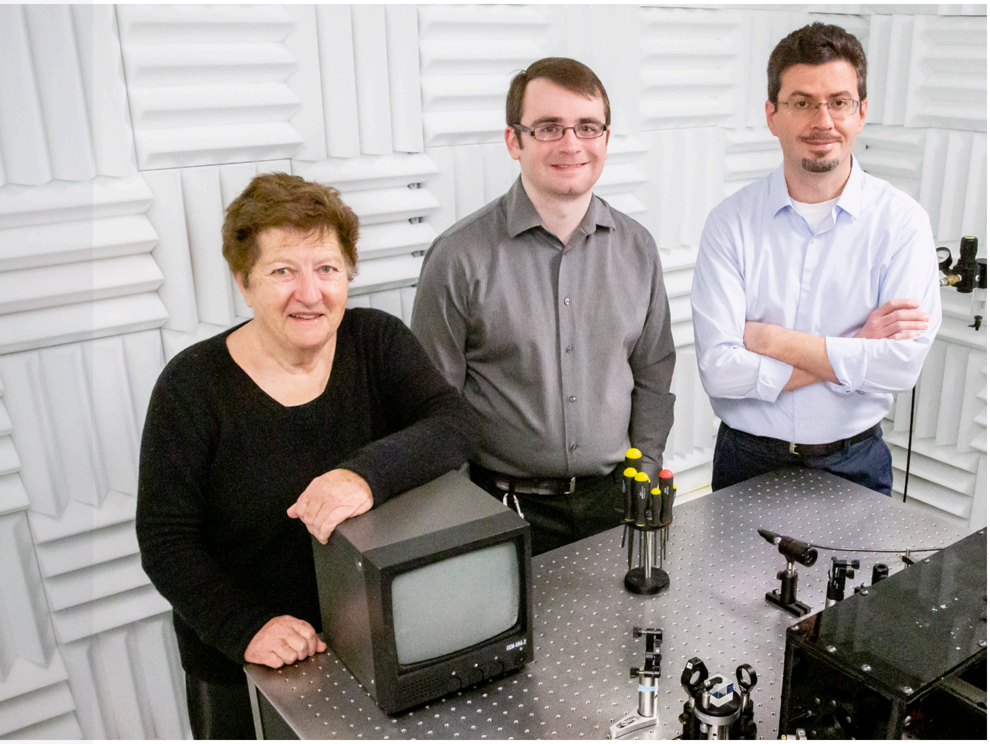
Illinois Physics Professor Eduardo Fradkin. Photo by L. Brian Stauffer, University of Illinois Urbana-Champaign

Recently, I showed that a novel form of superconductivity, the pair-density wave, is the natural explanation of many intriguing experiments seen in a family of high-temperature superconductors. The big challenges now are to determine the role of the pair-density wave in the phase diagram of these superconductors and, more broadly, to understand the microscopic origins of intertwined orders. These projects require strong collaborations with UIUC experimentalists.

Topological phases are quantum states of matter that do not break any symmetry and have large-scale quantum entanglement. More specifically, topological phases are ground states that exhibit a degeneracy determined by the topology of the space in which they live. These states are observed in two-dimensional electron fluids in high magnetic fields that exhibit the fractional quantum Hall effect. Strikingly, the excitations of these topological fluids are quantum vortices that carry fractional charge and fractional statistics, intermediate between fermions and bosons. These vortices constitute a natural platform for topological qubits.

This area of research is characterized by strong and mutually nurturing interactions among condensed matter, high energy physics, and mathematics. In my group, we construct effective field theories for fractionalized phases, particularly in quantum Hall fluids. We are developing models of how to interact with and control fractionalized excitations and are developing models representing three-dimensional fractionalized states.

Work in the Fradkin group is supported by the National Science Foundation under Grant No. DMR 1725401. The findings presented are those of the researcher and not necessarily those of the funding agency.



University of Illinois researchers tie structure of helicase molecule to its step size as it unzips and re-zips the DNA strand. The work has implications for the study of genetic disorders and genetic susceptibility to disease.

A measured step in our understanding of helicases

KARMELA PADAVIC-CALLAGHAN
for Illinois Physics Condensate

A team of physicists and chemists at Illinois are uncovering exactly how enzymes take apart the DNA double helix and then put it back together. A recent study combining computational and theoretical biophysics with advanced experimental methods offers an atomically detailed picture of how enzymes called helicases move along a DNA molecule as it is unzipping its strands or re-zipping them. These findings were published in the journal Nature Communications in the article "Kinetic and structural mechanism for DNA unwinding by a non-hexameric helicase."

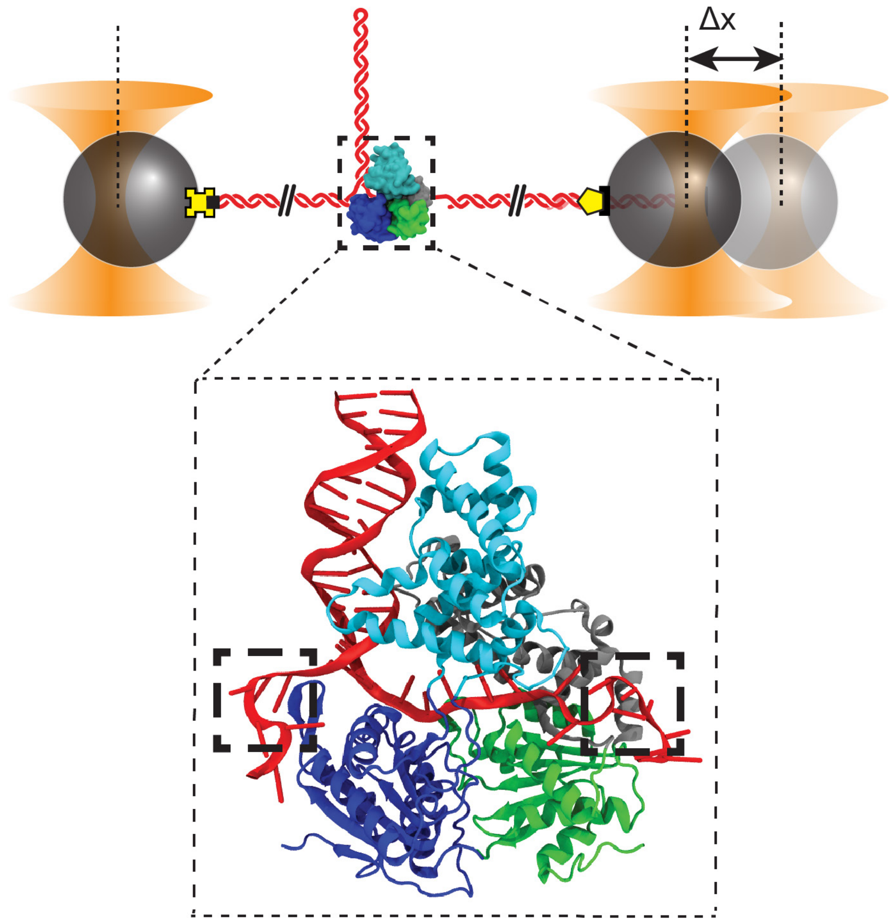
Helicases are a class of motor proteins, enzymes that use energy from the chemical reaction they catalyze to move along the backbone of molecules such as DNA. Many helicases play important roles in fundamental biological processes such as DNA replication, where they unwind the two DNA strands before each is copied. The new study focused on a type of helicase called UvrD, which is typically involved in DNA repair pathways in *E. coli*, explains Sean Carney, the article's first author and a doctoral student in Illinois Physics Professor Yann Chemla's research group. DNA can be damaged during some common cellular processes or by environmental factors such as uv light. Since damage to DNA can be lethal, all cells are equipped with machinery to repair their genome.

Detailing that process at the molecular level can consequently have implications for human health. Carney explains, "Helicases are linked to cancer, genetic disorders, genetic predisposition to cancer, and premature aging."

He and collaborators studied a UvrD helicase while it moved along a piece of DNA shaped like a hairpin and either took its strands apart, unzipping them, or re-zipped them together. Helicases move along the DNA backbone in a stepwise manner, much like a climber may move along a rope ladder.

One of the big insights of the new study is pinpointing the step size for the enzyme or, in the analogy, the separation between the rungs that the climber steps on moving up or down the ladder. The Illinois team

Opposite page: Pictured left to right, Illinois Chemistry and Physics Professor Zan Luthey-Schulten, Illinois Physics graduate student Sean Carney, and Illinois Physics Professor Yann Chemla pose in the Chemla lab at Loomis Laboratory of Physics in Urbana. Photo by L. Brian Stauffer, University of Illinois Urbana-Champaign



Right: A single DNA hairpin molecule (top) is tethered between two optically trapped beads and held at constant force while a single UvrD helicase unwinds the hairpin. As the helicase unzips the double-stranded (ds) DNA in the hairpin and converts it to single-stranded (ss) DNA, this released ssDNA causes the tether extension to increase. This increase in tether extension is used to calculate the number of base pairs unwound over time. From these data, the fundamental unwinding step size of the helicase is determined.

The dashed boxes depict in greater detail (bottom) how UvrD interacts with the ssDNA tails, based on a snapshot of molecular dynamics simulations in this study. The two thicker dashed boxes within the enlarged image show loops formed between the helicase and the ssDNA tails. The release of these loops helps to explain the experimentally determined step size. Image by Sean Carney, modified from Carney *et al.*, *Nature Communications*, 2021.

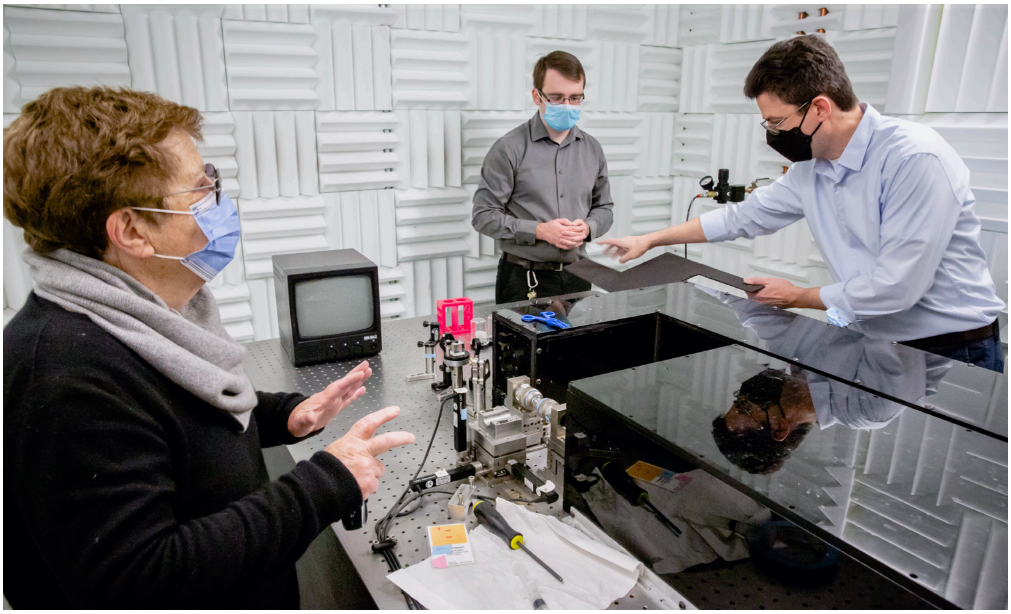
experimentally determined that during both unzipping and zipping of the DNA, UvrD helicase moved three base pairs at a time. Additionally, the team conducted sophisticated molecular dynamics simulations in order to understand structural reasons behind this step size, revealing that UvrD sequesters single DNA strands in loops before periodically releasing them.

"Our general goal was to understand the mechanism of DNA unwinding and specifically to quantify the step sizes for each discrete cycle of motion of the helicase along the DNA track. How many base pairs is the helicase unwinding at a time? How long does it dwell between steps?" Carney expands.

To determine these details experimentally, Illinois researchers used an experimental tool called optical tweezers. Here, each end of the DNA hairpin was connected to a polystyrene bead, which was in turn held by a beam of carefully focused laser light. When the helicase moved along the DNA and separated its strands (in the analogy, the climber undoing the ladder while moving upwards), one of the beads would move as well. In particular, the experiment was set up so that the tension of the DNA suspended between the beads had to be maintained at all times. When the helix got unwound and elongated, the connection between the beads went slack, and to become taut again, one of the beads would have to move. By recording the motion of this bead, researchers could determine how much longer the DNA had become. They then converted this information into how many base pairs UvrD had stepped over and unwound.

Carney emphasizes, "We can directly measure steps as small as an individual base pair. We can look at sub-nanometer-level stepping dynamics in high resolution. Similar measurements have been done before for other helicases, but this is the first work to directly measure the step size with base pair resolution specifically for the UvrD helicase. Because UvrD shares the same unwinding mechanism with other unrelated helicases, this is of great interest to the biophysics and chemistry research community."

He and collaborators, however, did not stop there. They complemented their



Illinois Chemistry and Physics Professor Zan Luthey-Schulten (left), Illinois Physics graduate student Sean Carney (center), and Illinois Physics Professor Yann Chemla collaborate in the Chemla lab at Loomis Laboratory of Physics in Urbana. Photo by L. Brian Stauffer, University of Illinois Urbana-Champaign

precise experimental work with computer simulations performed by theorists in the research group of Illinois Chemistry and Physics Professor Zaida Luthey-Schulten.

Wen Ma, at the time of this experiment a doctoral student in Luthey-Schulten's group and currently a postdoctoral researcher at University of California San Diego, explains, "We simulated the UvrD-DNA complex at the atomistic level. The motions of hundreds of thousands of atoms were computed using Newton's laws. We saw how the single-stranded DNA tails formed from the unwound helix's interacting with UvrD."

Ma's simulations showed that the enzyme sequesters single strands of DNA into loops as it moves along the strand, and it takes the single strands apart, instead of letting them go immediately after unzipping. When UvrD releases three base pairs, the DNA loop becomes extended, causing the slack that made the polystyrene beads in Carney's experiment move. The predicted step size distribution from simulations agrees well with the experimental distribution. "Our simulations show that the atomistic-level details are important in understanding the step size distributions measured in single-molecule experiments," Ma asserts.

Carney says, "Including this theoretical and computational component in our work further illuminates what we are observing. The agreement between theory and experiment regarding the UvrD step size validates our observations, and the simulations provide additional insight into the mechanism of unwinding."

Further, these simulations identify the specific part of the UvrD protein that contacts the DNA. While the delayed release mechanism has been proposed before, such a precise understanding of what part of the protein is responsible for loop formation was never before available to researchers.

"Additionally, previous work in the field only proposed models for DNA unwinding. Here, as a new addition, we also measure the stepping dynamics of DNA zipping and propose a mechanism for the zipping process similar to that for unwinding," Carney adds.

Going forward, the team wants to test its theory by using a mutated UvrD molecule that they predict will, as a consequence of mutation, move along the DNA with a different step size. Carney explains that detecting such a change in step size based on structural properties of the UvrD would offer the additional empirical confirmation to experimental and computational work researchers have done already.

"It would also be very interesting to show that the mechanism proposed for how exactly UvrD unzips and rezips the DNA can be applied more generally than to just this one helicase enzyme," Ma says. He is eager to broaden the impact of the work. "We found the loop-forming protein sites are consistent across a group of structurally similar helicases, called superfamily I helicases, based on bioinformatics analysis. We think that the mechanism might be utilized by other helicases in this superfamily." ■

This research was funded by the National Institutes of Health under Grant Nos. R01 GM120353, R01 GM45948, and R35 GM136632; and by the National Science Foundation Physics Frontiers Center (PFC) program under Grant No. PHY-1430124 (Center for the Physics of Living Cells). The findings presented are those of the researchers, and not necessarily those of the funding agencies.

In case this news hasn't reached you yet, here are some of the top headlines from our newsfeed. Check out these stories and more at physics.illinois.edu.

Moore Foundation grant to enable direct experimental investigation of correlated pairs of electrons in quantum materials

JENNY APPLEQUIST *for Materials Research Laboratory*

May 11—Strongly correlated materials are a special kind of quantum matter—matter that can't be described in terms of individual particles, only in terms of relationships among multiple particles—and they've been a tough nut for scientists to crack. Existing instruments can't perform the needed study of more than one electron at the same time. Thanks to a new $1.6 million grant from the Gordon and Betty Moore Foundation, that's about to change. Illinois Physics Professor and IQUIST member Fahad Mahmood will lead an effort to develop an instrument, called "Double-ARPES," that can reveal the elusive workings of entangled pairs of electrons.

Alumnus Patrick Walsh's Sun King provides off-grid solar energy to homes in Africa and Asia—having 38 percent of pay-as-you-go market

SUN KING *Press Release*

Apr 29 —Sun King, the largest provider of solar energy products for off-grid homes in Africa and Asia, announced it has raised $260 million in Series D funding, led by BeyondNetZero, the climate investing venture of General Atlantic, a leading global growth equity firm, along with M&G Investments' Catalyst team and Arch Emerging Markets Partners. Sun King is leading a transformation in how electricity is provided across Africa and Asia, where 1.8 billion people still lack access to a reliable electrical grid. To date, Sun King has powered the lives of 82 million people across 40 countries.

$7.5M DOD MURI award to explore creation of qubits based on Majorana zero modes

JENNY APPLEQUIST *for the Coordinated Science Lab*

April 15—The Department of Defense's Multidisciplinary University Research Initiative (MURI) has just announced a $7.5 million project that will explore one intriguing option: qubits based on Majorana zero modes (MZMs). MZMs are zero-energy quasiparticles with special properties that suggest they could be used as the basis for very good qubits. New York University's Javad Shabani will be the principal investigator of the six-university project, and a key piece of the work will be led by Illinois Physics Professor Angela Kou, who is also a member of the Illinois Quantum Information Science and Technology Center (IQUIST).

Physicists elucidate connection between symmetry and Mott physics in step towards understanding high-temperature superconductivity

DANIEL INAFUKU *for Illinois Physics*

Mar 21—From the development of Bardeen-Cooper-Schrieffer (BCS) theory at the University of Illinois Urbana-Champaign in 1957 to the discovery of high-temperature superconducting cuprate ceramics in 1987, superconductivity continues to command attention for its scientific importance as well as its potential applications. Researchers are continuing Illinois' strong tradition of breakthrough discoveries in this field: Illinois Physics postoctoral researcher Edwin Huang, Illinois Physics Professor Philip Phillips, and Illinois Math Research Professor Gabriele La Nave have recently uncovered a key connection between symmetry and Mott physics (the physics underlying high-temperature superconductors).

Frederick Lamb, chair elect of the APS Forum on Physics and Society

SIV SCHWINK *for Illinois Physics*

Jan 24—Illinois Physics Research Professor Frederick Lamb is currently serving as the 2022 chair-elect of the American Physical Society (APS) Forum on Physics and Society (FPS). Founded in the late 1960s and incorporated as the very first APS forum in 1972, FPS members work to better understand, analyze, inform the public, and advise government officials on societal issues relating to science, including climate change, proliferation of nuclear weapons, and national security. Among Lamb's goals as a leader of the Forum are to help increase understanding of important science-policy issues by members of the APS and by society at large. These include how best to address the COVID-19 pandemic, the growing climate emergency, and the dangerous new upward spiral of the nuclear arms race.

From fundamental physics to the practice of law—‘Who knew?’

How Illinois Physics alumnus Daryl Achilles went from student experiences at Fermilab to intellectual property lawyer at the global biotech leader PerkinElmer

BILL BELL
for Illinois Physics Condensate

Daryl Achilles remembers the people who helped guide him toward physics.

Several professors and researchers at Fermilab hosted weekly “Saturday Morning Physics” lectures when he was a high school student. Edwin Abbot—the Victorian satirist who thought he was critiquing social hierarchies in the United Kingdom but ended up writing *Flatland*, an enduring examination of the mathematical concept of multiple dimensions—makes the list too. So do Michio Kaku and his book *Hyperspace* and Kip Thorne and his book *Black Holes and Time Warps*. In fact, nearly 30 years later, Achilles can still pull the copy of *Black Holes and Time Warps* that he read as a teenager off his shelf.

It’s the sort of pop-science non-fiction that any student in an AP Physics course in the suburbs of Chicago was likely to get their hands on in the mid-1990s, after Carl Sagan and Stephen Hawking but before Neil deGrasse Tyson.

“At the time, I probably thought I understood better than I actually did. But I was hooked. It was so fascinating,” Achilles says.

The books and lectures might be a common origin story for an Illinois Physics alumnus, but his career is much more unusual. After graduating in 2002 and completing a doctoral degree focused on quantum optics at the University of Oxford, Achilles is now senior intellectual property (IP) counsel at PerkinElmer, an $18-billion biotech and instrumentation company headquartered in Massachusetts.

What motivated the shift? In part, it was probably that same tendency to feed his own curiosity that led him to *Flatland*.

"I've always liked knowing lots about many different things," he notes. While an undergrad he was hired by Illinois Physics Professor Leland Holloway—now an emeritus professor—to write software for the Collider Detector and to help upgrade the muon detectors at Fermilab, over one summer. He also worked with Illinois Physics Professor Paul Kwiat, who was new to campus and just setting up his lab focused on optical experiments related to quantum information.

The structure of Oxford—where student life is based around small "colleges"—multidisciplinary communities of students and faculty—was also a boon for him. At UIUC, his cohort was largely made up of other physics students.

"I learned so much from them—they were my people. A typical evening started in the lobby of Loomis for problem sets, then down to the IHOP for coffee, conversation, and more problem sets. It wasn't the most efficient way [to learn physics], but it was a great way of making friends. U of I Physics was so close-knit," he said.

"There are jobs that revolve around science that don't require doing research in the lab. These folks with PhDs working in other areas outside of academia? They're happy."

At Oxford, meanwhile, there were chemists, historians, archeologists, and students of many other fields constantly interacting at his college.

"I'm an introvert, but I knew no one in the country when I moved there, so I got really into college life," he said. He eventually became president of his Middle College Room, a governing and support body within Oxford's colleges.

Achilles' first job after completing his doctoral degree had an even bigger impact on his career trajectory.

As a researcher at a quantum information startup, he worked on laser-based systems for generating single photons. It involved a lot of tweaking and maintaining instruments and—for Achilles, anyway—a lot of tedium and monotony.

But there was another component to his job. He was frequently asked to review technology that other companies had patented to see if it might be licensed by his startup for its use.

"It reopened my eyes to broader contexts and different ideas. I was still getting to learn, but I wasn't in the lab. Before this, I had no idea that IP law was a career at all," he recalls.

It was a big realization and a bit of a scary one.

"There was an assumption that you'd go to grad school, then post-doc, then faculty. That was the path in my head— it wasn't 'pure' to do something else," Achilles says. "But there are interesting, fulfilling, exciting careers out there. There are jobs that revolve around science that don't require doing research in the lab. These folks with PhDs working in other areas outside of academia? They're happy."

He adds, "Companies do real science. They do R&D. And they hire scientists to do things other than active research. Who knew?"

Achilles followed up his realization with quick action. Within a year, he was an in-house science advisor at a law firm that specializes in patent litigation. From there it was 18-hour days working as a patent agent, writing patent applications for clients and arguing with patent examiners at the U.S. Patent and Trademark Office—all while attending law school at night.

Now at PerkinElmer, he and a team of two other attorneys are responsible for the company's ever-growing portfolio of more than 4,000 patents. Those patents cover techniques used in everything from mass spectroscopy to cellular imaging, genetic testing to point-of-care diagnostics, chromatography to lab automation.

"It's perfect for me," says Achilles. "People bring me a concept that they toiled over in the lab, I learn about the technology from them, and we figure out what intellectual-property strategy to take."

The IP team looks at things like how to avoid infringing patents owned by other entities, how patenting an invention will serve the company's interests, and whether to license IP from another company. They also manage the company's IP litigation strategy. PerkinElmer has acquired about 10 other companies in recent years, so the team helps assess any patent liability PerkinElmer may face in such acquisitions and develops ways to mitigate that risk.

"With an Illinois Physics degree, nothing seems too intimidating," Achilles sums up. "Optics, electronics, writing code, working on hardware—I had the chance to do it all at UIUC. Even if it's not directly in my wheelhouse, I've been exposed to it." ■

THE LOOMIS CONFESSIONS

F. Wheeler Loomis. Image digitized at the Emilio Segrè Visual Archives

These interview questions are inspired by a Victorian parlor game known as the confession album, famously known as the Proust questionnaire after French writer Marcel Proust's thoughtful and witty answers were discovered and published in 1924 in the French literary journal *Les Cahiers du Mois*. We have named our "album" for Wheeler Loomis, Illinois Physics department head from 1929 to 1957. Loomis is revered for having hired the highest caliber early-career scientists and for diligently nurturing them, expanding the department's research program and elevating it to world-class status, while putting special emphasis on good teaching. The collaborative, open-door "Urbana style of physics" emerged under Wheeler's supportive and strategic leadership.

Professor Barry Bradlyn

If you couldn't be a physicist, what career would you choose?

I think the thing that drew me the most to physics was the fun that comes from figuring out the rules of the game. We have what experiments tell us about the way the world works and use that information to build a model for reality. We then use that model to make predictions about things we haven't observed. I think that if I couldn't do physics, I would want to do something like history or archaeology. In those fields as well, the goal is to piece together a model for how life and society looked in the past from limited evidence. I've always been fascinated with the past, especially with trying to understand what life was like in the ancient world. Because I'm a theorist, I don't think archeological fieldwork would be a good fit for me, so I'll say that if I couldn't be a physicist, I'd want to be a historian.

What is your favorite place?

I've been lucky enough to be able to travel to San Sebastian on the north coast of Spain several times to work with collaborators there. It's definitely one of my favorite places to spend time. It has great food, great beaches, and great people.

What is the greatest scientific blunder in history?

I think the scientific racism that came to prominence in the nineteenth century was the biggest and one of the most damaging blunders in the history of science, as it was used to justify slavery, genocide, and discrimination.

Illinois Physics Professor Barry Bradlyn is a condensed matter theorist who also studies the spread of hate speech on social media platforms using machine learning and mathematical and statistical analyses. He is a member of the Institute for Condensed Matter Theory in Urbana. Photo by Fred Zwicky, University of Illinois Urbana-Champaign

Who is/are your favorite artist(s) in any medium—painters, composers, authors, filmmakers?

I have a bit of recency bias here, because I just finished reading *The Expanse* series by James S. A. Corey, and it was phenomenal. More broadly, I really appreciate the poetry of T. S. Eliot, the prose of Frank Herbert, and the music of the progressive rock band *Rush.*

Who is/are your favorite hero(es) in life or in fiction?

I like to think of heroes in terms of the question: if I found myself in a sticky situation and didn't know what to do, who would I trust to help me figure it out? In that regard, I don't think I could do any better than my wife Molly and Captain Jean-Luc Picard (from *Star Trek: The Next Generation*). If we are talking more narrowly about scientific heroes, then I'd have to go with my doctoral advisor Nick Read, as cliché as it sounds. The precision of thought that he brings to problems is something I aspire to.

Who is/are the villain(s) you love to hate?

The Daleks from *Doctor Who.*

What is your idea of happiness?

Coming home to spend the evening with my wife and pets after a long day of thinking about physics.

What is your idea of misery?

Working a 9-to-5 office job.

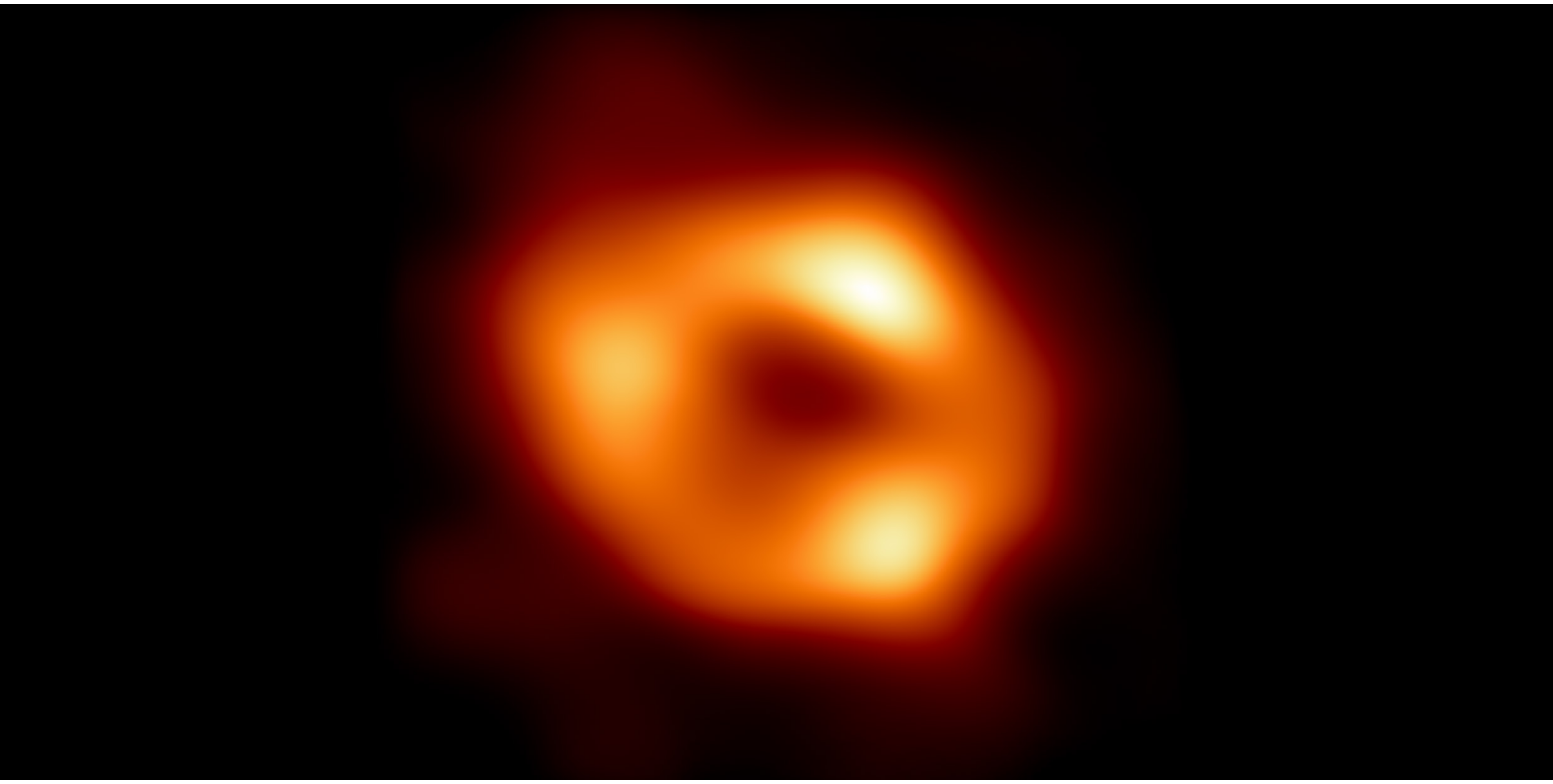
What quality do you most admire in others?

Kindness.

What scientific question do you hope will be answered in your lifetime?

The origins of life, both on Earth and in the universe as a whole. ■

Scientists release first image of giant black hole at Milky Way's galactic center



SIV SCHWINK

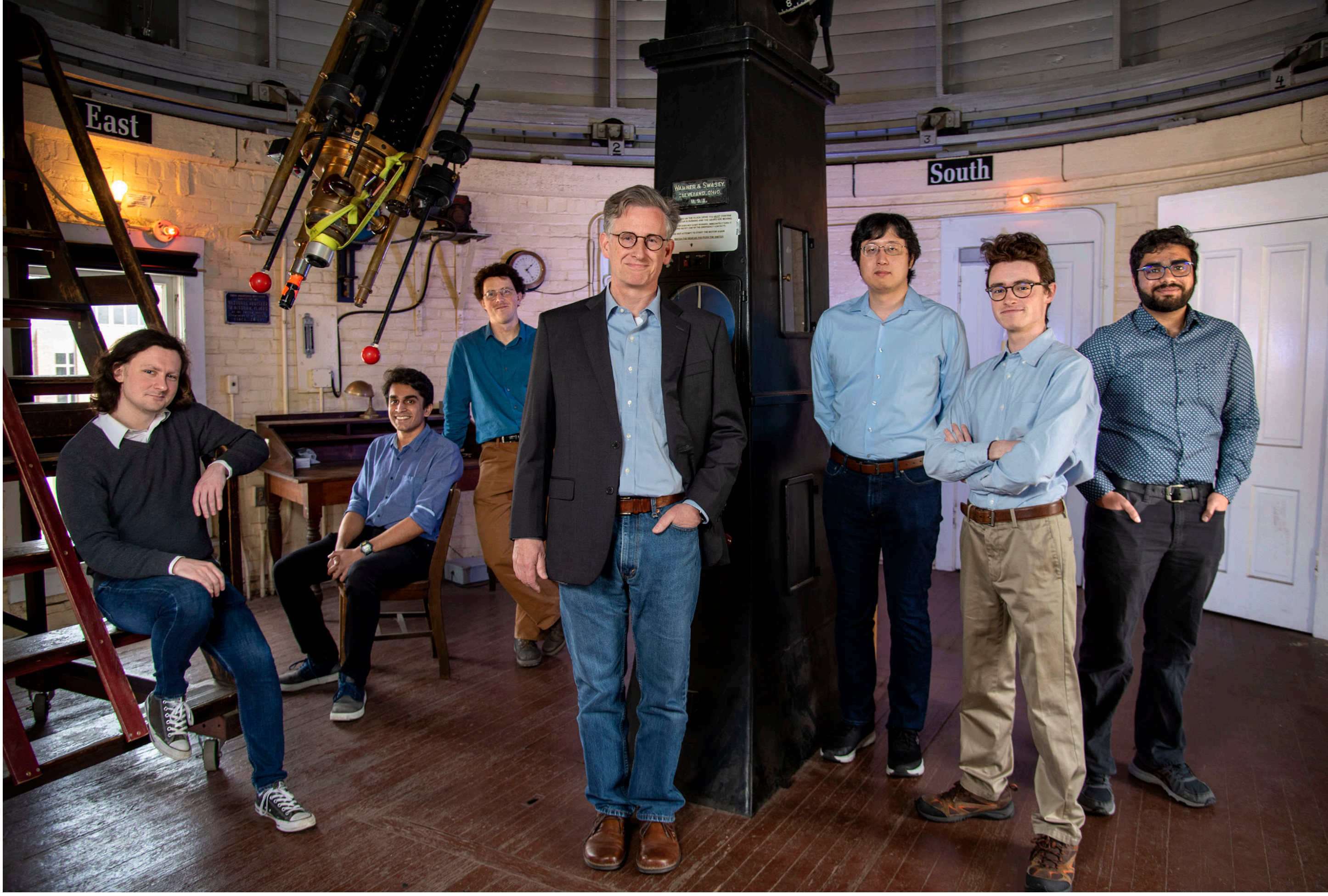
for Illinois Physics Condensate

On May 12, 2022, the Event Horizon Telescope (EHT) Collaboration released the first-ever image of the supermassive black hole at the center of our own Milky Way galaxy, attracting global media attention. Black holes are the most compact and energetic known objects in the universe and are by their very nature extremely challenging to study. Beyond its capturing the imagination of the public, what does this latest black hole image tell astronomers and astrophysicists about the nature and history of the universe?

The image of Sagittarius A* (Sgr A*, pronounced "sadge-A-star") was reconstructed from observations taken in April 2017, using an array of eight existing radio telescopes positioned around the globe—all pointed at the same target, at the same time. In this way, the EHT array forms a virtual Earth-sized telescope, capable of delivering the unprecedented resolution and sensitivity needed to investigate the massive compact object at the galactic center, 27,000 light-years away from Earth. The image is the first-ever direct visual evidence that this object is indeed a supermassive black hole.

This achievement reflects the ingenuity of the more than 300 researchers from 80 institutes around the world who together comprise the EHT Collaboration. Processing the huge collection of Sgr A* data and developing the algorithms to reconstruct the image took EHT scientists five years, which was longer than anticipated—the accretion flows surrounding Sgr A*'s event horizon are turbulent, rapidly changing, and exceedingly complex.

Illinois Physics and Astronomy Professor Charles Gammie co-leads the EHT theory working group. He and his research group in Urbana contributed a vast library of numerical models to this effort, which



Above: The Illinois EHT team poses at the historic campus observatory in Urbana. Pictured from left to right are Illinois Physics graduate students Ben Prather and Vedant Ketan Dhruv, Illinois Physics postdoctoral researcher Michi Baubock, Illinois Physics and Astronomy Professor Charles Gammie, Illinois Physics graduate students David Lee, Nicholas Conroy, and Abhishek Vidyadhar Joshi. Photo by Heather Coit, Grainger Engineering

Opposite page: The first-ever image of Sagittarius A* (or Sgr A* for short), the supermassive black hole at the center of the Milky Way galaxy, reveals a glowing gaseous ring surrounding a black 'shadow,' which is the black hole. Captured by the Event Horizon Telescope collaboration, it is the first direct visual evidence of the presence of this black hole. The image is an average of the different images the EHT Collaboration extracted from its April 2017 observations of the galactic center. Image courtesy of EHT Collaboration

were compared with EHT's Sgr A* data, to elucidate the astrophysics observed.

"My group and I have spent more than a decade developing key techniques for building models of Sgr A star," notes Gammie. "The models do a terrific job of explaining nearly all the data. But we uncovered a mystery—Sgr A star is much quieter than we expected."

The state-of-the-art simulations developed by the Gammie group in Urbana use general relativistic magnetohydrodynamics (GRMHD) to solve for the flow of hot gas around the black hole. These numerical solutions are then fed to general relativistic ray-tracing algorithms to generate predicted images of the black hole.

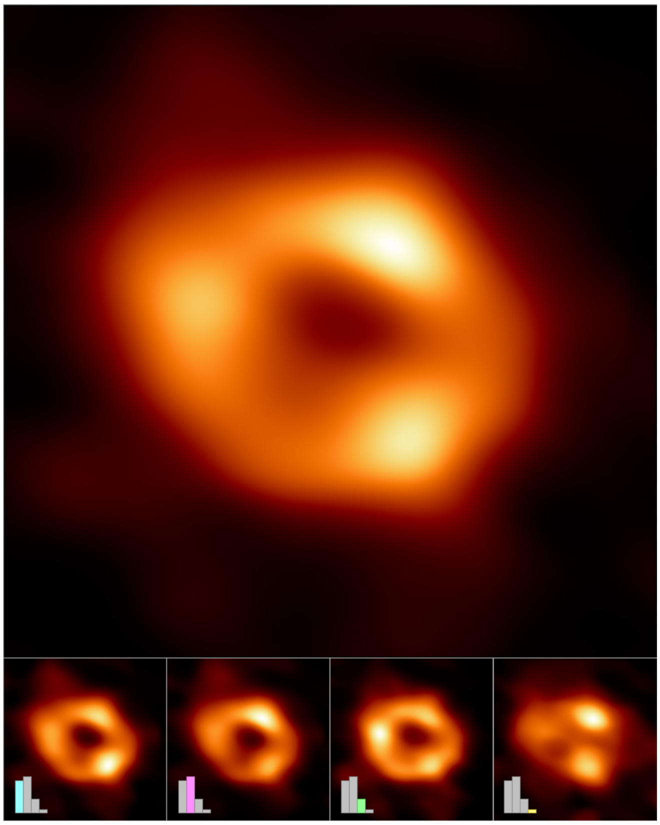
"Our team at Illinois works to explain what the image means," says Gammie. "Black holes can spin like a flywheel. Does the image tell us anything about the black hole spin and the direction it's rotating? How strong are the magnetic fields around the black hole?"

By comparing these predicted images with the horizon-scale resolution images taken by the EHT, scientists are also finally able to ask, does Einstein's general theory of relativity correctly predict the spacetime near a supermassive black hole?

"To answer these questions," Gammie continues, "we build computer models that track the flow of gas into the black hole and then make synthetic observations. Many of the beautiful animations you saw in the press release are based on our computer models. We then compare the models to the data using sophisticated statistical techniques."

Gammie says EHT scientists gleaned three key scientific takeaways by comparing the Sgr A* image with the numerical models.

"We learned a lot from this result," notes Gammie. "First, the image is a ring. It's consistent with what we expected,



How the Sagittarius A* image was made

The Event Horizon Telescope (EHT) Collaboration created a single image (top frame) of the supermassive black hole at the center of our galaxy, called Sagittarius A* (or Sgr A* for short), by combining images extracted from EHT observations.

The main image was produced by averaging together thousands of images created using different computational methods—all of which accurately fit the EHT data. This averaged image retains features more commonly seen in the varied images, and suppresses features that appear infrequently.

The images can also be clustered into four groups based on similar features. An averaged, representative image for each of the four clusters is shown in the bottom row. Three of the clusters show a ring structure having differently distributed brightness around the ring. The fourth cluster contains images that also fit the data but do not appear ring-like.

The bar graphs show the relative number of images belonging to each cluster. Thousands of images fell into each of the first three clusters, while the fourth and smallest cluster contains only hundreds of images. The heights of the bars indicate the relative "weights," or contributions, of each cluster to the averaged image.

Image courtesy of EHT Collaboration

based on earlier Nobel Prize–winning measurements by Andrea Ghez of UCLA and Reinhard Genzel of the Max Planck Institute in Germany. They followed the orbits of stars around the center of the galaxy over decades. That allowed a very precise measurement of the black hole mass and distance, which in turn allowed us to predict how big the ring should be.

"Second, the image is consistent with Einstein's theory of gravity. It could have been much bigger or smaller, and it's not—it's right on the button.

"Third, we interpret the image by comparing it to simulations, and although we're less confident about this, the models that match the best are nearly face-on (in other words, we're looking nearly at the pole of the black hole), have a spinning black hole, and have strong magnetic fields."

In 2019, the EHT collaboration released the first-ever image of a black hole, and it is strikingly similar to this latest image: a glowing gaseous ring at the event horizon surrounds a dark "shadow," which is the black hole. Gammie says the much larger M87* black hole—tens of millions of light years away at the center of the more distant Messier 87 galaxy—was actually easier to capture than Sgr A*.

"Our black hole is a thousand times smaller than the black hole in Messier 87, but also a thousand times closer, so it appears about the same size from our vantage point on Earth," explains Gammie.

Black hole mass scales with size, unlike the mass of other celestial objects such as planets and stars.

"Because the black hole is a thousand times smaller," Gammie continues, "the pattern of glowing gas around the black hole changes a thousand times more quickly in our galaxy than in Messier 87. This makes it really hard to get a clear picture. Where Messier 87 posed for us like an old great Dane, our Sgr A* is like a puppy chasing its tail—it won't sit still!"

The researchers developed sophisticated new analytical tools to account for the gas movement around Sgr A*. The latest image is an average of the thousands of different images the EHT collaboration captured of the galactic center during its April 2017 observations. The picture was made using a technique called VLBI, which stands for "very long baseline interferometry": data from pairs of telescopes were compared and used to generate images.

It was a five-year process—and all told, a huge step forward in black hole physics.

"This result is an important building block in our understanding of black holes and the role they play in our galaxy and in our universe," Gammie sums up. "More broadly, it's just an exciting result. Kids see it, and it raises their interest in astronomy and in science more broadly." ■

The Gammie group's work on the EHT Collaboration experiment is funded by the National Science Foundation under Grant Nos. NSF AST 17-16327, NSF OISE 17-43747, and NSF AST 20-34306. The results presented are those of the researchers and not necessarily those of the funding agency.

Notes from the Gammie EHT research team in Urbana

ILLINOIS PHYSICS POSTDOCTORAL RESEARCHER MICHI BAUBOCK

"Our simulations model the motion of a fluid. In our case, the fluid is an ionized plasma with a magnetic field that experiences the effects of the strong gravity near a black hole. We generated on the order of thousands of models, simulating a huge range of parameters, and we found that only a couple really match the picture very closely. This is exciting—we have simulations that can accurately describe the region very close to the black hole. And even more exciting is that none of the simulations work perfectly, which is probably a sign that there are ingredients missing from our models. We can continue to look at the aspects that don't match the observations and work to figure out, what's the missing piece in our simulations?"

ILLINOIS PHYSICS GRADUATE STUDENT NICK CONROY

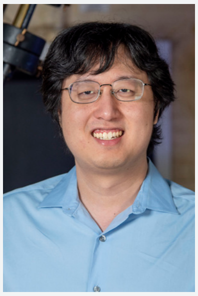
"It's been a joy to study these astronomical mysteries with so many scientists from around the globe. And it's wonderful to see how many people are learning about black holes. Recently, we spoke at a local elementary school, and every one of the kids knew about the first photo of a black hole. Now that we've revealed the first photo of a black hole in our own galaxy, we've been getting even more questions. It's incredible to be working on something that might inspire the next generation of scientists!"

ILLINOIS PHYSICS GRADUATE STUDENT VEDANT DHRUV

"Working toward the Sagittarius A* results as a member of the Event Horizon Telescope Collaboration was an exhilarating and humbling journey. As theoreticians we generated hundreds of models and examined over a million synthetic images. Analyzing these data and coordinating with collaborators across the globe in the midst of a global pandemic has been a feat in itself. Personally, I have learned a lot from the discussions with fellow members, and it has been an immensely gratifying experience."

ILLINOIS PHYSICS GRADUATE STUDENT ABHISHEK JOSHI

"Physics and astronomy were always interesting subjects in school, but to be a part of such a significant discovery is very surreal to me. It's both awe-inspiring and humbling to see how so many brilliant collaborators around the world (and here at UIUC) are able to work together to produce both sound and profound results. I hope there are others around the world who are inspired by this work and will pursue their dreams in astrophysics."



ILLINOIS PHYSICS GRADUATE STUDENT DAVID LEE

"It's been an incredible experience working with the Event Horizon Telescope. Beyond just the scientific challenges, we also needed to work with the struggles of coordinating and organizing a large, global collaboration of scientists in such a monumental undertaking, especially in times of COVID. It's been very exciting to collaborate with teams across the world on small projects and to watch our efforts slowly but surely coalesce into the results that we've put out—not only the beautiful image of Sgr A* but also the wealth of scientific data that came with these observations."

ILLINOIS PHYSICS GRADUATE STUDENT BEN PRATHER

"I think the most exciting thing about this result has been the sheer scale! The analysis effort has involved hundreds of thousands of simulated images from dozens of large-scale computer simulations, covering a huge breadth of possibilities for what might be producing the emission that the EHT sees. Working on generating and analyzing this much data has been a fun challenge. The scale of collaboration and community effort that has gone into these results is also immense. We've worked with teams all over the world contributing models and ideas together, filling out a whole mosaic of possibilities to evaluate against the observational results."

SPENCER HULSEY

SPREADING THE SPARK OF CURIOSITY

JAMIE HENDRICKSON
for Illinois Physics

In her career, Spencer Hulsey shares the excitement of science, technology, engineering, and math (STEM) with Wisconsin residents, especially with young people. It's her dream job, a position she has unofficially been training for since she first came to Illinois Physics as an undergraduate.

In fact, you could say the initial spark that led Spencer to her career happened even before that, when she was a high schooler visiting the University of Illinois campus in Urbana to participate in the Worldwide Youth in Science & Engineering (WYSE) Academic Challenge in the biology category. WYSE is a competitive series of regional-, sectional-, and state-level tests, created at the University of Illinois for high schoolers, now run by Eastern Illinois University.

During the WYSE lunch break, Hulsey sat in on a lecture by Illinois Physics Professor Mats Selen, an experience she credits with first igniting her love of physics.

Hulsey says the wonder and excitement she felt that day watching Selen illustrate the law of conservation of energy via a bowling ball pendulum kickstarted her on the path to becoming a STEM advocate—someone who can light that same spark of interest and wonder in others.

"Finding something that excites you is a valuable part of the human experience," Hulsey shares. "For me, this meant finding understanding in the phenomena that define our lives. When I look up at night, I find comfort in knowing what stars are and how they work. More importantly, I find purpose in the questions that remain."

Left page: Illinois Physics alumna Spencer Hulsey poses for a photo on the University of Wisconsin-La Crosse campus, where she works as the STEM outreach program coordinator. Photo by Michael Lieurance, UW-La Crosse

Lower right: Hulsey meets with Holmen Middle School science teacher, Mr. Baumgart, to discuss scholarships for his students to attend UW-La Crosse science camps.

That excitement in learning physics stayed with Hulsey throughout her undergraduate program at Illinois Physics. In fact, she was known for leaving a trail of smiles in her wake wherever she went. And sometimes where she went was to local grade schools, with the Physics Van.

Hulsey served as a volunteer coordinator for the student outreach group from her freshman to her senior year. Taking part in engaging youth with a fun and literally explosive (referring to soap suds) traveling science show fed Hulsey's need to spread the spark of curiosity about physics. She loved the show's many flashy demonstrations that challenged kids' understanding and showed them what science is all about.

Still spreading that spark of curiosity

After graduating with her bachelor's degree in physics in May 2020, Hulsey followed her passion for STEM outreach into a career that benefits Wisconsin youth. Now a STEM outreach program coordinator for the University of Wisconsin-La Crosse (UWL), she spends her days helping plan and organize events and programs aimed at inspiring and mentoring the next generation of scientists and mathematicians.

Hulsey's outreach efforts extend beyond the UWL campus and its students. Her work centers on creating engaging and accessible learning opportunities for all interested age groups in the region.

"Our department facilitates many different activities for lots of audiences," she notes. "This spring semester, we put on a Science and Math Expo and a Kid's College—two really fun examples of the opportunities we offer.

"The Science and Math Expo is a huge science fair attended by about 300 students from up to 14 different middle schools. The students present their research posters, answering questions you never knew you had, like, 'How does parachute shape affect fall time?' or, 'Does refrigerating batteries make them last longer?'"

In another effort, Hulsey recently proposed a program that will involve all University of Wisconsin schools. It's an academic STEM-test competition for high schoolers, and the prizes are UW scholarships. Hulsey recently received word that the University of Wisconsin System will move forward with her plan.

"This program is actually a partnership with 50-plus Illinois colleges, on a program that UIUC used to run, called WYSE. I did it in high school—it was part of why I chose to attend Illinois. I reached out to EIU's delegate—the U of I handed off the program to EIU in 2018 or so—and we partnered to build the program anew in a new state! The other UW campuses seem excited to start it up next year. We renamed it WYTS—Wisconsin Youth Testing in the Sciences—and it is the first youth program that all our schools have worked together on!"

Hulsey is also a regular guest on the WIZM 92.7 La Crosse Radio Show every third Thursday from 5:00–6:00 p.m. She talks about upcoming outreach events and summer camps, UW-La Crosse science, and other current science topics, such as DNA found on meteorites or the recent black hole image produced by the Event Horizon Telescope collaboration.

"That was fun because I got to talk about knowing some of the professors who worked on the black hole photos!" Hulsey beams.

Of course, creating the opportunity to ignite curiosity takes some planning and ingenuity.

Hulsey notes, "My day-to-day work involves a lot of what goes on behind the scenes—budgeting, contracting, setting up registration, and finding resources to fill in the gaps. But I'm also doing my best to introduce even more physics when I can. UWL doesn't currently have a student-led outreach program, so I'm working to change that with the help of the physics student club on campus."

Top: Spencer Hulsey talking science during an appearance on the WIZM 92.7 La Crosse Radio Show.

Bottom: A participant in a UW-La Crosse science camp enjoys learning through a hands-on experiment.

Always an Illini

Hulsey's career has taken her far from the UIUC campus, but she remains invested in her University of Illinois community.

"I'm still quite close with many of the physics majors I graduated with, and I connect with my former professors from time to time with questions about outreach and teaching strategies. For me, Illinois Physics is and always will be a home. I found my people there, and though we've now gone on to make our own careers, we're all still connected by the memories we share."

As the student who in late 2019 proposed the belted kingfisher bird be adopted as UIUC's mascot, Spencer has also maintained her involvement in the mascot-adoption process since graduating. Since 2019, she has worked closely with the student body, the alumni network, and a chancellor-appointed committee. Spencer's kingfisher design was first shared with the UIUC community on Reddit, where it received tremendous initial support. It later passed both a student vote and a faculty senate vote.

Where does that proposal stand now? The kingfisher is still under consideration. With so many in the broader UIUC community having strong feelings about the historical UIUC mascot, Chancellor Robert Jones charged his Building New Traditions Working Group of the Native American Representation and Reciprocity Initiative to "develop a framework for introducing new traditions to the university community," which "may include considerations of a new mascot." The steering committee's report with the working group's recommendations has been sent to the Chancellor for his consideration. Hulsey says a decision is anticipated by Spring 2024, and she is glad her kingfisher is still in the running.

In the meantime, Hulsey is working to strengthen her network up in Wisconsin, doing work that isn't so far afield from her undergraduate experiences.

"I'm still traveling around to local schools like I did with Physics Van, but this time I'm meeting with the teachers, rather than students, to help them to either start their own after-school outreach events with the support of UWL staff or to participate in the events offered on our campus," she says. "A STEM outreach program coordinator is a representative of STEM itself, and STEM outreach is all about discovering and sharing knowledge with others—hard earned and often very niche knowledge, but knowledge nonetheless. My job is to inspire others to share whatever inspires them."

Giving back to student outreach efforts at Illinois

Hulsey is among the ≈34 former Physics Van coordinators who set up a new student outreach scholarship fund at Illinois Physics, in honor of the official retirement of Selen, the Physics Van's founder. The group crowd-sourced donations and solicited donations from businesses and have exceeded their initial fundraising goal of $25K, with donations still coming in. As of publication of this magazine, the fund had reached about $35,000.

"Tamara McArdle and Matthew Wenger spearheaded the effort with the University of Illinois Foundation, and I did some leg work soliciting donations from friends, professors, alumni, and Physics Van alumni and I designed the plaque for Mats with all the coordinators' signatures on it.

"All the other former coordinators donated and likely reached out to the alumni that they worked with during their time with the Physics Van. I would guess a majority of the donations came from current physics professors and former students of Mats. Celia Elliott has been helping us out as well, keeping us up to date on the goings-on in Loomis. It's really been a sizable effort." ■

The **Mats Selen Outreach Achievement Award** will support an annual award in the Department of Physics for students who have participated in physics outreach programs.

For more information about this new fund, please contact Director of Advancement Jana Zollinger at jmzollin@illinois.edu.

To support this special initiative, please visit physics.illinois.edu/make-a-gift.

Below, top left: A current iteration of Illinois Physics alumna Spencer Hulsey's kingfisher mascot design. Courtesy of Spencer Hulsey

Below, right: A new campus town mural titled "Alma" includes a kingfisher. The mural, which appears on the side of the Skyline Tower building at 519 E. Green Street, Champaign, is by local artists Ryan 'Yanoe' Sarfati and Eric 'Zoueh' Skotnes, who say they were inspired by Hulsey's mascot design. Photo by Siv Schwink for Illinois Physics

Bottom left: A mural of a kingfisher by local artist Osiris Rain appears on the side of a detached garage at 604 ½ S. 3rd Street, Champaign, near the Boneyard Creek. The artist says he was inspired by Hulsey's proposed mascot. Photo by Siv Schwink for Illinois Physics

ILLINOIS PHYSICS
Student Awards

A.C. Anderson Undergraduate Research Scholar

This award supports summer research positions. It's named for Ansel Anderson (1933–2015), an alumnus (PhD, 1961), faculty member (1962–1992), and department head (1986–1992), who made seminal contributions to low-temperature condensed matter physics, particularly in characterizing the thermal properties of metals and glasses.

Jered Zhang

I am a senior in Professor Dale Van Harlingen's research group, working under Sam Cross on the growth of a BKBO superconducting thin film. Enrolled in both engineering physics and materials science, I am also a James Scholar and recipient of the MatSE Allen Award and the Friedberg Scholarship.

Commonwealth Edison/Beryl Bristow Endowed Award

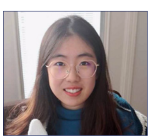
This award recognizes outstanding women physics majors. It was established by Commonwealth Edison in memory of alumna Beryl Love Bristow, the first woman to earn both a bachelor's and a master's degree in physics at Illinois.

Vedhasya Muvva

I am a sophomore in engineering physics, a Chancellor's and a James scholar. After undergrad, I hope to use my mechanical engineering concentration to apply physics to the design process. This past year, I've been the treasurer of both Society of Physics Students and Society for Women in Physics, working on networking, education, and creating a safe space to meet like-minded students.

Ernest M. Lyman Prize

This award recognizes outstanding graduating senior physics majors. It's named for Professor Ernest M. Lyman, who served on the Illinois Physics faculty for 36 years and made seminal contributions to experimental nuclear physics.



Shunyue Yuan

I have been working with Professor Lucas Wagner on measures of electronic correlation.

Mihir Katare

I am an engineering physics major with a minor in computer science. I recently worked with the Neubauer group on machine learning applications to the Matrix Element Method. I am excited to apply the problem-solving skills acquired through physics research in industry as a software engineer.

Jeremiah D. Sullivan Undergraduate Research Scholar

This award supports deserving undergraduates in their first research experience. It was established by family, friends, and colleagues of Jeremiah Sullivan (1938–2016), a professor of physics (1967–2006) and department head (2000–2006). Sullivan was a pioneer in theoretical high-energy physics. He was influential in arms control and international security.

Brian Petro

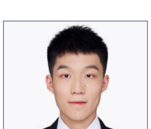
I am a junior undergraduate majoring in physics. This summer I will be working in Professor Paul Kwiat's quantum information group optimizing an independent polarization switch. The switch is used in hyperentanglement setups to easily operate on-time qubits without affecting their polarization states.

John A. Gardner Undergraduate Summer Research Award

This award supports summer research positions for outstanding physics undergraduate students. The award is named for alumnus John Gardner (MS, 1963; PhD, 1966), who has made important contributions to materials physics.

Devont Felix

I am a sophomore studying physics on the computational physics track in the College of Liberal Arts & Sciences. I'm working with Professor Bryce Gadway in the atomic, molecular, and optical (AMO) physics lab studying synthetic multidimensional lattice structures.



Yidi Liu

I am a physics major working with Professor Fahad Mahmood on single-molecule magnets and terahertz wire grid polarizers. I am looking forward to spending a productive summer in the lab.

Laura B. Eisenstein Award

This award recognizes outstanding women physics majors. Established by the department in cooperation with the American Physical Society and its Committee on the Status of Women in Physics, the award is named for Illinois Physics Professor Laura Eisenstein (1942–1985), a biological physicist who served the department with distinction (1969–1985).

Yichao Guan

I am a senior. I have been able to find opportunities that helped me gain knowledge and advance biophysics research at the University of Illinois. After graduation, I will work toward a doctoral degree in biophysics.

Yuting Maggie Liu

Over the past year, I studied mRNA degradation using computational models of diffusion under the supervision of Professor Sangjin Kim. I would also like to recognize the Yee Seung Ng scholarship and the Amateur Illustrator Club for their support.

Lewis C. Hack Scholarship

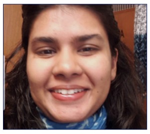
This award provides support toward fall tuition for an outstanding physics major. It was established by a gift from Lois E. Hack in memory of her husband, Lewis C. Hack. Both the Hacks devoted their lives to teaching math and science in the public schools.

Josiah Chong

I am working to become a high school physics teacher. In high school I was inspired by my science teachers because not only were they excellent teachers, but also great role models. I hope I can be a teacher who not only educates, but inspires as well.

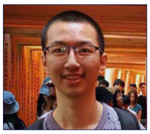
Lorella M. Jones Summer Research Award

This fellowship supports summer research positions for outstanding physics undergraduate students. It is named for Illinois Physics Professor Lorella Jones (1943–1995), a theoretical high-energy physicist who served the department with distinction (1968–1995). Jones was the first woman to attain tenure and full professorship in the department.



Yaashnaa Singhal

I will be working with Professor Jake Covey on building a single-neutral-atom optical-tweezer project.



Jing Zhou

I am currently a junior, pursuing a dual degree in physics and computer science. This summer I'm working with Professor Stuart Shapiro on astrophysics topics, doing simulation and data analysis.

Mok Wing Ho Scholarship

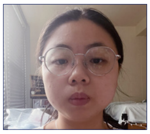
This scholarship is named in honor of Mrs. Mok Wing Ho, mother of alumnus Dr. Yee Seung Ng (BS '74). It recognizes superior academic achievement as well as commitment to the field through participation in physics-related extracurricular activities.

Elizabeth Zhang

I'm currently a sophomore majoring in engineering physics. I've served as the secretary and vice president of the Society for Women in Physics, as well as internal affairs and engagement officer and secretary of Society of Physics Students. Additionally, I'm a Chancellor's and James Scholar. After graduating, I hope to work in the mechanical engineering industry.

Philip J. and Betty M. Anthony Undergraduate Research Scholar

This award, made possible by gifts from Illinois Physics alumnus Philip J. Anthony, supports summer undergraduate research.



Jessie Wei

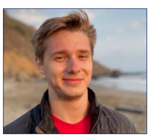
My research with Professor Bryce Gadway is about synthetic dimension. I am currently a sophomore in engineering physics with an Engineering Premier Scholarship. I am a James Scholar. I am also the outreach chair of the Society for Women in Physics.

Shuen Wu

I am a sophomore majoring in physics, math, and electrical engineering. Working with Professor Paul Kwiat, I am building a free-space optical classical channel for use in air-to-air, drone-based quantum key distribution. I hope to contribute to the field of quantum computing as a graduate student.

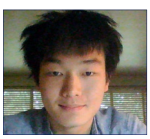
Pedro Rodrigues De Almeida Prado

I am a sophomore majoring in engineering physics. I will be doing research this summer with Professor Elizabeth Goldschmidt in quantum optics and quantum information science.



Nathan Zachar

I am a junior in engineering physics doing research under Professor Jacob Covey. The research that I am involved in focuses on how to use the hyperfine states of ytterbium atoms as qubits in a quantum computer. This has been a great way for me to learn more quantum and atomic physics and explore its applications.



Jiahao Zhang

I am a freshman physics major working with Professor Russ Giannetta and Professor Eugene Colla on detecting nuclear quadrupole resonance. I am a student senator of Illinois Student Government and UC Senate. I am the treasurer of Cirkle K International and active member of the Society of Physics Students.

Ralph O. Simmons Undergraduate Research Scholarship

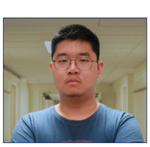
This scholarship supports summer research projects. Established by Ralph O. Simmons, Illinois Physics alumnus (PhD, 1957), faculty member (1959–), and department head (1970–1986), who has made seminal contributions to experimental condensed matter physics,.

Aniketh Balagonda

I am a second-year James Scholar undergraduate research assistant working in Elizabeth Goldschmidt's lab. This summer I will be performing saturated absorption spectroscopy in iodine to stabilize a titanium sapphire laser used for spectral-hole-burning experiments.

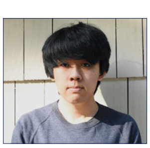
Jaydeep Pillai

I am a junior in engineering physics. I am working with Nadir Jeevanjee of NOAA Geophysical Fluid Dynamics Laboratory, studying arctic amplification of climate change. I am a Chancellor's Scholar, Provost Scholar, and a NOAA Hollings Scholar. I have served as president of the Society of Physics Students.



Jiarui Yu

I am a junior in engineering physics. I am working with Professor Bryce Gadway. We aim to finish building and tuning a group of over 20 synthetically coupled oscillators and to use them to simulate lattice models in solids. Besides research, I am also a James Scholar and Tau Beta Pi member.



Eric Yu

During the summer of 2022, I will be working with Professor Stuart Shapiro's group. Among other projects, I will be working on the visualization of the merger of spinning black holes.

Sahaj Patel

This summer I'm working with Professor Fahad Mahmood to develop new demos for the Physics Van. As Physics Van coordinator, I am creating a new show that includes quantum physics concepts. I plan to graduate in Fall 2022 with an Engineering Physics major. Along with running Physics Van, I also serve as Physics Student Advisory Board president.

Richard K. Cook Scholarship

This scholarship recognizes an outstanding physics student at the end of the sophomore year. It is named for Richard Cook (1910–2016), an Illinois Physics alumnus (PhD, 1935) who spent his entire career at the National Bureau of Standards.

Nicolás Patiño

I am a junior majoring in physics and mathematics and a Chancellor's Scholar. I am working on research under Professor Nicolás Yunes. I hope to earn a doctoral degree in physics and pursue a career in academia.

Robert A. Stein Award

This award was established in memory of alumnus Robert A. Stein (BS, 1955) by his family and friends to provide opportunities to physics students at UIUC who hail from the Chicago area.

Owen Stephenson

I am a sophomore studying engineering physics and philosophy, a James Scholar in The Grainger College of Engineering, and a member of Tau Beta Pi. I am enjoying my time here as an undergraduate research assistant in Professor Wolfgang Pfaff's quantum circuitry lab. I am grateful to receive this award.

Kayleigh Excell

I'm a sophomore in engineering physics minoring in Latin and math, with the goal of a doctoral degree in astrophysics. On campus, I'm the secretary of the Society for Women in Physics. I've also been fortunate to be named a Commonwealth Edison/Beryl Bristow Award recipient, a Chancellor's scholar, and a James Scholar.

Robert E. Hetrick Outstanding Undergraduate Research Award

This award recognizes outstanding independent research by an undergraduate physics major. It was established by W. Dale Compton (1929–2017), an Illinois Physics alumnus (PhD, 1955) and faculty member (1961-1970), in honor of his first U of I graduate student, Robert E. Hetrick (BS, 1963; MS, 1964; PhD, 1969).

Amanda Skittone

I am a graduating senior in engineering physics. I am being granted this award for my work on the Solar Array Research Group in the Electrical and Computer Engineering department with Professor Arijit Banerjee and research engineer Kevin Colravy. I was the coordinator of Physics Van and received the Undergraduate Outreach Achievement Award last year.

Undergraduate Outreach Achievement Award

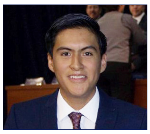
This award recognizes outstanding undergraduates involved in the Society of Physics Students and/or the Physics Van.

Sahaj Patel

This summer I'm working with Professor Fahad Mahmood to develop new demos for Physics Van. As Physics Van coordinator, I am creating a new show that includes quantum physics concepts. I plan to graduate in Fall 2022 with an engineering physics major. Along with running Physics Van, I also serve as Physics Student Advisory Board president.

Yee Seung Ng Award

This award, established in memory of alumnus Yee Ng (BS, 1974) by his family and friends, recognizes an outstanding junior or senior international engineering physics student.



Cesar Diaz Blanco

I will enter my final year towards a degree in engineering physics with a concentration in computational physics. I am deeply thankful for this support as it will help me to stay on campus over the summer to do research on computational astrophysics with Professor Charles Gammie.

Student Awards

Charles P. Slichter Fellowship

This fellowship supports stellar graduate students who are engaged in promising original research. The fellowship was created by family, friends, and colleagues of Charles P. Slichter to recognize and carry forward his tremendous legacy at the University of Illinois, where he served 57 years on the faculty of the Department of Physics. He is particularly noted for his pioneering use of nuclear magnetic resonance (NMR) spectroscopy to elucidate the structure and behavior of matter at the atomic scale.

Chenxi Huang

I am a second-year doctoral student in physics, working with Professor Bryce Gadway. My research interests focus on cold-atom experiment for quantum simulation and quantum information science.

Donald C. and F. Shirley Jones Fellowship

This fellowship supports an outstanding physics graduate student. It was generously bequeathed by Donald Jones, an industrial physicist, and F. Shirley Jones, an astronomer, who were the parents of the late Lorella M. Jones, the first woman to attain tenure and a full professorship in physics at the University of Illinois Urbana-Champaign.

Davneet Kaur

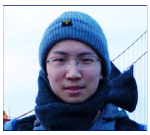
I'm a final-year physics doctoral student, working with Professor Thomas Kuhlman on the study of the dynamics of transposable elements of DNA. Following graduation, I want to use the skills I've gained to develop new genetic-based technologies.

Dr. Frank L. Lederman Award

This award, established by Dr. and Mrs. Frank Lederman, recognizes outstanding achievement by a graduate student in condensed matter physics (both experiment and theory). Dr. Lederman earned his doctoral degree from Illinois Physics in 1975, having written two separate doctoral theses on solid state physics, one on his experimental work and the other on his theoretical work. Lederman went on to a long, successful career in industry. He is especially noted for having led the development of General Electric's first medical ultrasound system.

Varsha Subramanyan

I am a sixth-year graduate student in Professor Smitha Vishveshwara's group. She works on several areas of condensed matter theory including applications of black hole physics to quantum Hall systems, investigations of topological features in biophysical systems, and probes of Majorana bound states.

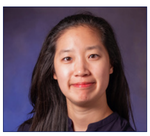


Xuefei Guo

I am a fourth-year doctoral student, working in Professor Peter Abbamonte's group. In my research, I use resonant x-ray scattering and momentum-resolved electron energy-loss spectroscopy to investigate quantum materials.

Drickamer Research Fellowship

This fellowship recognizes outstanding research by a physics graduate student. It is named for Professor Harry G. Drickamer, a distinguished faculty member at UIUC who contributed extensively to our understanding of the physics and chemistry of matter at high pressure.

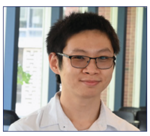


Soho Shim

I am studying the transport properties of metallic antiferromagnets as a fourth-year physics doctoral student in Professor Nadya Mason's research group. After completing my doctoral degree, I hope to develop my interest in magnetic phenomena and continue my research career in academia.

Felix T. Adler Award

This award recognizes outstanding work by a graduate student in nuclear physics. It's named for Professor Felix T. Adler, a theoretical nuclear physicist who served on the faculty at Illinois Physics from 1958 to 1979. His work spanned the development of nuclear energy.

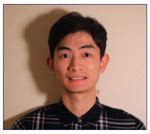


Ching Him Leung

I am a fourth-year doctoral student working with Professor Jen-Chieh Peng on the SeaQuest experiment. My current research is focused on extracting the charmonium production cross section from the experiment's data, as well as extracting the Drell–Yan cross section ratio from the second half of our data.

Giulio Ascoli Award

This award recognizes an outstanding physics graduate student working in high-energy physics. It's named for Professor Giulio Ascoli, who served with distinction on the faculty at Illinois Physics from 1950 until his retirement in 1986. His colleagues described his work on experiments at CERN, Argonne National Laboratory, and Fermi National Accelerator Laboratory as "innovative, elegant, and thorough."



Dewen Zhong

I am a sixth-year doctoral student working under the supervision of Professor Mark Neubauer in high-energy physics. My doctoral work searches for new physics beyond the standard model via the di-Higgs *bbVV* channel and explores the application of machine learning for the ATLAS detector at CERN's Large Hadron Collider, including through jet tagging and pion energy calibration.

John Bardeen Award

This award recognizes an outstanding physics graduate student working in condensed matter physics or electronic devices. It's named for Professor John Bardeen, the two-time Nobel laureate who was a professor of physics and of electrical engineering from 1951 to 1991. During his 60-year scientific career, he made significant contributions to almost every aspect of condensed matter physics.

Ryan Levy

I am a sixth-year physics doctoral student advised by Professor Bryan Clark, whose work spans a wide range of theoretical and computational topics from condensed matter to quantum computing. Recently, he has focused on new methods for solving strongly correlated electronic problems using quantum devices.

L. S. Edelheit Family Biological Physics Fellowship

This fellowship is awarded annually to an exceptional student in biological physics (experiment or theory). It was established through a generous gift from Illinois alumni, Lonnie and Susan Edelheit.

Ayesha Bhikha

I am a second-year physics doctoral student. My current research focuses on the hypothesis that infection by bacteriophage *lambda* affects the process of phase separation by RNA polymerase in *E. coli*.

Maurice Goldhaber Research Scholar Award in Nuclear Physics

This award recognizes an outstanding graduate student in nuclear physics. Maurice Goldhaber (1911–2011) was a member of the Illinois Physics faculty from 1938 to 1950. His remarkable achievements in research, teaching, and science administration made him one of the world's most distinguished nuclear and particle physicists.

Aric Tate

I am a nuclear, plasma, and radiological engineering doctoral student working in Professor Matthias Grosse Perdekamp's research group on a cross-section analysis that will help to improve the understanding of nucleon structure. I also contribute to the ATLAS zero-degree calorimeter upgrade for the high-luminosity Large Hadron Collider at CERN.

Miles V. and Barbara P. Klein Graduate Fellowship

This fellowship recognizes an outstanding graduate student in condensed matter physics. It was established through the generosity of Miles V. Klein, a distinguished member of the Illinois Physics faculty (1962–2017) who has made seminal contributions to our understanding of electronic, vibrational, and magnetic excitations in solids and their mutual couplings.

Caitlin Kengle

I am a fourth-year doctoral student studying experimental condensed matter physics. I work with Professor Peter Abbamonte to measure and understand elementary collective modes in condensed matter systems. I aspire to finish my doctoral degree and continue working in experimental condensed matter physics at a national lab.

Renato Bobone Award

This award recognizes a physics graduate student who has demonstrated academic excellence. In accordance with the donor's wishes, preference is given to Italian citizens. This award was endowed by alumnus Renato Bobone.

Vincent Hickl

I am a doctoral student in Illinois Mechanical Science & Engineering Professor Gabriel Juarez's group. I have a graduate fellowship from the Oil Spill Recovery Institute. In my research, I perform experiments to investigate interfacial deformations caused by the growth of bacterial colonies on oil droplets.

Scott Anderson Award

This award recognizes the year's outstanding physics teaching or research assistants. It is named after Illinois Physics alumnus Dr. Scott Anderson, who founded Anderson Physics Laboratories in Urbana in 1944. It was through his initiative as president of our Physics Alumni Association and his generous philanthropy that the Anderson Award was endowed.

Rohit Chandramouli

I am working with Professor Nicolás Yunes on gravitational waveform modeling of hierarchical triple systems and investigating waveform systematics due to astrophysical mismodeling. I am working towards my doctoral degree in physics and hope to continue research in gravitational physics.

Jia Pern Neville Chen

I am a first-year physics graduate student working with Professor Jacob Covey. My doctoral research is on the use of neutral alkaline-earth atoms in an optical-tweezer array for novel schemes in quantum information processing.

Dmitry Manning-Coe

I am a graduate student working on interacting topological states. This year I was involved in the Physics Graduate Student Association. We were back in person and, thanks to Professor Lance Cooper and the committee, we revived the tradition of the Physical Revue, held craft nights, bar nights, and generally tried to nudge the grads back into the "Urbana style."

Arjun Raghavan

I am a fourth-year doctoral student in Professor Vidya Madhavan's lab, probing materials at the single-atom scale using scanning tunneling microscopy (STM). With novel STM-based tools, I'm working on measuring the nanoscale magnetism and picosecond-scale non-equilibrium optical responses of a range of quantum materials.

Garrett Williams

I am a third-year doctoral student working under the direction of Bryce Gadway toward quantum simulation using ultracold polar molecules.

Danielle Woods

I'm a third-year physics graduate student working with Elizabeth Goldschmidt, making rare-earth quantum devices. I've had the opportunity to help our graduate community through my work as co-president of the Physics Graduate Student Association. After I graduate, I will continue researching and helping our community.

Steven M. Errede Award

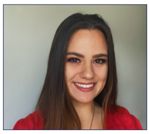
This award recognizes outstanding work by a graduate student in the area of high-energy physics. The award is named for Illinois Physics Professor Emeritus Steven Errede, who contributed to the discovery of the Higgs boson as part of the ATLAS experiment at the Large Hadron Collider at CERN in Switzerland.

Asad Khan

I'm honored that my work with Professors Eliu Huerta and Ed Seidel was selected for this award. From pioneering efforts in numerical relativity led by Ed Seidel in the 1990s to the recent innovative efforts in AI for gravity by Eliu Huerta, the gravity group has a rich legacy, and I feel humbled to have been part of it.

Vijay R. Pandharipande Prize in Nuclear Physics

This prize recognizes the year's outstanding nuclear physics graduate student. Professor Pandharipande served with great distinction on our faculty for 34 years.



Debora Pias Mroczek

I am a second-year doctoral student working with Professor Jacquelyn Noronha-Hostler. Her research focuses on applications of modern machine learning and statistical techniques in understanding different phases of hot and dense nuclear matter.

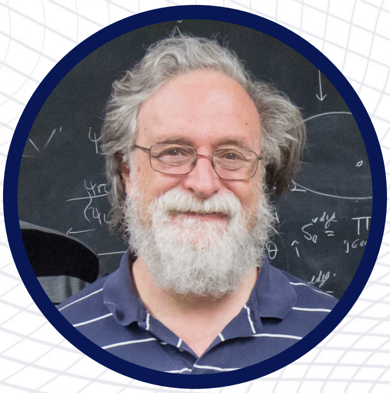
To learn more about our student awards or to support a student award fund, please visit the Honors and Awards pages on our website, under the People tab, at physics.illinois.edu.

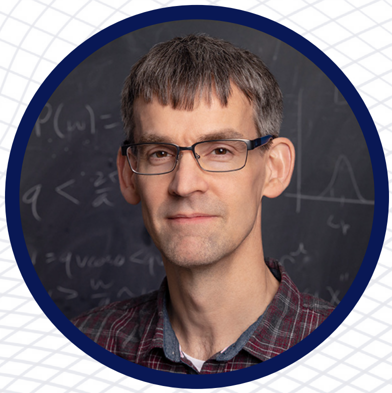
Questions? Please contact our Director of Advancement Jana Zollinger at jmzollin@illinois.edu.

Peter Abbamonte and Inprentus Inc. team make finals of Illinois Manufacturers' Association's 'Makers Madness'

Illinois Physics Professor Peter Abbamonte and his Inprentus Inc. team pose for a photo with Illinois Governor J.B. Pritzker, after making the final four in a statewide competition for "The Coolest Thing Made in Illinois." Abbamonte founded Inprentus in 2012 to supply researchers and industry with high-precision diffraction gratings used in synchrotron radiation facilities, semiconductor manufacturing, and AR/VR headsets. Pictured left to right are Abbamonte, Inprentus Administrator Cynthia Ottemann, Governor Pritzker, Inprentus Nanomanufacturing Lead Subha Kumar, and Inprentus Vice President of Business Development Marty Dugan. Photo courtesy of Peter Abbamonte.

NEW STUDY SUGGESTS CHARGE ORDERINGS IN SUPERCONDUCTING CUPRATES SHARE A COMMON ORIGIN


Eduardo Fradkin


Peter Abbamonte


Gregory MacDougall


Edwin Huang


Sangjun Lee


Thomas Johnson

DANIEL INAFUKU

for Illinois Physics Condensate

Considered the biggest open problem in condensed matter physics, high-temperature superconductivity has posed a formidable challenge to scientists for over 35 years. Since the discovery of high-temperature superconductors in 1986 by Georg Bednorz and K. Alex Müller, physicists have faced the difficulty of developing an adequate theory that explains the host of different ordered phases of matter displayed by these materials and their mutual relationships.

Now, a collaborative team of condensed matter experimentalists and theorists at the University of Illinois Urbana-Champaign have begun to untangle a web of different effects found in a class of high-temperature superconductors known as the cuprates. The researchers discovered that differences in patterns of charge density among different cuprates may be manifestations of the same general behavior—behavior that is possibly universal across the cuprate family. These findings were published on April 4, 2022, in the *Proceedings of the National Academy of Sciences*.

Charge density waves behave differently in different materials—or do they?

The cuprates are a class of compounds made up of planes containing both copper and oxygen, as well as two (or more) elements between the copper-oxide planes. These materials have the highest transition temperatures among the high-temperature superconductors. Recent attention has focused on the behavior of the cuprates' charge densities, which form ordered spatial patterns called charge density waves (CDWs). Since their discovery in lanthanum-based cuprates in the mid-1990s, the roles that CDWs play in cuprate superconductivity have been the subject of much debate and generated additional interest when about a decade later, CDWs were also found in other, non-lanthanum-based cuprates.

"The source of the different cuprate behaviors has been a big mystery in condensed matter physics for years. We showed that the charge order, which we thought was unique to each cuprate family, was actually just different incidences of a larger, universal behavior."

— Gregory MacDougall

Today, CDWs are widely recognized as fundamental features of cuprates and respond to changes in temperature and doping—the addition of chemical elements that change the number of mobile charge carriers, which enables and enhances superconductivity. Studying CDWs, however, is far from straightforward, because they can interact with other effects present in a material, such as spin density waves (SDWs), leading to unexpected material-specific CDW behaviors.

This complex maze of interacting effects prompted condensed matter physicists, including Illinois Physics Professor Eduardo Fradkin and Stanford University Physics Professor Steven Kivelson, co-principal investigators of the current study, to describe the orderings of different effects as "intertwined."

Fradkin explains, "These cuprates are strongly interacting materials, and as you change the amount of mobile charge—usually through doping—you end up in a regime where you observe superconducting states having the highest known transition temperatures, typically in the range of 40K to 150 K.

"As physicists have learned more about the cuprates, it has become apparent that there are significant differences between different cuprate families. Among lanthanum-based cuprates, for example, the CDW wave vector—the reciprocal of the CDW's period—appears to first increase then flatten out as the degree of doping increases. By contrast, the wave vector decreases for yttrium- and bismuth-based cuprates. This apparent discrepancy seems to suggest that the origin of this phenomenon may be specific to each material and hence not the reflection of a general physical origin."

A central task to understand the cuprates, therefore, is to separate out CDW-interacting effects from each other. Specifically, the authors wanted to learn if CDWs among different cuprate families share similar physics.

Co-principal investigator and Illinois Physics Research Professor Gregory MacDougall is an expert in growing crystals for condensed matter experimentation. He notes, "There are dozens of cuprate families, and they each have slightly different properties. One challenge is to sift through these properties to possibly find a generic one that contributes to superconductivity. Our goal was to determine whether these properties are family-specific or something more general."

As a starting point, the team looked at the interaction between CDWs and spin density waves (SDWs). SDWs, which encode magnetic ordering, are prominent features of lanthanum-based cuprates, whereas SDWs are absent in yttrium-based and bismuth-based cuprates, suggesting the possibility that a CDW-SDW interaction is the source of the lanthanum-based cuprates' unusual doping dependences.

Scattering experiments reveal some surprises

To study the CDW-SDW interaction in detail, the researchers conducted resonant soft X-ray scattering (RSXS) and neutron scattering experiments to characterize CDWs and SDWs in the lanthanum-based cuprate $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ (LESCO) and developed the theory needed to interpret the experiments. Notably, the researchers studied LESCO crystals enriched with the isotope ^{153}Eu, enabling neutron scattering studies of the SDW in this system for the first time.

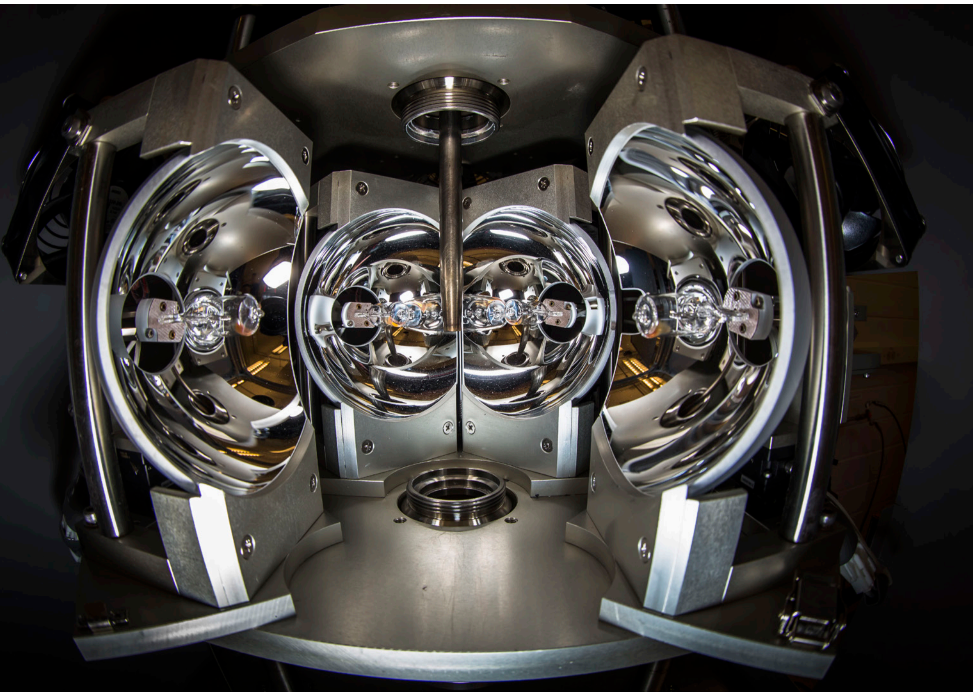
In true "Urbana style," this work was a collaborative effort: MacDougall and his group grew the unique samples and carried out the neutron scattering experiments; Illinois Physics Professor Peter Abbamonte and his group performed the RSXS studies of the CDW; and Fradkin and Kivelson, in collaboration with Illinois Physics postdoctoral scholar Edwin Huang, developed theory that accounted for the temperature and doping dependences of the CDW and SDW orders.

Lanthanum-based cuprates often possess a structural transition found near the onset temperature of CDWs as doping is adjusted.

This transition can interfere with the CDW and obscure its measurement. LESCO is unique in that its structural transition temperature is well separated from the CDW onset temperature, making LESCO a tractable yet typical representative of lanthanum-based cuprates.

Co-lead author and Illinois Physics graduate student Thomas Johnson, who grew the LESCO samples and performed the neutron scattering experiments, explains, “One advantage of LESCO is that the structural transition—from orthorhombic to tetragonal—is nearly doping independent. This feature makes it easier to identify which behaviors are attributable to which effects.”

Neutron scattering experiments, which probe magnetic ordering, showed that the CDW and SDW orders in LESCO strongly couple to each other at low temperatures. In particular, the SDW wave vector was found to be exactly half the value of the CDW wave vector. This relationship allowed the researchers to infer that the CDW wave vector first increased with doping before flattening out, as expected from a lanthanum-based cuprate. In addition, detectable SDWs died out at higher temperatures.



The four-mirror optical image furnace in the MacDougall lab at the Frederick Seitz Materials Research Laboratory in Urbana, used to grow the LESCO crystals for this study. Illinois Physics graduate student Thomas Johnson used the traveling solvent float zone method in an oxygen overpressure environment. The furnace is manufactured by Crystal Systems.

The CDW is an ordered state of electrons, which, like all waves, is described by an amplitude and a phase. These materials contain disorder, which tends to make the phase fluctuate from one location in the material to another while leaving the amplitude essentially unaffected. Consequently, there is no true long-range CDW order. The RSXS experiments showed that the CDW amplitude (not to be confused with the CDW wave vector) does not vary much with temperature. In fact, at all temperatures up to the highest recorded temperature of 270 Kelvin, the amplitude appeared to be nearly constant.

But the results also contained some surprises.

Remarkably, the CDW wave vector exhibited a non-monotonic dependence on temperature. At sufficiently high dopings, the CDW wave vector developed a V-shaped “kink” having a sharp minimum at a characteristic temperature, a new feature not seen before in lanthanum-based cuprates. The kink lay near the temperature corresponding to the emergence of spin order, as shown by the neutron scattering experiments, suggesting the presence of CDW-SDW interactions.

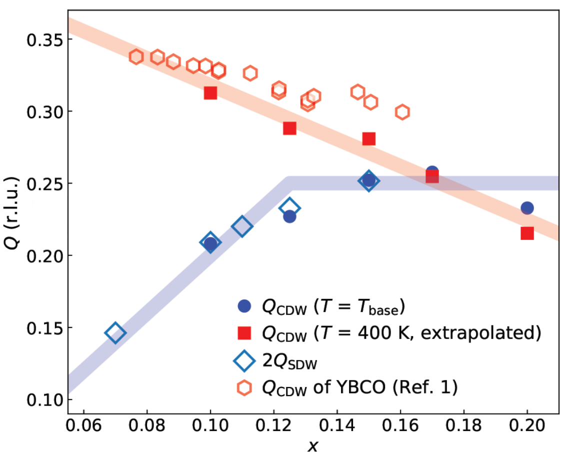
Untangling interacting effects

To explain the possible causes of these experimental surprises, the authors developed a theoretical model that incorporates an additional effect: because the samples are actually metals, electron interactions are screened, or damped, inside the material over long distances; when such screening occurs, charge carriers in the material form a compressible fluid. The compressibility of the charged fluid is the key to understanding why the CDW wave vector changes with temperature and doping.

By including compressibility as an adjustable parameter in their model—together with parameters encoding both charge and spin—the researchers obtained fits in good agreement with the RSXS data: the theory predicted kinks in the CDW wave vectors just as the experiments showed.

Critically, the model also enabled the researchers to simulate what would happen at temperatures beyond those used in the experiments—in particular, beyond temperatures where they suspected spin order is relevant. In other words, since detectable SDWs disappeared at higher temperatures, the researchers were able to numerically observe what they believe to be the intrinsic, “actual” CDW behavior in the absence of the suspected CDW-SDW interactive influence.

Huang, a co-lead author and the lead theorist of the study, explains, “According to our model, we found that if one



Plot of the charge density wave (CDW) wave vector versus the degree of doping. The lower curve (solid blue line) depicts the low-temperature behavior of LESCO and is typical for lanthanum-based cuprates. The upper curve (solid red line) depicts the extrapolation of experimental data for LESCO to high temperatures, showing a decreasing trend similar to yttrium- and bismuth-based cuprates such as YBCO. Figure originally published in Lee *et al.*, *PNAS* 119 (15) e2119429119.

extrapolates the CDW wave vector from our experimental data to much higher temperatures, up through 400 K, then the wave vector follows a doping dependence that's different from the one seen at lower temperatures."

And that doping dependence wasn't arbitrary: it obeys the same doping dependence seen in yttrium- and bismuth-based cuprates, where the wave vector decreases with increasing doping. This result indicates that lanthanum-based cuprates are more similar to non-lanthanum-based ones than previously thought, pointing to a universal mechanism shared by all the cuprates.

Huang continues, "We believe that at high temperatures, the CDW and the SDW are not interacting much. There's some unknown mechanism that prefers this decreasing wave vector behavior in the yttrium-based cuprates and LESCO.

"Using the extrapolated results from our physically motivated model, we're seeing behavior in LESCO, a lanthanum-based cuprate, that is quantitatively consistent with the behaviors in other, non-lanthanum-based cuprates. Our extrapolation showing an yttrium-like trend in LESCO was a real surprise."

Fradkin elaborates, "The physics of this problem is that the CDW forms at high temperatures, whereas the SDW forms only at much lower temperatures. The change in the CDW wave vector is explained by separate effects. First, these materials studied are actually metallic, which leads to screening effects on charge fluctuations. This screening—this suppression of interaction among charges at long distances—is the origin of the temperature and doping dependences of the CDW wave vectors.

"Second, at lower temperatures where the SDW begins to form, a strong interaction arises between the nascent SDW and the already well-formed CDW. Because of this interaction, these modulated states tend to become commensurate with each other. In other words, below some temperature, the period of the modulations of the CDW and SDW wave vectors become locked to each other by a factor of 2. The process by which the CDW and SDW become locked together occurs within a very narrow temperature range. The interaction between the CDW and the SDW is the origin of the kink observed in the RSXS experiments."

What's next for the cuprates?

Having characterized the CDW-SDW interaction, the researchers have opened the door to a host of new experimental and modeling opportunities aimed at understanding the cuprates.

MacDougall sums up, "The source of the different cuprate behaviors has been a big mystery in condensed matter physics for years. We showed that the charge order, which we thought was unique to each cuprate family, was actually just different incidences of a larger, universal behavior."

The researchers also acknowledge that their work says nothing yet about the exact microscopic physics of the cuprates' CDWs.

Huang notes, "Regarding our model, we haven't made a microscopic prediction for the value of the compressibility parameter, and it allows us to characterize only the behavior that we're seeing.

"While we can't say exactly what's happening at high temperature from our data alone, our theoretical findings are still strong evidence for a universal mechanism of intertwined orders underlying the physics of the cuprates."

Clearly, a next step is to study the root cause of intertwined orders in the cuprates and other strongly correlated systems.

Fradkin says, "Another open problem is to explain the microscopic physical mechanism behind the specific way that the charge and spin orders interact. Understanding this interaction is the key to understanding the origin of intertwined orders seen in these and many other materials." ■

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JAMES WOLFE

1943–2022

BY CELIA ELLIOTT AND DALE VAN HARLINGEN

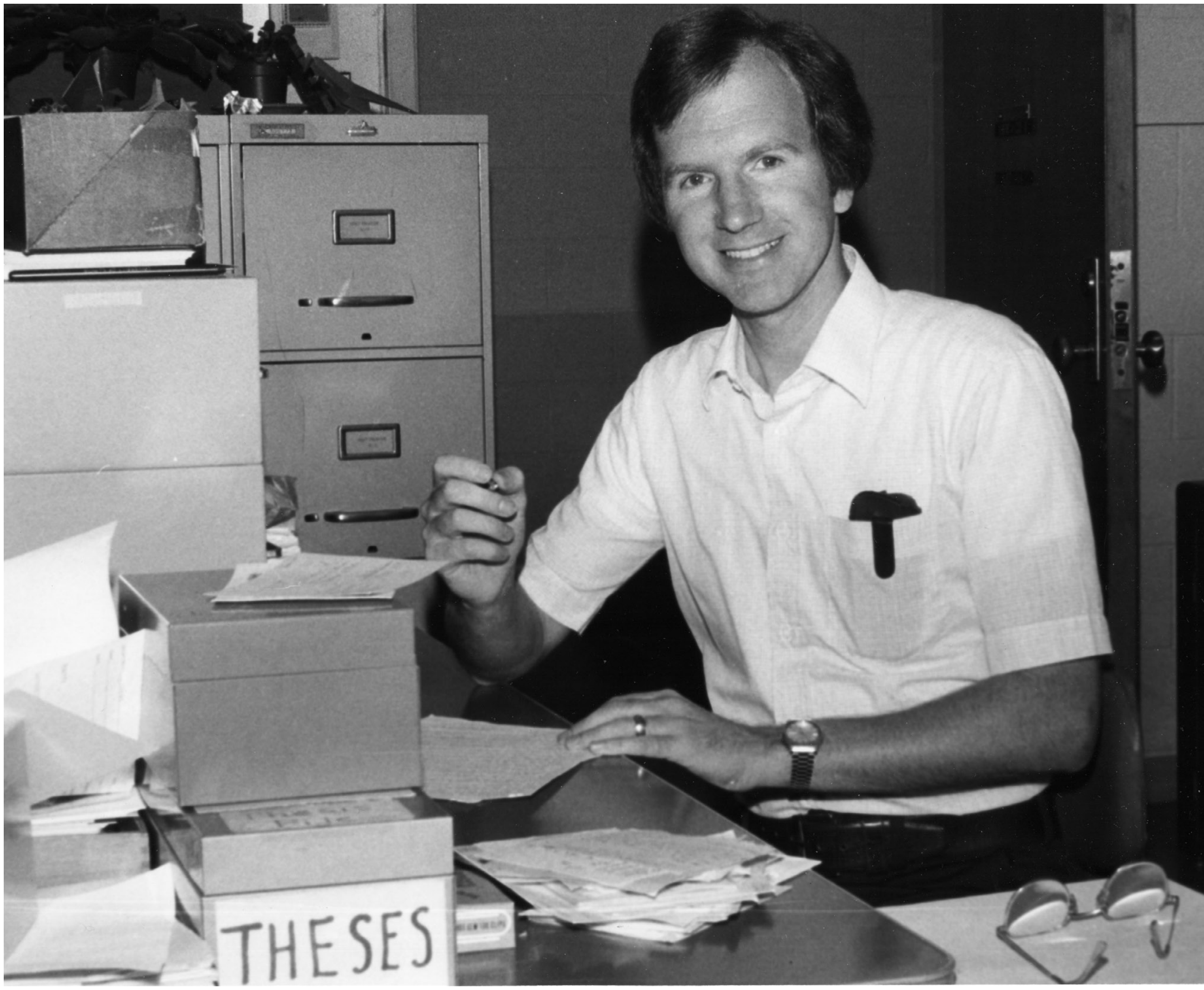
for Illinois Physics

Professor James P. Wolfe spent his entire faculty career at the University of Illinois, retiring in 2006 after 30 years in Urbana. He was a principal investigator in the Frederick Seitz Materials Research Laboratory (MRL), where he concentrated on the physics of excitonic matter and phonons in solids. Phonons are vibrations of atoms or molecules in the crystal structure of materials that propagate as sound or heat, depending on the frequency of the vibrations, as they pass through the material.

Wolfe received his bachelor's and doctoral degrees in physics from the University of California, Berkeley. He remained at Berkeley as an assistant research physicist, and with Carson Jeffries' group, he applied optical and microwave techniques to the newly discovered phenomena of electron-hole droplets in germanium. Using infrared imaging, they took the first photo of an electron-hole droplet. He joined the Department of Physics at Illinois in 1976.

Best known for developing novel imaging techniques to study excitonic matter and phonon propagation at ultracold temperatures, Wolfe's group created time-resolved luminescence imaging techniques to determine the spatial distribution and mobilities of electron-hole droplets and excitons in bulk semiconductors, such as silicon, germanium, and copper oxide. Wolfe's group combined picosecond laser spectroscopy and micro-imaging techniques to measure the in-plane motion of photoexcited carriers in semiconductor quantum wells. Since its introduction in 1978, "phonon imaging" has contributed graphically and quantitatively to far-reaching topics in phonon physics. Utilizing tiny superconducting detectors and laser-scanned heat sources, phonon imaging has elucidated diverse physical phenomena—phonon focusing, lattice dynamics, and phonon scattering at interfaces, superlattices, and defects.

Wolfe directed multi-investigator projects for the National Science Foundation and the U.S. Department of Energy at the MRL. Between 1999 and 2002, he served the Department of Physics as the associate head for graduate programs, heading up one of the largest physics doctoral programs in the nation. He also served



on several high-level campus administrative committees over the years and supervised the thesis research of 25 doctoral students during the course of his prolific career. A dedicated and gifted teacher, Wolfe developed an introductory textbook after his retirement, “Elements of Thermal Physics,” that is used by approximately 1000 undergraduate engineering students at Illinois every year. His research textbook, “Phonon Imaging,” has become a staple for graduate students and researchers alike.

In 2004, Wolfe was awarded the Frank Isakson Prize of the American Physical Society “for contributions to the fundamental understanding of excitonic matter in semiconductors, including its propagation, made possible by pioneering development of imaging techniques that lend graphic insights to electronic and vibrational processes in solids.” In 2010, Wolfe received the Paul G. Klemens Award of the International Conference on Phonon Scattering in Condensed Matter for his investigations of a phonon “wind” and his groundbreaking contributions to the phonon physics involved in dark matter detection. He received a U.S. Senior Scientist Award in 1988 from the Alexander von Humboldt Foundation (Germany) and a Japan Society for the Promotion of Science Fellowship in 1991. He was elected a Fellow of the American Physical Society in 1980 and a Beckman Fellow of the University of Illinois Center for Advanced Study in 1982. ■

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