Vol. 2, No. 1 Fall 2018

ILLINOIS PHYSICS

condensate

PROFILE

Next-gen camera for South Pole Telescope takes data on early universe

PROFILE

The next scientific and technological revolution: quantum information science

RESEARCH

Disorder induces topological Anderson insulator

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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THE NEWS MAGAZINE *of the* DEPARTMENT OF PHYSICS

ILLINOIS PHYSICS CONDENSATE

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Please send us your comments or ideas for future stories:

Siv Schwink
sschwink@illinois.edu
or (217) 300-2201

Department of Physics
1110 West Green Street
Urbana, IL 61801-3080

Cover image: U of I astronomy graduate student Andrew Nadolski stands in front of the South Pole Telescope (SPT) in Antarctica. A member of Professor Joaquin Vieira's research group, Nadolski helped design and build the optics for the third-generation SPT. He was stationed at the South Pole for the first year after installation of the third-generation camera on the telescope. Photo courtesy of A. Nodolski

Back cover image: Loomis Lab's Goodwin Street entrance, with signage commemorating Professor Anthony J. Leggett's research in superfluidity and superconductivity, for which he won the Nobel Prize in 2003. Photo by Siv Schwink for Illinois Physics

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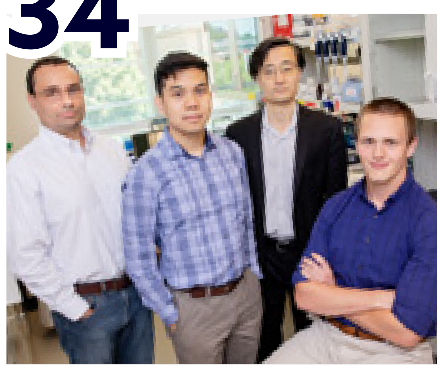

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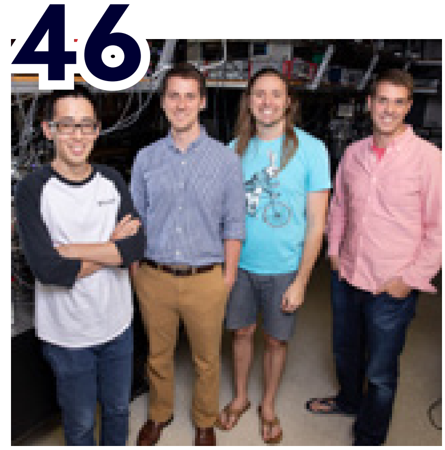


GIVING

FROM OUR *Department Head*

MATTHIAS GROSSE PERDEKAMP

Dear Alumni and Friends,

The Department of Physics at the University of Illinois at Urbana-Champaign is one of the largest and best physics programs in the U.S., educating highly qualified physicists for academia and training STEM-field employees for the U.S. workforce. Over the last five years, we have graduated an average of 130 undergraduate physics majors per year. We maintain the largest doctoral program in physics in the U.S., and since the summer of 2005, we have graduated a total of 505 doctoral students.

Our students are trained in the rigorous academic environment of a leading research university. Each year, we teach about 600 physics majors and more than 4,000 non-majors in our introductory physics courses. This effort is based on the innovative work of our physics education research group, which is driving the continuous development of modern, evidence-based pedagogies and pedagogical tools. In addition to the large educational effort, we maintain one of the most highly regarded fundamental physics research programs in the world.

New leadership.
This term, new leadership was introduced at the campus, college, and departmental levels. Our former dean, Andreas Cangellaris, now serves as the new provost, and Rashid Bashir, as the new dean of the College of Engineering. In the Department of Physics, Brian DeMarco has stepped up as associate head for undergraduate programs, and I have taken on the head position. The vision and direction we share for the College of Engineering is advancing knowledge and technology through a science-based approach. This method relies on close collaboration between the Department of Physics and other units in the College, both in education and research. Many of our scientific strengths in Physics are closely connected to technology research pursued by the faculty, researchers, and students in Engineering.

Quantum information science at Illinois.
Quantum information science (QIS) is an exciting, fast-growing field with important implications for future technologies that will support secure communications and exponentially greater computational power. Federal support for QIS research continues to grow, and a national initiative is being launched. Our department is a principal stakeholder in the university's strategic plan to expand research efforts and build partnerships in this field. The university is a key player in a larger plan to put the State of Illinois at the forefront of this emerging field. The university has pledged $15 million to create an Illinois Quantum Information and Technology Center (IQUIST) that will facilitate collaborations among faculty from different units and will foster partnerships with industry, national laboratories, and other academic units. The university also joined the Chicago Quantum Exchange as its final core member, initiating collaboration with the University of Chicago, Argonne National Laboratory, and Fermi National Accelerator Laboratory in QIS. Paul Kwiat, Brian DeMarco, and Dale Van Harlingen are leaders of this important initiative at the U of I, in the State of Illinois, and nationally.

Strength through diversity.
My own research takes place in a multi-national environment at CERN, and I have seen firsthand how diversity benefits both creativity and research output. The positive impact of diversity at CERN has been studied by social scientists from Finland and Italy: diversity plays an important role in the efficient knowledge creation at CERN and in the knowledge transfer to collaborating institutions and companies. These strengths are certainly at work in our department as well. Our faculty, researchers, staff, and students come from many different backgrounds, and we continue to seek ways to better benefit from the broad diversity we have in American society.

As a department, we support measures that advance gender

and racial equality and inclusion in physics at all levels. We actively work to ensure that the climate for our students, postdocs, faculty, and staff is collegial and supportive. This semester, we welcomed 147 new undergraduate students, of which 16 percent are women and 8.5 percent are from groups underrepresented in physics. We also welcomed 41 new graduate students, of whom 34 percent are women. This significant increase is thanks in large part to the efforts of Lance Cooper, our associate head for graduate programs. We are strongly committed to further improve diversity and inclusion, and your suggestions are highly welcome.

New faculty.
One important way we will maintain our top-ten standing among physics programs in the U.S. is through strategic hiring of new faculty members. This semester, we welcomed three outstanding new members to our physics faculty: Assistant Professor Barry Bradlyn, a condensed matter theorist from Princeton; Assistant Professor Patrick Draper, a high-energy theorist from University of Massachusetts Amherst; and Assistant Professor Lucas Wagner, a condensed matter theorist who had been a research professor in our department.

In Spring 2019, we will welcome Assistant Professor Sangjin Kim, an experimental biophysicist from Yale, and Associate Professor Joaquin Vieira, an astrophysicist and cosmologist from the U of I Department of Astronomy. In Summer 2019, we will welcome back Professor Ido Golding, an experimental biophysicist returning to us from Baylor. And in Fall 2019, we will welcome Fahad Mahmood, a condensed matter theorist from Johns Hopkins University, and Yonatan Kahn, a theoretical particle physicist coming to us from the University of Chicago. Paperwork is underway for two excellent nuclear theorists to join us in 2019, and we currently have three open faculty searches, in quantum information science, gravitational theory, and physics education research.

We have an aggressive hiring strategy in place for the upcoming years. We have requested four to five new hires per year for the next five years, in part to compensate for upcoming faculty retirements, and in part to support future growth of the department. We plan to increase our core tenure-track faculty positions to 65. This will make it possible to create a strong quantum information science group and to support planned new degree programs and future increases in student enrollment.

Thanks to our outgoing leadership.
At Illinois, we stand on the shoulders of giants whose work wrote science history and who created our unique collaborative and collegial way of doing physics here in Urbana. This valuable tradition was kept alive and well under the outstanding leadership of Dale Van Harlingen for the past 12 years! I know I can speak for the entire department when I thank Dale, who served as head from June 2006 to August 2018, and Mats Selen, who served as associate head for undergraduate programs from January 2014 through June 2018, for their superb leadership and commitment to this department. Many of the improvements we are seeing this semester are a result of their efforts, including the excellent new faculty hires, the newly opened drop-in Undergraduate Help Rooms, staffed by professors and TAs, the town hall meetings that continue as a forum for students and faculty to brainstorm new initiatives, and the energy-saving infrastructure projects that are nearing completion, including our new high-efficiency HVAC systems that will reduce heating and cooling costs for the department into the future. We are better and stronger for having had Dale and Mats in these important roles.

With warm regards,

Matthias Grosse Perdekamp

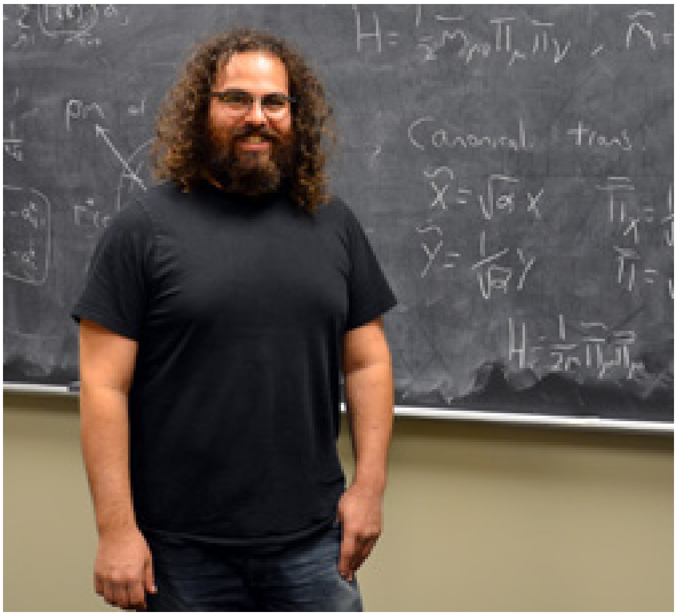
ILLINOIS PHYSICS
Spectrum

The Department of Physics at the University of Illinois at Urbana-Champaign is known for its collegial style of research—the "Urbana style"—that often involves collaborations across research areas and among theoretical and experimental physicists. Here is an inside glimpse of what some of our leading physicists are working on.

BARRY BRADLYN

THEORETICAL CONDENSED MATTER PHYSICS

Broadly speaking, my research interests lie in studying the interplay between geometry and topology in condensed matter systems. Geometry enters into condensed matter physics in the guise of order parameters for symmetry breaking, conserved quantities, crystal symmetry groups, and elasticity theory. Topology, on the other hand, enters when we try to describe properties of systems which are robust to perturbations, such as quantized response functions, surface states, and vortex-like excitations. Since the initial discovery of systems with topologically protected behavior, the influence of topology has spread across all areas of condensed matter physics. It is this—in addition to individual realizations of topological phases—that is in my opinion the biggest boon of this new paradigm. Topology now stands alongside abstract algebra (as it pertains, for instance, to symmetry groups) as one of our main tools for exploring quantum phenomena in solids and liquids.



Professor Barry Bradlyn poses in his office at the Institute for Condensed Matter Theory in Urbana. Photo by Siv Schwink for Illinois Physics Condensate

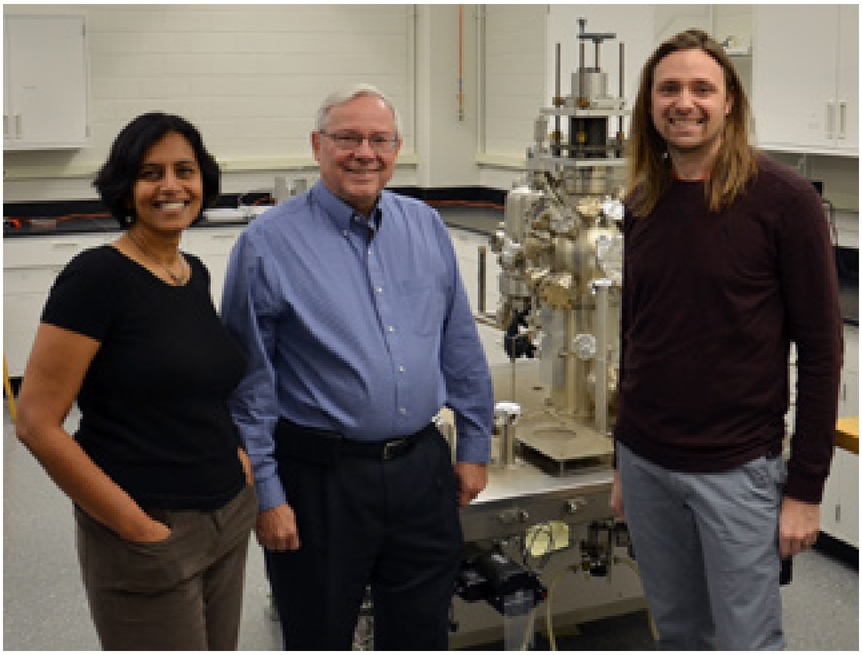
My current research focuses on using symmetries to learn about the topological properties of materials. As a theoretical physicist, one way that I do this is by asking about how different systems respond to geometric deformations like shears and strains. The electrons in topological materials behave like a fluid, and can be assigned properties like density and viscosity, which can be both constrained by symmetry and dependent on the topological phase of the system. A second focus of my research is in using the tools of crystal symmetry to design new topological materials. I am developing tools to better understand the role of chemical bonding in determining the topological properties of materials, and I apply these tools to discover new topological properties in previously synthesized materials.

THE ILLINOIS MATERIALS RESEARCH AND ENGINEERING CENTER'S NEW TOPOLOGY SEED:

TAYLOR HUGHES, VIDYA MADHAVAN, AND DALE VAN HARLINGEN

CONDENSED MATTER PHYSICS COLLABORATION

We are combining forces to bring complementary experimental and theoretical expertise to bear on a new topic in condensed matter physics. Our group collaboration was recently awarded seed funding through the I-MRSEC iSuperSEED program to study higher-order topological phases of matter.



(Left to right) Professors Vidya Madhavan, Dale Van Harlingen, and Taylor Hughes pose in the SEAMS lab in the Materials Research Laboratory. Photo by Siv Schwink for Illinois Physics Condensate

While the three of us have worked together in the past, we are now able to really unite our strengths of materials growth, quantum devices and measurement, and theoretical modeling to approach this nascent field of condensed matter physics. The work on this new topic is a natural outgrowth of our previous research efforts, in which the three of us have separately established strong track records in the study of topological matter. Dale has made breakthroughs in topological superconductivity, Vidya pioneered experimental efforts on topological crystalline insulators, and Taylor has made a number of important theoretical contributions, including the initial work that spawned the field that is now the focus of our joint work.

Our collaborative work begins with quantum materials growth that will take place in Vidya's lab. After joining the faculty at the U of I, she has quickly established a flourishing materials-growth capability in addition to her primary expertise in scanning tunneling microscopy (STM). Vidya and Taylor are working together to design the precise materials needed to create higher-order topological insulators, starting with films of bismuth and moving on to more exotic materials from there. Once the materials are grown, it is Taylor's and Dale's job to help design the devices and experiments needed to characterize these new phases of matter. Vidya is planning to carry out STM measurements, and Dale will build devices that interface these materials with superconductors, which will enable us to explore a wide-range of exciting quantum phenomena.

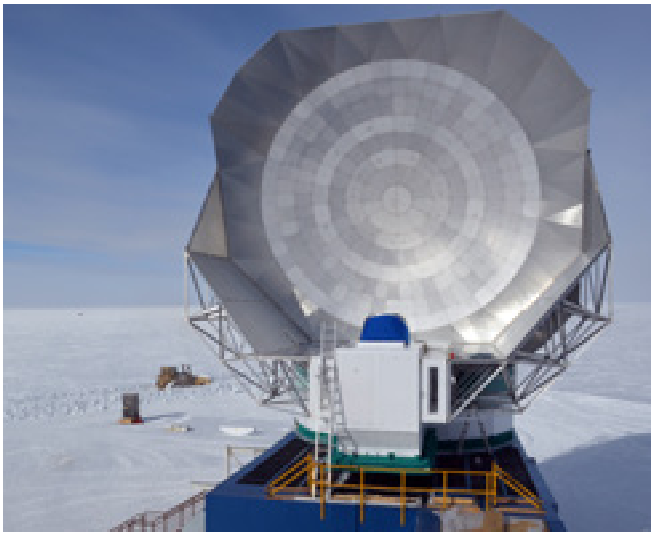
We are all excited to have the opportunity to work on such a well-defined, focused project together. Typically, awards for groups of faculty investigators would have a diverse set of projects, but in our case we have one goal, and if we are successful, there is a chance we could expand our effort into a broad range of interconnected scientific disciplines and departments. It's not often the case that you have the chance to explore a high-impact and possibly risky project with a strong coordinated effort, and we are eagerly anticipating our next few years of research.

GILBERT HOLDER

THEORETICAL ASTROPHYSICS AND COSMOLOGY

How did the universe begin? What is the universe made of? How did the rich structure we see around us arise? Long the domain of philosophers and theologians, these are now physics questions. I am always looking for new ways to find answers to these questions.

As we look out in the universe, we are looking back in time. This allows us to trace the evolution of galaxies and galaxy clusters, to see how the visible matter has evolved. We can use these measurements to learn about the expansion history of the universe, which appears to be entering a phase of accelerated expansion driven by a mysterious form of energy density that has been dubbed "dark energy." We can also use deflections of light by fluctuations in the gravitational potentials to trace the behavior of the total mass, which is found to be dominated by "dark matter," a form of matter which is well studied but still not detected in the lab. We map this dark matter on a wide variety of scales, ranging from the scale of the entire universe down to scales much smaller than individual galaxies, searching for clues about the nature of dark matter. Ideas that we are investigating include self-interacting dark matter, warm dark matter, and dark matter that is actually acting as a Bose-Einstein condensate on small scales.



The South Pole Telescope at the Amundsen-Scott South Pole Station, Antarctica, is 10 meters (394 inches) in diameter. Photo by Peter Rejcek, courtesy of National Science Foundation

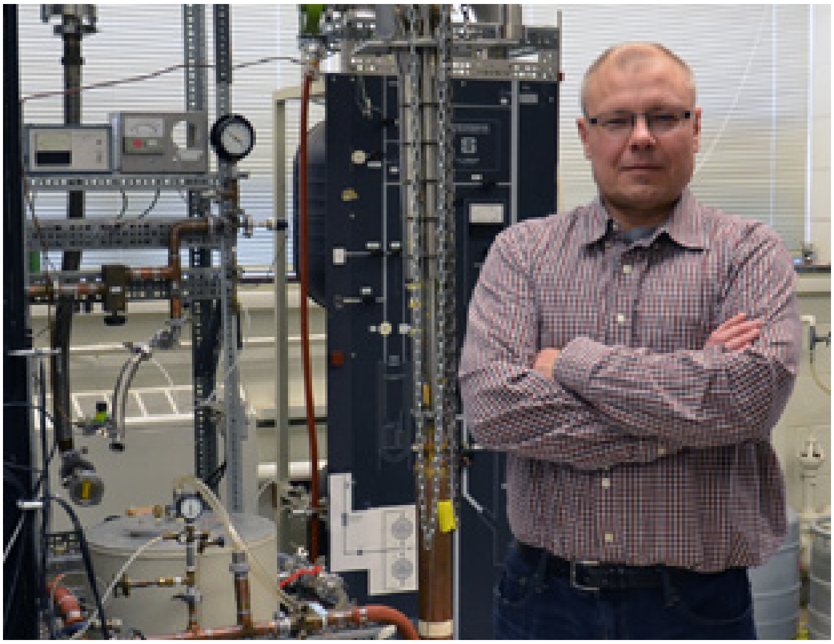
Going back further in time, the cosmic microwave background was formed when the universe was only one-thousandth its current size, the earliest moment from which we can measure electromagnetic radiation. I am currently a member of a team with a telescope at the geographic South Pole (the South Pole Telescope), which is currently making the most detailed maps of this background to date, and am looking forward to the next generation experiment, CMB-S4. These data provide a wealth of knowledge about our universe, with perhaps the most exciting possibility being to use the universe as a whole as a gravitational wave detector. Whatever happened at the beginning of time, it is likely to have roiled spacetime in a way that produces gravitational waves that have been propagating through the universe ever since. These waves will slightly distort the cosmic microwave background; measuring this effect would let us reconstruct the very first moments in time, when the universe as we know it began.

In the course of these measurements, there are always new discoveries, and it is important to be aware of possible serendipitous discoveries. For example, there has been recent evidence of a possible extra planet in the outer solar system, more than a hundred times farther from the Sun than the Earth, with a mass five to ten times the mass of the Earth. Such a planet would be easily discovered if it happened to be in the field of view of the South Pole Telescope, as would any other dwarf planets (like Pluto) that remain to be discovered. Other serendipitous sources include accreting black holes and gamma-ray bursts. While the motivation for our surveys are big questions about the structure and evolution of the universe, we may also be discovering new answers to the oldest question in astronomy, our solar system.

ALEXEY BEZRYADIN

EXPERIMENTAL CONDENSED MATTER PHYSICS

My fields of interest include condensed matter physics, nanotechnology, and quantum physics. In my lab, we fabricate and study nanometer-scale superconducting devices, such as memory elements made of superconducting nanowires, superconducting qubits and nanocapacitors. Arguably, the spectacular, very rapid evolution of the computer and information processing technologies is happening because of the critical contributions of researchers working in nanotechnology and quantum physics. Quantum mechanics (QM), originating from Planck's discovery of the energy quantization followed by Heisenberg's discovery of an exact mathematical description of quantum phenomena, was originally invented to describe very small (elementary) particles, such as electrons and protons. After a hundred years of evolution, QM can now describe macroscopic systems. The idea of macroscopic quantum mechanics, originally proposed by our colleague A. Leggett, has been realized in the form of qubits, or quantum bits. These devices mimic electrons and atoms in the sense that they can be prepared in quantum superpositions of macroscopically distinct states, and their evolution is governed by Schrödinger's equation rather than by the Newtonian equations that usually apply to macroscopic systems.



Professor Alexey Bezryadin poses in his lab at the Loomis Laboratory of Physics in Urbana. Photo by Siv Schwink for Illinois Physics Condensate

My group aims to develop new qubits having longer coherence times—a necessity for the creation of practical quantum computers. We have collaborated with J. Eckstein's group and developed and tested transmon qubits with impressive characteristics, namely a very long relaxation time of about 50 microseconds. Yet this is still not enough to realize practical quantum computers. For that reason, we are focusing now on developing topological qubits—hybrid devices combining topological insulators and superconductors. Topological qubits are predicted to harbor so-called non-Abelian particles, namely Majorana particles. These particles are peculiar in the sense that they remember their mutual history of mutual exchange operations, where "exchange" means an exchange or swapping of the positions of two particles. Thus, quantum information can be encoded, at least in theory, in an ensemble of non-Abelian particles by performing braiding operations, or more simply put, by moving the particles around one another. Each such motion changes the ground state of the system into a new independent ground state. Unfortunately, non-Abelian systems have never been observed. If realized in the laboratory, they would give rise to topologically protected qubits, which would hold their quantum coherence for a long time. As of today, utilization of Majorana zero modes represent one of the main routes for the realization of quantum computers. ■

LHC's latest heavy-ion run recreates conditions of early universe in quark-gluon plasma

University of Illinois Professor Anne Sickles leads ATLAS's Heavy Ion Working Group

SIV SCHWINK
for Illinois Physics Condensate

For a few millionths of a second shortly after the big bang, the universe was filled with an extremely hot, dense soup of elementary particles moving at near the speed of light. The quark-gluon plasma (QGP), so called because it was predominantly made up of quarks and gluons, can be recreated and studied only in particle accelerators, in the high-energy collisions of heavy ions such as gold or lead.

In early November, the Large Hadron Collider (LHC) at CERN in Switzerland began its first lead-lead run since 2015, the final run of this season before a long shutdown for upgrades to the accelerator. Beams of lead nuclei (having been stripped of their electrons) were collided head-on at an energy of 5.02 TeV during a run of three-and-a-half weeks.

Lead nuclei comprise 208 protons and neutrons, which in turn are made up mostly of quarks and gluons. When the 416 protons and neutrons of two lead nuclei are smashed together, they form a tiny fireball that "melts" everything into a very fleeting QGP, which scientists have learned is a nearly perfect fluid having small viscosity. But the fireball cools very quickly, and the quarks and gluons recombine into ordinary matter, which speeds away in all directions. This collision debris contains particles such as pions and kaons, which are made of a quark and an antiquark; protons and neutrons, made of three quarks; and even copious antiprotons and antineutrons, which may combine to form the nuclei of antiatoms as heavy as helium.

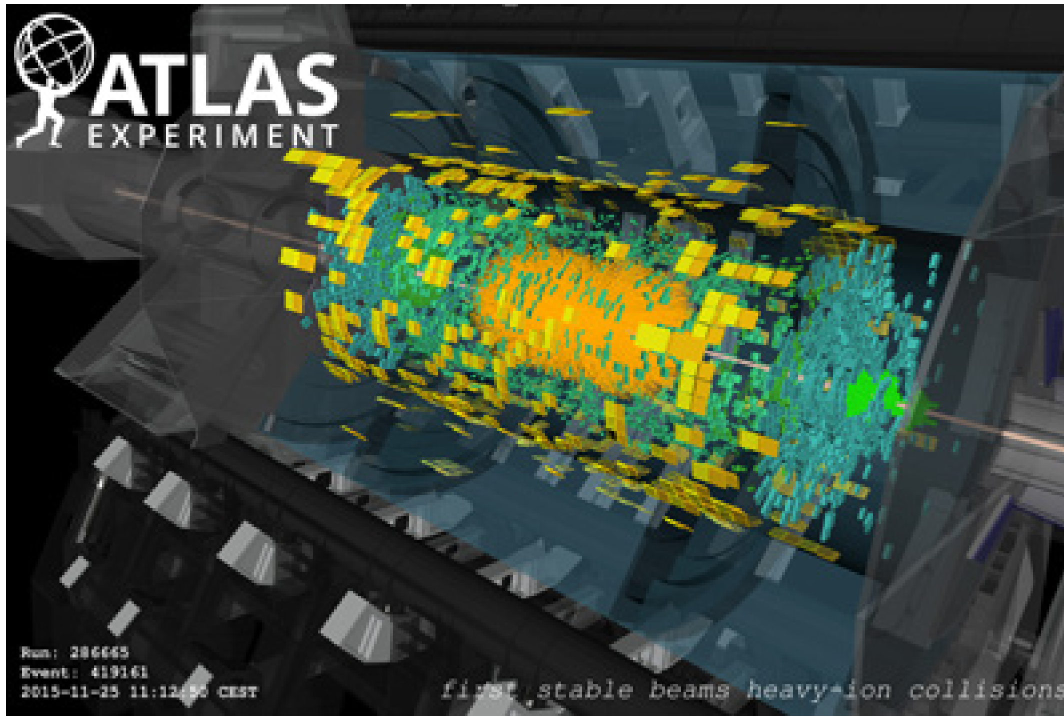
Scientists on the four experiments at the LHC—ALICE, ATLAS, CMS and LHCb—study the QGP to shed light on some of the most fundamental unanswered questions about matter. Each experiment uses its own detectors to trace, plot out, and selectively record the immediate aftermath of the collisions, looking at the QGP and the subsequent decay paths of the subatomic particles. Only a small fraction of these collision events can be recorded, however, and deciding what to record and what to throw out has everything to do with what specific questions the researchers are trying to answer.

The ATLAS group is collecting data at a rate of 4.5 GB per second while the accelerator is actively running, which it does for about 50 percent of the total scheduled runtime. Professor Anne Sickles of the University of Illinois at Urbana-Champaign is a co-convener of the ATLAS experiment's Heavy Ion Working Group, alongside Professor Martin Spousta of the Charles University in Prague. As such, Sickles and Spousta manage the ATLAS experiment's heavy-ion analytical strategy, which in turn informs its "trigger strategy"—what collision data are automatically preserved for analysis.

"Most of what the LHC delivers are proton-proton collisions," Sickles points out. "We are the only working group in the ATLAS experiment that has a distinct data set. That puts us in the unique position of deciding what kind of triggers we take. The working group has grown and matured since the last heavy-ion run three years ago, and we're asking more complicated questions now that build on what we learned then. Martin and I coordinated among the 60 members of our working group—scientists from institutions around the globe—to devise a trigger strategy to maximize our physics opportunities within this short run. The trigger plans balance our physics goals and take full advantage of the tremendous capabilities of ATLAS for selecting and recording data."

During the heavy ion run, two students and a postdoc from Sickles' group, as well as Sickles herself, were at CERN, validating the data as they were being recorded. Sickles' research group in Illinois is particularly interested in jets—sprays of elementary particles having tremendous momentum. Jets occur when one quark or gluon within a nucleus collides head-on with another quark or gluon within the other nucleus.

Sickles' group is especially interested in what happens to the QGP when lighter quarks in the jets scatter through it.



An ATLAS event display of a heavy-ion collision recorded on November 25, 2018, shows three jets, one having high transverse momentum and on the opposite side of the detector two having lower transverse momentum. The display was created by University of Illinois graduate student Mike Phipps, a member of Sickles' research team. Image courtesy of ATLAS, CERN

"There are six different kinds of quarks," explains Sickles. "Light quarks—the up, down, and strange quarks—are most abundant, and we have good data on these, but there are still unresolved questions. For example, if we turn up the momentum of these light quarks, make them go faster and faster through the QGP, one might imagine their eventually moving so fast they don't even notice they are going through the QGP. But we haven't seen that—as fast as they are going, we still see big effects, and that's puzzling."

Scientists in the ATLAS Heavy Ion Working Group are also interested in looking at more massive quarks and what happens when they move very quickly through the QGP.

"Charmed quarks are heavier and less abundantly produced," she continues. "They are challenging to study for that reason and because it's hard to trigger on them. We've devised a trigger strategy that simply involves keeping a whole lot more events, and we will filter out the charmed quarks later."

The ATLAS working group is also interested in properties exhibited when the heavy ions fail to collide, passing by one another in a near miss.

"As a program, we are also very interested in what happens when the nuclei don't quite hit each other," Sickles comments. "If you think about these nuclei, lead is big—it's at the bottom of the periodic table. We've stripped away all of the electrons, so each nucleus has a positive 82 charge—in other words, there are 82 protons in each lead nucleus. The nuclei each have huge electromagnetic fields and when they pass closely by each other, they create interesting interactions that couldn't happen anywhere else."

One surprising example of this is the scattering of two photons into two photons, a finding the ATLAS group published in August 2017 in the journal Nature Physics.

Sickles explains, "We don't think of photons as something that would interact with themselves, but we found they can. In a near miss event, the lead nuclei pass by each other and shed photons—because electromagnetic interactions happen via the exchange of photons. And every now and then, two photons collide and scatter. Our result was the first direct evidence of the scattering of two photons. We observed about 10 events using the previous data. With these new data we are interested in following up on this and improving the precision of the previous measurement."

"What's also interesting, though a little further afield," Sickles adds, "this could be a way to look for physics beyond the standard model. In the heavy-ion program, our headlining program is making the QGP and studying its properties. However, there's been interest from many people in this idea, both within the Heavy Ion Working Group and outside of it. Photons colliding and scattering: maybe they could create dark matter, maybe they create something else. We don't know. It's possible, if we had more data, we could find something more exotic. I don't have high expectations in terms of this run, but with future increases in luminosity, I expect our program will expand its efforts along these lines in the search for new physics." ■

University of Illinois team finds Wigner crystal—not Mott insulator—in 'magic-angle' graphene

SIV SCHWINK
for Illinois Physics Condensate

Recently, a team of scientists led by Pablo Jarillo-Herrero at the Massachusetts Institute of Technology (MIT) created a huge stir in the field of condensed matter physics when they showed that two sheets of graphene twisted at specific angles—dubbed "magic-angle" graphene—display two emergent phases of matter not observed in single sheets of graphene. Graphene is a honeycomb lattice of carbon atoms—it's essentially a one-atom-thick layer of graphite, the dark, flaky material in pencils.

In two articles published online in March 2018 and appearing in the April 5, 2018 issue of the journal Nature, the team reported the twisted bilayer graphene (tBLG) exhibits an unconventional superconducting phase, akin to what is seen in high-temperature superconducting cuprates. This phase is obtained by doping (injecting electrons into) an insulating state, which the MIT group interpreted as an example of Mott insulation. A joint team of scientists at UCSB and Columbia University has reproduced the remarkable MIT results. The discovery holds promise for the eventual development of room-temperature superconductors and a host of other equally groundbreaking applications.

Researchers at the University of Illinois at Urbana-Champaign have recently shown that the insulating behavior reported by the MIT team has been misattributed. Professor Philip Phillips, a noted expert in the physics of Mott insulators, says a careful review of the

Above: Professor Philip Phillips (right) and graduate student Bikash Padhi pose in the Institute for Condensed Matter Theory on the Urbana campus. Photo by Siv Schwink for Illinois Physics Condensate

Opposite page: Proposed Wigner crystals for magic-angle bilayer graphene. In the leftmost figure, the criterion for observing this lattice structure is not satisfied experimentally, resulting in metallic transport when a single electron occupies a moiré cell. The remaining two figures show the insulating state, explaining the experimental observation when 2 or 3 electrons are in a moiré cell. Image courtesy of Philip Phillips, University of Illinois at Ubana-Champaign

MIT experimental data by his team revealed that the insulating behavior of the "magic-angle" graphene is not Mott insulation, but something even more profound—a Wigner crystal.

"People have been looking for clear examples of Wigner crystals since Wigner first predicted them in the 1930s," Phillips asserts. "I think this is even more exciting than if it were a Mott insulator."

Lead author of the U of I study, graduate student Bikash Padhi, explains, "When one sheet of graphene is twisted on top of another, moiré patterns emerge as a result of the offset in the honeycomb structure. By artificially injecting electrons into these sheets, the MIT group obtained novel phases of matter which can be understood by studying these extra electrons on the bed of this moiré pattern. By increasing the electron density, the MIT group observed an insulating state when two and three electrons reside in a moiré unit cell. They argued this behavior is an example of Mott physics."

Why can't it be Mott physics?

Phillips explains, "Mott insulators are a class of materials that should be conductive if electronic interactions are not taken into account, but once that's taken into account, are insulating instead. There are two primary reasons why we suspect the tBLG does not form a Mott insulator—the observed metal-insulator transition offers only one characteristic energy scale, whereas conventional Mott insulators are described by two scales. Next, in the MIT report, in contrast to what one expects for a Mott system, there was no insulator when there was only one electron per unit cell. This is fundamentally inconsistent with Mottness."

The figure at the bottom of the page displays the crystalline states that explain these data.

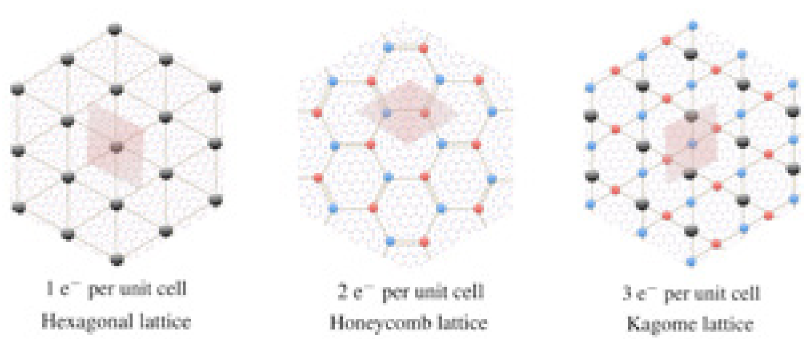
Zorbing, rolling and bouncing in an inflated transparent ball, has become popular around the world. Bikash Padhi, a University of Illinois at Urbana-Champaign graduate student in theoretical condensed matter physics, compares Wigner crystallization to swelling zorbs in a closed field, where the zorb passengers are electrons and the zorb itself is a measure of each electron's repulsion to other electrons. Credit: Username:Rodw/Wikimedia Commons/Public Domain

What is a Wigner crystal?

To understand Wigner crystals, Padhi offers this analogy: "Imagine a group of people each inside a large orb and running around in a closed room. If this orb is small they can move freely but as it grows bigger one may collide more frequently than before and eventually there might be a point when all of them are stuck at their positions since any small movement will be immediately prevented by the next person. This is basically what a crystal is. The people here are electrons, and the orb is a measure of their repulsion."

Phillips credits Padhi with providing the impetus for the study. Chandan Setty, who was until recently a postdoctoral researcher working in Phillips' group at the Institute for Condensed Matter Theory in Urbana, also made significant contributions to the study, according to Phillips.

These results were pre-published online in the journal Nano Letters in the article, "Doped Twisted Bilayer Graphene near Magic Angles: Proximity to Wigner Crystallization not Mott Insulation," on September 5, 2018, with the final official publication to be included in the journal's October 2018 issue.



This research was funded by the Center for Emergent Superconductivity, a Department of Energy–funded Energy Frontier Research Center, and by the National Science Foundation. The conclusions presented are those of the researchers and not necessarily those of the funding agencies.

Physics graduate student Jason Merritt works on his automated bacterial population sampling device in the Kuehn Lab at the Loomis Laboratory of Physics in Urbana. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

High precision microbial population dynamics under cycles of feast and famine

Automated sampling and measuring provides around-the-clock data collection

SIV SCHWINK
for Illinois Physics Condensate

Scientists at the University of Illinois at Urbana-Champaign have produced the most precise picture to date of population dynamics in fluctuating feast-or-famine conditions. Professor Seppe Kuehn, a biological physicist, and his graduate student Jason Merritt found that bacterial population density is a function of both the frequency and the amplitude of nutrient fluctuations. They found that the more frequent the feast cycles and the longer a feast cycle, the more rapid the population recovery from a famine state. This result has important implications for understanding how microbial populations cope with the constant nutrient fluctuations they experience in nature.

The team's findings were made possible by extraordinarily precise measurements of population dynamics in bacterial communities. The measurement, based on automated imaging of hundreds of millions of single cells, allowed the team to capture population dynamics over periods of more than a week with a temporal resolution of one minute. Those numbers and the extended duration of the experiment couldn't have happened without Merritt's continuous-culture systems, coupled to automated-sampling fluorescence microscopes.

These findings were published in the August 28 issue of Physical Review Letters.

The experimental setup took about two years and many prototypes to develop. Merritt built six identical systems for the experiment, each one automated to continuously pump in fresh media and pump out bacterial cultures for sampling. The samples were continuously imaged to track changes in population density and structure. Software developed by Merritt automatically segments images to count bacterial cells, producing massive data sets. The software takes advantage of machine learning to resolve otherwise difficult-to-solve problems in image recognition and processing.

Kuehn comments, "Scientists studying populations of bacteria typically take samples manually and do their counting offline, in person. What Jason's systems do is automatically remove a sample, pass it in front of a microscope to be imaged, and then put it back. And they do that once a minute, 24 hours a day, with no input, for up to a month. His software counts the cells in the images, extracting information in real time."

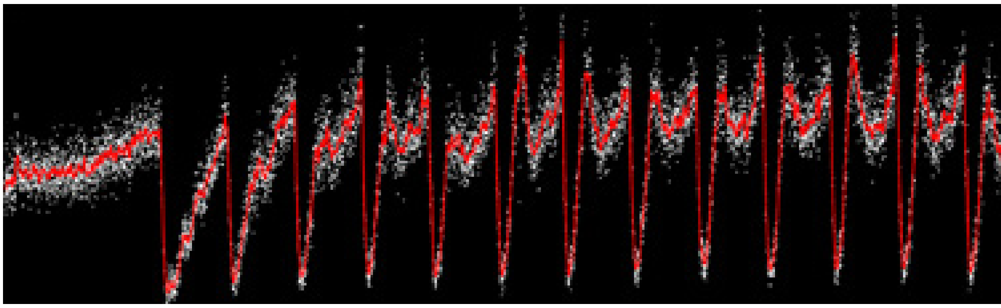
He continues, "So that's a big step forward—this has never been achieved before. Short-timescale quantitative studies have been done using microfluidic devices, but these are limited to about three days' runtime. We can run for 30 days, producing long-timescale highly quantitative measurements. We can easily run duplicate experiments, reproducing the same results. Because of this, we were able to use the system to test hypotheses about the underlying mechanisms governing the dynamics we observed."

Merritt comments, "The idea for the system grew out of previous work Seppe had done. The device I built is basically a metal block with glass vials within it. The most important part of our system and the part that was the most difficult to get to work reliably is the coupling to a fluorescence microscope."

The system continuously draws samples out of the liquid culture into flexible tubing and then into a thin glass capillary in the path of the microscope. The bacteria pass through the capillary many at a time, but are spaced apart from one another. The biggest challenge overall was on the software side, doing proper image segmentation to convert the images to data.

Above: Professor Seppe Kuehn (left) and graduate student Jason Merritt confer in the Loomis Laboratory of Physics in Urbana. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

Below: A graph illustrating population density as a function of the frequency and amplitude of available nutrients. Courtesy of Kuehn Lab, University of Illinois at Urbana-Champaign



The main finding, that populations apparently recovery faster from more frequent or larger pulses of nutrients, puzzled the team at first. However, the precision of the measurement allowed them to uncover the mechanism.

Merritt continues, "What we found out is that the fast recovery rates for the planktonic population are driven by dispersal from aggregated cells (biofilms) during feast conditions. So basically when there's a lot of food, these cell aggregates start shedding cells rapidly, and the cells that shed off start growing rapidly. But during famine conditions when there's not very much food, these cells start coming back together and forming the aggregates again. This is the mechanism driving the frequency and amplitude dependence."

Kuehn adds, "Variations in a natural population may be the result of any one or a combination of many different variables—the amount of nutrients, temperature, competition and predation, etc.—so it's difficult to measure cause and effect. In the lab, we tightly control all of the parameters of our experiment. And now we can make a really robust and reproducible quantitative measurement. Going forward, we would like to modify these systems to study topics in evolutionary history. We also plan to do studies in which we use feedback control of microbial communities, to see whether we can push the communities back into a particular state. These are studies that wouldn't be possible without an automated system like the one we used in this study." ■

This work was funded in part by the National Science Foundation Physics Frontiers Center Program. The findings are the authors' and not necessarily those of the funding agency.

Hong-Yan Shih wins 2019 APS GSNP Dissertation Award

SIV SCHWINK
for Illinois Physics Condensate

Dr. Hong-Yan Shih, a postdoctoral researcher at the Department of Physics and at the Carl R. Woese Institute for Genomic Biology at the University of Illinois at Urbana-Champaign, has been selected for the 2019 Dissertation Award in Statistical and Nonlinear Physics of the American Physical Society (APS). This award recognizes exceptional young scientists who have performed original doctoral thesis work of outstanding scientific quality in the area of statistical and nonlinear physics. Shih will be presented with the award at the APS March Meeting, where she will give an invited talk.

Shih completed her doctoral dissertation titled "Spatial-temporal patterns in evolutionary ecology and fluid turbulence" in 2017 working in Professor Nigel Goldenfeld's theoretical physics group. It explores "the turbulence of ecosystems and the ecology of turbulence." In her thesis, Shih reports on three projects at the boundaries of ecology and evolution, analyzed using methods from statistical mechanics, and a fourth project that made a major advance to the important problem of the laminar-turbulent transition of fluids in pipes. This latter problem was first scientifically studied in 1883, and Shih's contribution arose from an unusual perspective.

Shih comments, "Perhaps this sounds a bit eccentric, but ecosystems and turbulent fluids are both highly non-equilibrium, and both exhibit spatiotemporal complexity during the course of their evolution. It might seem that they are too complicated for us to extract universal properties—if there even are any. But surprisingly, it turns out that each system can shed light on the other, enabling both to be solved."

Goldenfeld remarks, "Hong-Yan's results—the theory for the universality class of the laminar-turbulence transition in pipe flow, a theory for the collective dynamics of bacteria/phage horizontal gene transfer, and the stochastic theory for rapid evolutionary dynamics—show what can be accomplished if one is prepared not to follow the crowd, but to take risks and strive for something original, unconventional, and potentially important."

The first part of Shih's dissertation investigates the interplay between evolutionary dynamics and ecological structure in three different biological situations.

"First I looked at anomalous dynamics in rapid evolution, where I explained how the trade-off between selection from reproduction on the one hand and predation on the other is exhibited in the patterns of eco-evolutionary dynamics, such as the abnormal phase relationship," Shih describes.

These results were published in 2014 in *Physical Review E* (Rapid Communications).

In a second example, Shih worked out how phenotypic fluctuations evolve in directed evolution, in collaboration with Professor Seppe Kuehn's research group.

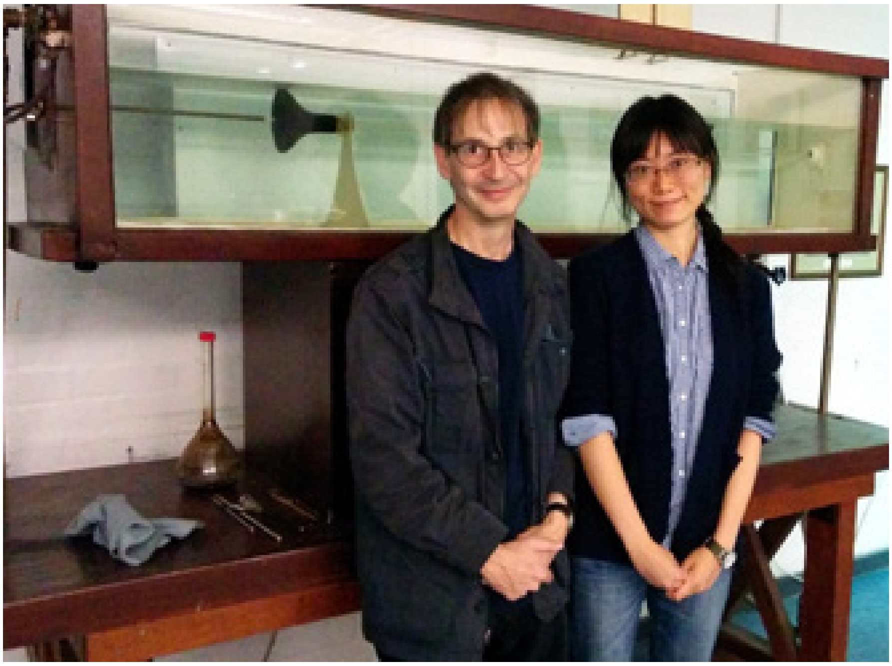
"We worked with Seppe and his students David Fraebel and Harry Mickalide on their bacterial chemotaxis experiments," she notes, "and we came up with a model that can explain how the evolutionary trajectory of a phenotype would be shaped by the repeated selection."

This collaborative work was recently published in *Physical Biology*.

In her dissertation, Shih provides a third example of evolutionary dynamics and ecological structure: the collective coevolution between viruses and marine bacteria being mediated by horizontal gene transfer.

"We made a detailed analysis of simulations in a series of models," she continues, "and we discovered that horizontal gene transfer between bacteria and viruses drives the coevolution of their ecosystem. In other words, collective mutualism can emerge during evolution, even though it's mediated through the bacteria and viruses' antagonistic predator-prey interaction."

The second part of Shih's dissertation elucidates the transition to turbulence in fluid dynamics, a problem that had remained unsolved for over 130 years. It turns out, according to Shih, that "the scaling form of turbulent



Nigel Goldenfeld and Hong-Yan Shih pose in front of the apparatus used by Osborne Reynolds in 1883 to conduct the first scientific studies of the laminar-turbulent transition in pipe flow. Reynolds' apparatus is on display at The University of Manchester, School of Mechanical, Aerospace and Civil Engineering, UK. Photo submitted

lifetime near transition is governed by the universal distribution of critical fluctuations, which is also exhibited in other physical systems."

This ground-breaking research was published in 2016 in *Nature Physics*, with additional results in 2017 in the *Journal of Statistical Physics*.

Shih recalls, "The development of the turbulence project during my Ph.D. turned out to be a serendipity. When I first worked on this project with Nigel, we did not realize how exactly pipe flow turbulence is connected to the predator-prey ecosystem. Then I worked on my first ecology project on population dynamics in rapid evolution. After that I returned my focus to the turbulence project, and we discovered the connection between pipe flow turbulence and the predator-prey dynamics."

"It was our experience in the ecology projects that helped us to work out the modeling and to map out the phase diagram of transitional turbulence in the pipe flow," she continues. "So this is an interesting and quite inspiring example! Usually we think of physicists applying the tools of physics to solve biological problems, but in this case it was our knowledge and experiences in biology that helped us to solve the physics problem."

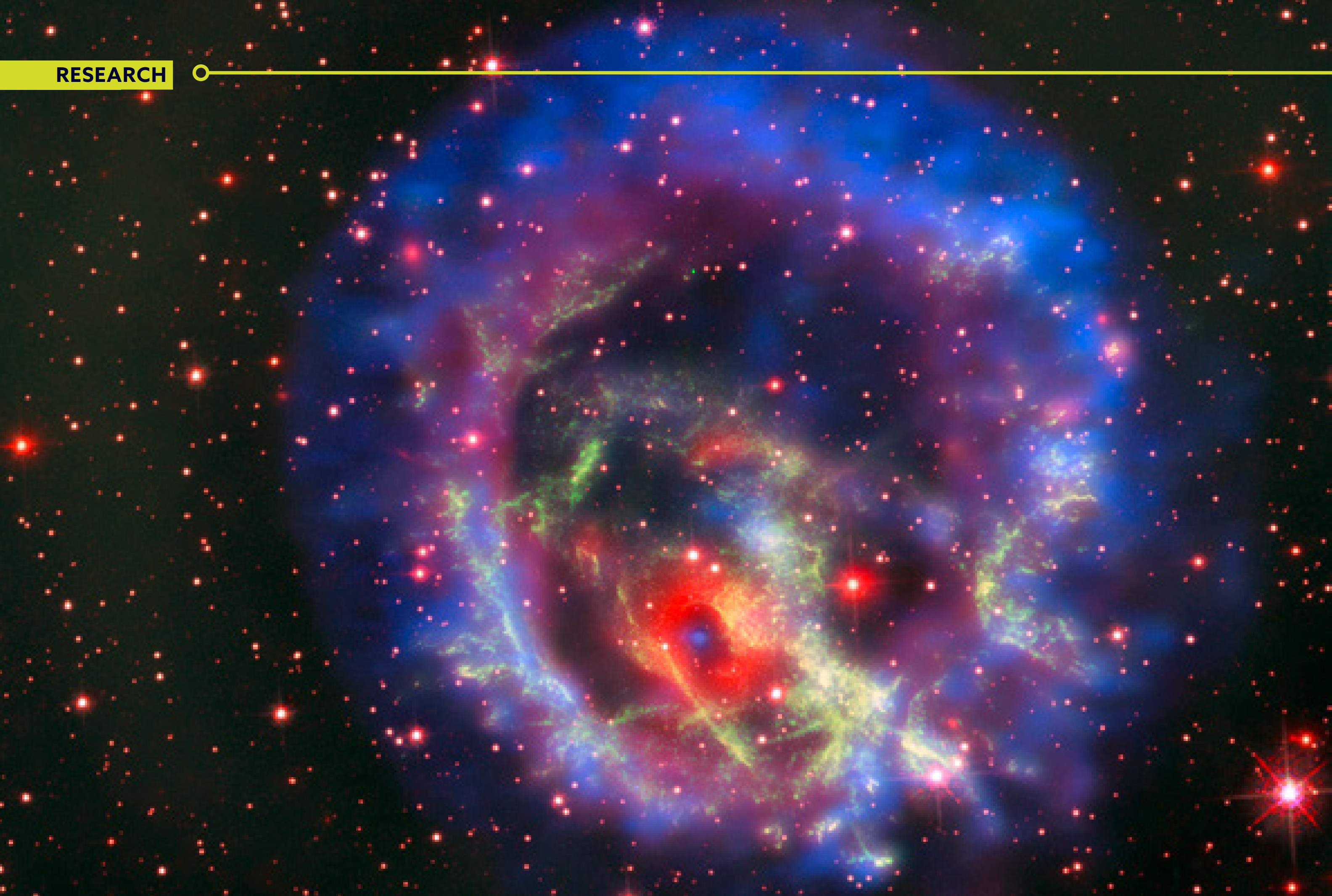
Goldenfeld adds, "It was incredibly exciting to collaborate on the turbulence and biological projects in Hong-Yan's thesis and to discover the surprising connection between them. Hong-Yan's thesis was an ideal choice for the APS dissertation award in statistical and non-linear physics because it brings so many elements from different areas of science together, exemplifying the power and broad applicability of statistical mechanics."

Now a postdoc in Goldenfeld's group, Shih is expanding on her dissertation research and taking it in new directions. In line with her application of nonequilibrium statistical mechanics to biology, Shih is currently attempting to unify population dynamics with stochastic thermodynamics in microbial ecosystems. And, in her fluid turbulence research, she is collaborating with experimentalists and performing theoretical calculations to elucidate how the directed percolation universality class emerges near the transition to turbulence, in explanation of new experimental results.

Before coming to the University of Illinois, Shih received her bachelor's (2008) and master's (2010) degrees in physics from the National Tsing Hua University in Taiwan. In her master's research, Shih applied the renormalization group method to analyze the relevant couplings in strongly correlated electronic systems. She credits her master's advisor, Professor Hsiu-Hau Lin, with sparking her interest in applications of physics to biology and complex systems. ■

Shih's doctoral research was partially supported by the National Science Foundation NSF-DMR-1044901, NASA Astrobiology Institute award NNA13AA91A, the L. S. Edelheit Family Fellowship in Biological Physics (2016), and the Government Scholarship for Study Abroad (2015–2016), Taiwan.

RESEARCH



Neutron stars may hold an answer to neutron puzzle on Earth

CELIA ELLIOTT
for Illinois Physics Condensate

According to University of Illinois physicist Douglas H. Beck, "Neutrons play some unusual roles in our world. Free neutrons decay in about 900 s but, bound in nuclei, they are stable and make up somewhat more than half the mass of the visible universe."

In nuclei, the strong force provides the binding that overcomes the weak-interaction-decay of the free neutron, forming nuclei that have of order 10^2 neutrons. Neutron stars, containing some 10^{57} neutrons, form when the gravitational collapse of a supernova is stopped by the strong interaction. In this situation, the strong interaction is repulsive and balances the extreme gravitational forces associated with having a solar mass compressed into a city-sized object.

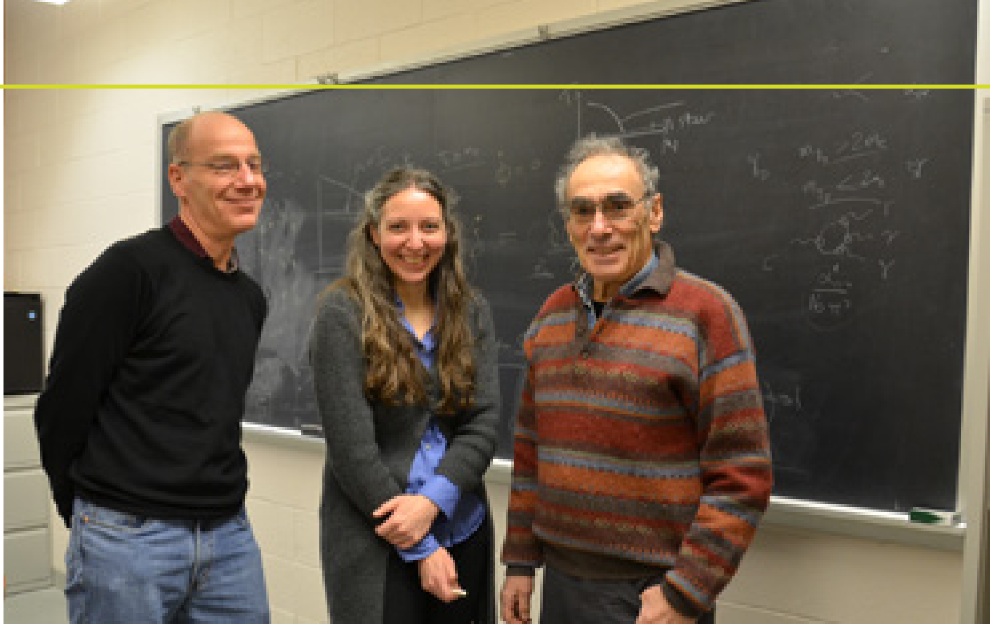
But exactly how long do free neutrons live? According to Beck, this question has been remarkably elusive to answer. "In fact, at the moment we seem to have two different answers," says Beck.

Scientists use two different experimental methods to determine the value of τ, the neutron lifetime.

Above: A special kind of neutron star, spotted for the first time in May 2018 outside of the Milky Way galaxy, is pictured with an X-ray image superimposed on an optical image. X-ray courtesy of NASA/CXC/ESO/F.Vogt et al; Optical courtesy of ESO/VLT/MUSE & NASA/STScI

Opposite page: (L-R) Professors Doug Beck, Jessie Shelton, and Gordon Baym in Shelton's office at the Loomis Laboratory of Physics in Urbana. Photo by Siv Schwink for Illinois Physics Condensate

Experiments that measure the products of neutron decay—protons, electrons, and neutrinos—tend to predict a longer lifetime than do experiments where the number of neutrons at a specific starting time and ending time are simply compared. In fact, despite intense effort on both fronts in recent years, the value of τ determined in the two types of experiments differs by about 8 s, with uncertainties of about 2 s. As experiments have gotten more and more precise, the discrepancy could indicate new physics, not just experimental error. Physicists care, because they must know the precise neutron lifetime to test various cosmological models of the universe's evolution.



In January, theorists Bartosz Fornal and Ben Grinstein at UC San Diego posited that the difference could be explained by an "invisible" decay missed by the decay-product experiments; namely, that some 1 percent of the time, neutrons decay to dark matter particles that go undetected. Remarkably, the stability of ordinary nuclei does not completely rule out such a possibility.

This idea of a new decay process is appealing to physicists, because it could account for the dark matter present in the universe. While the existence of dark matter, having gravitational but not ordinary electromagnetic, strong or weak interactions, is beyond dispute, its origin and composition is unknown. That dark matter could be "hiding in plain sight" in terrestrial neutron decay experiments sparked intense interest by physicists and a number of stories in the popular press earlier this year.

However, as shown in a paper by Gordon Baym, Doug Beck, Peter Geltenbort (ILL, France) and Jessie Shelton, published in the August 6, 2018, issue of *Physical Review Letters*, the physical properties of observed neutron stars effectively rule out the possible decay of neutrons to dark matter particles.[*]

The physics argument has two pieces. Neutrons have a spin of ½ ħ, i.e., they are fermions, and to conserve angular momentum, at least one of the possible decay products would also have to be a fermion. Even though the decay of neutrons to dark-matter particles would be relatively rare in the Fornal–Grinstein picture, over the life of a neutron star, the neutrons and dark fermions would come to equilibrium, leaving two fermion species in place of the one that was originally there. The so-called degeneracy pressure that prevents two fermions from being in the same place at the same time would thus be reduced.

Furthermore, the interactions between dark particles themselves are expected to be very weak. The strong repulsion of neutrons required to withstand the intense gravitational pressure inherent in neutron stars would therefore also be substantially reduced. The authors conclude that the maximum mass of a hybrid neutron–dark-matter star would be only about 0.7 times the mass of the sun, contradicting the observations of numerous neutron stars having masses up to about 2 solar masses.

Jessie Shelton points out, however, that if the dark fermions were to have some sort of exotic self- interactions, it would be possible to have both neutron decays and neutron stars of the observed 2 solar masses, because these interactions would provide the missing component of pressure to hold up the neutron star.

"If we did discover exotic neutron decays, then we would in the same stroke also learn something amazing about the dark side of our universe—the survival of massive neutron stars would then immediately tell us that there isn't just one dark matter particle, but a whole set of dark particles with their own dark forces!" explains Shelton. ■

[*] The development of this idea was not unique. A Physical Review Letters companion paper by David McKee (Pitt), Anne Nelson (UWash), Sanjay Reddy (UWash) and Dake Zhou (UWash), together with one by Theo Motta (Adelaide), Pierre Guichon (CEA, France) and Tony Thomas (Adelaide) published separately—both describing the same physics ideas—appeared on the arXiv within a few days of one another.

This research was funded by the National Science Foundation and by the U.S. Department of Energy. The conclusions presented are those of the researchers and not necessarily those of the funding agencies.

An interview with PER grad student and community builder Brianne Gutmann

Brianne Gutmann, a physics education research graduate student at Illinois Physics, is a staunch supporter of inclusion of all genders, ethnicities, and cultures in STEM enterprises. Through her active involvement in student clubs and her willingness to take a leadership role, she has contributed to the department's climate of openness and support.

Gutmann grew up in Cary, IL, a northwest suburb of Chicago. She received her bachelor's degree in physics from Carleton College in Northfield, MN. Her graduate advisor is Professor Tim Stelzer. She has also worked closely with Professor Emeritus Gary Gladding. Gutmann plans to graduate with her doctoral degree in physics in Summer 2019.

What is the greatest joy of being a physics education research (PER) grad student?

The biggest joy for me is interacting with students and feeling that what I'm doing impacts how they see physics and how they see themselves as physicists. I end up teaching about a hundred students each fall. I love walking around campus or through Loomis and seeing familiar faces and catching up with how they're doing.

There's also a lot of gratification in developing something for students and watching them interact with it. On the flip side, when things don't go well, I also get to listen to them complain about it! (Ha ha!)

And the greatest challenge?

As far as research, one challenge is that most of my data collection comes on a rigid schedule. If I'm running an experiment in a course, I have to wait a full year for the course to run again to collect a new set of data.

The PER group at Illinois is renowned for its evidence-based pedagogies and innovative teaching tools and technologies. How did working in a well-established PER group benefit you?

The University of Illinois has been a great place to do PER, and I've learned a lot of quantitative analysis skills. We're in a good place to do data with big numbers because we have so many

Above: Illinois GPS (Guidance for Physics Students) organizers pose in front of their poster at the 2018 The Access Network assembly. Pictured left to right are Luis Miguel de Jesús Astacio, Karmela Padavić, Gloria Lee, Brianne Gutmann, and Damerrick Perry. Opposite page, from the top: (1) GPS organizers (L-R) Gloria Lee, Brianne Gutmann, and Jacob Rangel (an undergraduate student in the PER research group and Gutmann's mentee through GPS) at a 2017 Access event. (2) The Physics GEO Tutor-In. Standing to the right of Gutmann are Professors Lance Cooper and Nigel Goldenfeld who participated in the event. (3) Physics GEO (Graduate Employees Organization) members take a meal together.
Photos courtesy of Brianne Gutmann

students. And most of our activities are online, so we get a lot of information about how students use the homework and quizzes.

My favorite part of working in our group is the chance to work collaboratively with other graduate students. I've worked with older students on projects and then been able to be the older graduate student on a project with younger group members. I really value all members of our group and have learned a lot from them, not just about science, but about everything. Sharing a space for so many years creates a sense of comaraderie, and I love being part of that.

What is the focus of your doctoral dissertation?

My dissertation work focuses on creating tools for underprepared engineering students enrolled in *Physics 100 Thinking about Physics*. More specifically, I've been creating and improving the mastery-style online homework. Our delivery method asks students to retry different similar problems until they have mastery of the material, before moving on to the next material. This is important because some first-year engineering students haven't taken physics at all, or some have taken it but their class wasn't conceptually based or just wasn't as good. This course is meant to get students prepared to do well in *Physics 211 Mechanics*, regardless of how prepared they were at the start of the term.

I love working with the first-term freshmen in this course. It's a time of big transitions, and I love being able to reassure folks and act as a resource in whatever way I can.

We use data to iteratively improve the homework to better suit the strengths and weaknesses of the students. Similarly, we implement frequent low-stakes quizzes. I really want students to feel that learning is a process, and I like that we've developed ways to help students improve without punishing them for where they are at any given moment.

You are involved in a good number of student groups and initiatives, often in a leadership role. Could you share a little bit about the scope of these groups and your roles?

I'm going to give you this as a list!

Illinois GPS (Guidance for Physics Students). I was a co-founder of GPS in 2015, along with grad students Will Morong, Gloria Lee, and Angela Chen. We pair graduate student mentors with undergraduate mentees and plan activities, including an annual retreat. I have acted as one of the leaders of GPS since its inception. We recently were joined by Karmela Padavić, Eli Chertkov, and Luis Miguel de Jesús Astacio (and I'm so relieved, because many of us are graduating soon!).

The Access Network. Illinois GPS is also part of The Access Network, a network of equity-centered mentoring groups in STEM. I have been involved since 2015 and am now a core organizer. The Access Network lets Illinois GPS students make connections with students in like-minded groups. We work together to create reflective activities about equity in STEM. The network is funded by the National Science Foundation (we just got our second grant this year!), and the money goes toward compensating students for sharing their time and experience and sending students to conferences (like SACNAS and an annual Access Assembly). We have had three physics students as Access Fellows in the last two years (Jake Rangel, Damerrick Perry, and Luis Miguel de Jesús Astacio). The next Access Assembly (Summer 2019) is scheduled to happen at the U of I!

Graduate Diversity Committee. I am a founding member and a coordinator. Since 2016, we have worked together to come up with ways to make the department more inclusive. We work with Lance Cooper [professor and associate head for graduate programs] to implement our ideas. Here's a partial list with notes on my roles:

- Mandatory microaggressions workshop for incoming graduate students
- LGBTQ+ Coffee Hours (I initiated and run this group.)
- ASL (American Sign Language) Learning Group (I work with Colin Lualdi and Rita Garrido Menacho to organize bi-weekly meetings for people to come together and learn signs and have a space to practice.)
- Physics Diversity Journal Club (helped to organize; the main organizer is Shivesh Pathak.)
- LGBTQ+ Allies Workshop for Faculty (I was the organizer.)
- LGBTQ+ Logo Contest (I was the organizer.)

Women in Physics and Astronomy (WIPA). In 2018, I co-organized with Karmela Padavić, Cristina Schlesier, and Carla Stelsel a two-day Women and Genderqueer Physics and Astronomy Retreat. We had 30 participants. I also organized a WIPA Celebration and Solidarity Hour.

GEO (Graduate Employees' Organization). Since 2017, I have served as Stewards' Council co-chair with Roshni Bano. As co-chairs, we do outreach to physics grad students and create agendas for meetings with the steward. Last year, we participated in a 12-day strike to ensure tuition waiver guarantees and advocate for better graduate conditions (such as a living wage, health care, a better non-discrimination clause, immigration leave, childcare, etc.). I think this is really important as part of my work to make the department inclusive—not all students are traditional students who can afford academia without support from the university.

March for Science 2017. I was an organizer starting in 2016. I was the coordinator of volunteers and served on the Diversity Committee. This isn't totally department specific, but there were a lot of physics folks present! We worked hard to make sure that the march was accessible and inclusive. Our speakers emphasized scientists' responsibility to self-reflect on issues of equity and to think critically about the intersection of science and oppression. Topics included the whitewashing of math history taught in schools, indifference during the HIV/AIDS epidemic, and the effect of the Muslim Travel Ban on the research and livelihood of an Iranian graduate student. This past year, I also participated in a March for Science Summit, which focused on the ways society, policy, and science interact. I strongly believe

This page, top: Attendees of the Women and Genderqueer Physics and Astronomy retreat. This page, bottom: Attendees of the 2018 The Access Network assembly.
Opposite page, top: The bubble activity at the 2017 annual Illinois GPS retreat—Gutmann is enveloping Illinois Physics sophomore Alexandra Trauth in a bubble. Opposite page, bottom: Illinois GPS members at the 2018 annual retreat. Photos courtesy of Brianne Gutmann

that, as scientists, we must hold ourselves accountable and be critical of oppressive structures, and I feel really proud of the march! With Gloria Lee, we led the march with children from the community, to put the emphasis on our future scientists.

Why is it important to get involved in student groups/initiatives?

It has been important to me to connect with others in the department who also care about these initiatives. The people I've worked with on these projects have been some of my best friends and allies in grad school. It's important for me to try to reciprocate that feeling. The department is huge and I think without active effort, it's easy to feel lost in a large university.

Did you feel supported in your efforts by other students or faculty/staff?

Nearly all of the things I've done have been joint efforts by a lot of fantastic people, and Lance has always been enthusiastic and supportive. As soon as I realized that our ideas could happen, it became much easier to keep pushing for more. Each successful project or initiative made me that more confident that the next could also be successful.

"If you want something to happen, be the person to initiate it. Don't just wait for it to happen."

What do you enjoy most about departmental life?

I love that whenever I'm having a bad day or week, I can find someone to get lunch or coffee or just take a quick break and pop into someone else's lab. I feel surrounded by people who get me and care about things that I care about.

What is next for you?

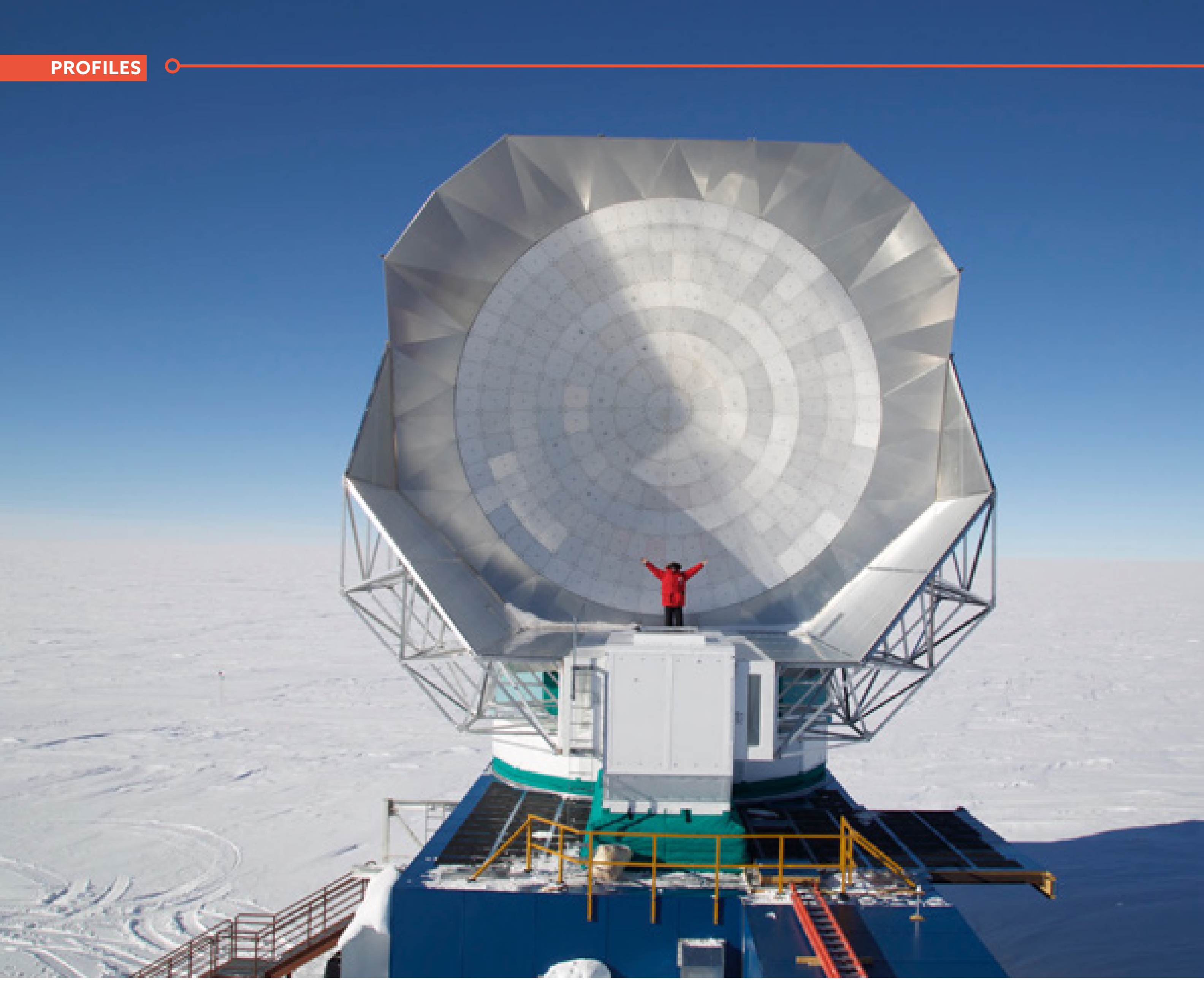
I'd like to focus more explicitly on supporting underserved populations in STEM. I'm currently applying to postdoc positions, with the long-term goal of becoming physics faculty in a department that supports physics education research. A lot of my passion work has been focused on equity, which has been somewhat aligned with my work in Physics 100, but I'd love to find a position where I can study student ownership and belonging, adaptive learning, and identity-based mentoring.

How did your time at Illinois Physics benefit you in terms of your future goals?

My time at Illinois has given me a lot of space to self-educate and to be part of initiatives that support students and equity, and I'm grateful to have been able to have that space. My adviser is extremely patient and understands my need to spend time on these projects, while still helping me get closer to graduation. I'm expecting to graduate this summer and hope to begin a postdoc next fall in physics education research.

What advice do you have for students just beginning their graduate studies?

If you want something to happen, be the person to initiate it. Don't just wait for it to happen. You'll find others who want it too, and often lots of people are thinking the same thing, and it just takes someone to get the ball rolling. I've learned a lot over the last few years, but even if you know nothing when you start (me), you'll learn. Also, take time for what makes you happy and fulfilled! ■



Next-gen camera for South Pole Telescope takes data on early universe

Deep in Antarctica, at the southernmost point on our planet, sits a 33-foot telescope designed for a single purpose: to make images of the oldest light in the universe.

This light, known as the cosmic microwave background, or CMB, has journeyed across the cosmos for 14 billion years—from the moments immediately after the big bang until now. Because it is brightest in the microwave part of the spectrum, the CMB is impossible to see with our eyes and requires specialized telescopes, cameras, optics, and detector technologies.

The South Pole Telescope, the largest telescope on the planet specially designed to measure the CMB, will use its third-generation camera (SPT-3G) to carry out a 5-year survey to observe the earliest instants of the universe. Since 2007, the SPT has shed light on the physics of black holes, discovered a galaxy cluster that is making stars at the highest rate ever seen, redefined our picture of when the first stars formed in the universe, provided new insights into dark energy, and homed in on the masses of neutrinos. This latest upgrade improves its sensitivity by nearly an order of magnitude—making it among the most sensitive CMB instruments ever built.

U of I astronomy graduate student Andrew Nadolski stands in front of the South Pole Telescope in Antarctica. Nadolski was stationed at the South Pole for the first year after installation of the third-generation camera on the telescope. Photo courtesy of Andrew Nadolski

Gil Holder, a theoretical astrophysicist and professor at the University of Illinois at Urbana-Champaign, is a member of the SPT collaboration. He comments, "The SPT is able to take pictures of the very first instances in the history of the universe. By analyzing these images, we can measure what the universe is made of and understand the how the universe has evolved over cosmic time."

The telescope is funded and maintained by the National Science Foundation in its role as manager of the U.S. Antarctic Program, the national program of research on the southernmost continent. Located at NSF's Amundsen-Scott South Pole Station, the telescope is operated by a collaboration of more than 80 scientists and engineers from a group of universities and U.S. Department of Energy national laboratories, including four institutions in Illinois. These research organizations—the University of Chicago, the University of Illinois at Urbana-Champaign, Argonne National Laboratory, and Fermi National Accelerator Laboratory—have worked together to build a new, ultra-sensitive camera for the telescope, containing 16,000 specially manufactured detectors.

U of I Professor Joaquin Vieira and his team built all of the cryogenic optics for the SPT-3G camera, which were a critical component of the project. Work entailed developing a new type of anti-reflection coating for the optics that could survive down to 0.3 degrees above absolute zero, a feat that required about four years of research and development.

'Baby pictures' of the cosmos

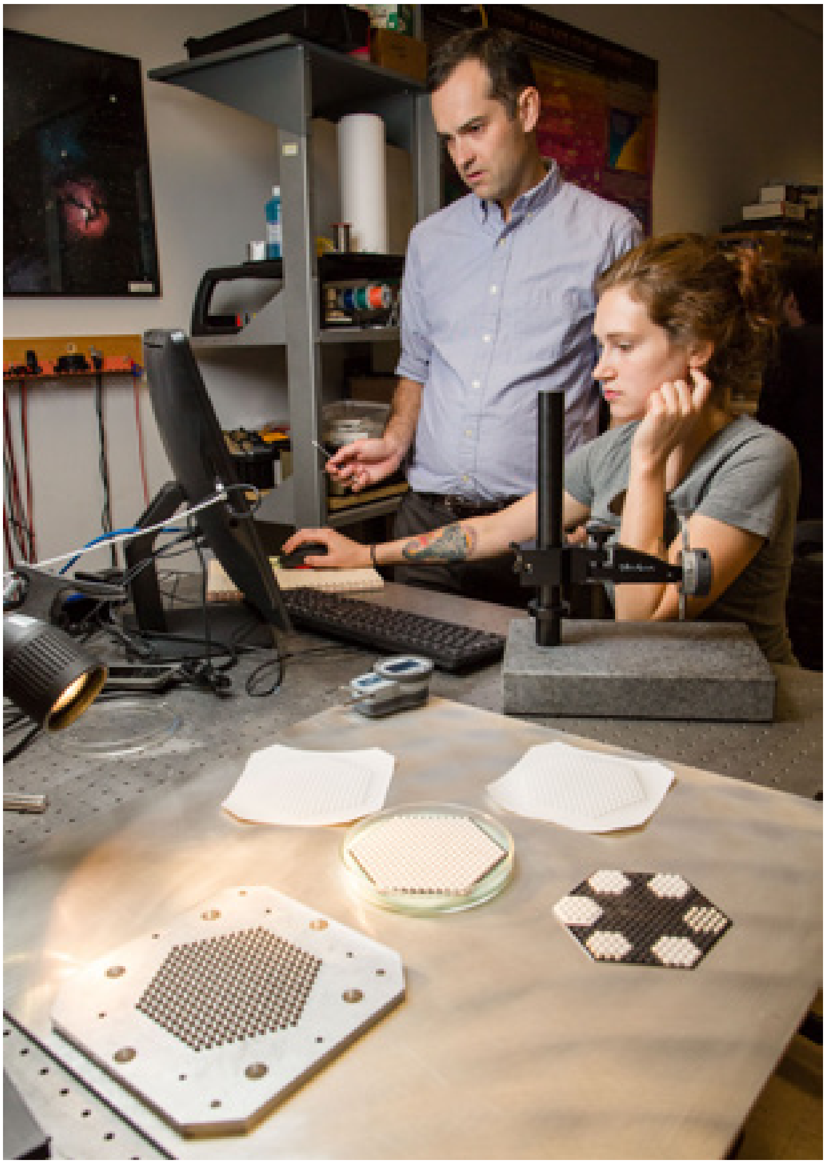
The CMB is the oldest light in our universe, produced in the intensely hot aftermath of the big bang before even the formation of atoms. These primordial particles of light, which have remained almost untouched for nearly 14 billion years, provide unique clues about how the universe looked at the beginning of time and how it has changed since.

Vieira explains, "The cosmic microwave background, despite being the oldest light in the universe, is incredibly bright and outshines every other source in the Universe—but you have to build cameras that can see at millimeter wavelengths to observe it."

However, because most of the energy is in the microwave part of the spectrum, to observe it we need to use special detectors at observatories in high and dry locations. The South Pole Station is better than anyplace else on Earth for this: it is located atop a two-mile thick ice sheet, and the extremely low temperatures in Antarctica mean there is almost no atmospheric water vapor.

The details of this "baby picture" of the cosmos will allow scientists to better understand the different kinds of matter and energy that make up our universe, such as neutrinos and dark energy. They may even find evidence of the gravitational waves from the beginning of the universe, regarded by many as the "smoking gun" for the theory of inflation.

This baby picture also serves as a rich astronomical survey; one of the things the researchers will be looking for are some of the first massive galaxies in the universe. These massive galaxies are increasingly of interest to



Left: Professor of Astronomy and of Physics Joaquin Vieira works in his lab with then undergraduate student Angelina Hake-Hosemann (BS Physics 2016). In the foreground are cryogenic optics developed for the South Pole Telescope 3-G Camera. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

Opposite page: U of I physics undergraduate student Anna Kofman poses with REU student Sierra Barone from Wheaton College, in the Vieira lab, Summer 2017. In the foreground is a large lens with a specially developed anti-reflection coating for the South Pole Telescope 3G Camera. Kofman is now a graduate student at the University of Pennsylvania. Photo courtesy of Joaquin Vieira, University of Illinois at Urbana-Champaign

astronomers as "star farms," forming the first stars in the universe, and since they are nearly invisible to typical optical telescopes, the South Pole Telescope is perhaps the most efficient way to find them.

All new technology

For the SPT-3G, scientists needed equipment far more sensitive than anything made commercially. They had to develop their own detectors, which use special materials for sensing tiny changes in temperature when they absorb light. These custom detectors were developed and manufactured from scratch in ultra-clean rooms at Argonne National Laboratory. The detectors went to Fermilab to be assembled into modules.

These modules included small lenses for each pixel, made at the U of I. The research effort at Illinois included important contributions from graduate students and even undergraduate students.

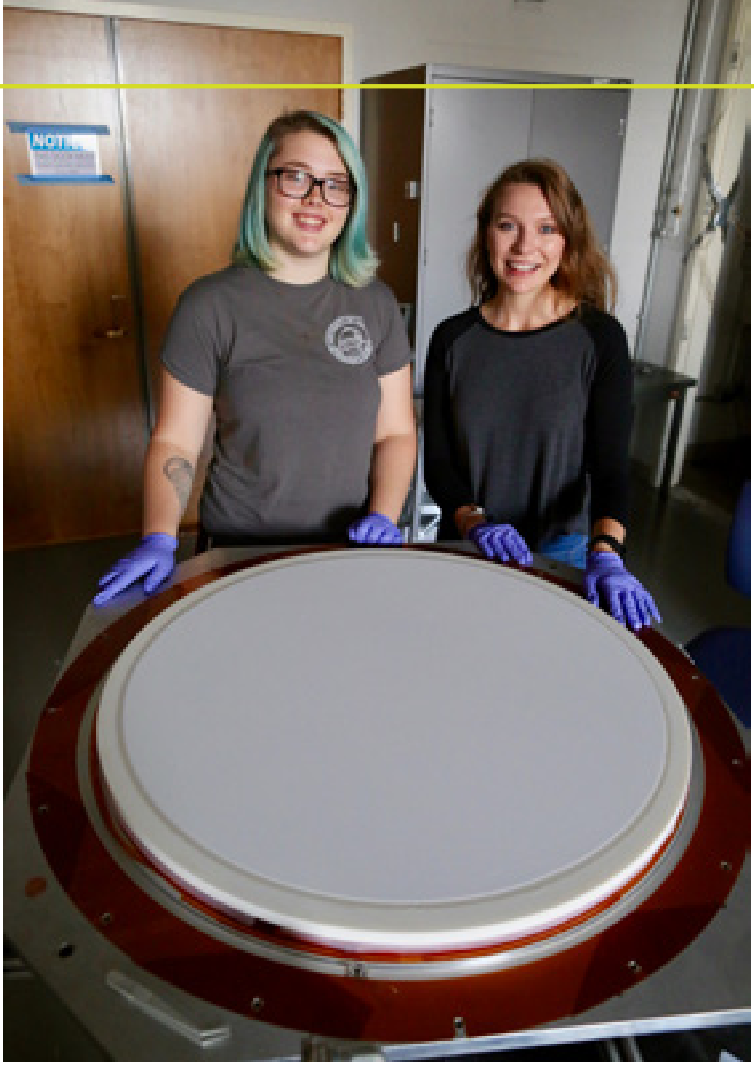
Astronomy graduate student Andrew Nadolski helped design and build the optics for SPT-3G and spent the first winter at the South Pole babysitting the new camera for its initial year of operation.

Nadolski comments, "A lot of research and development has to go into a big, state-of-the-art cosmology experiment like SPT-3G. I went from finding new ways of working with basic materials like ceramics and plastics to develop new cryogenic optics, to climbing around a giant telescope at the South Pole in –80°F and pitch darkness—all in the name of cosmology."

"It's been a wild ride," he adds, "but it's just getting started, because now we are getting the data and it's a whole new adventure."

After being tested at multiple collaborating universities around the country, the detectors made their way back to

The South Pole Telescope collaboration is led by the University of Chicago and includes research groups at Argonne National Laboratory, Case Western Reserve University, Fermi National Accelerator Laboratory, Harvard-Smithsonian Astrophysical Observatory, Ludwig Maximilian University of Münich, McGill University, SLAC National Accelerator Laboratory, University of California, Berkeley, University of California, Davis, University of California, Los Angeles, University of Colorado Boulder, University of Illinois at Urbana-Champaign, University of Melbourne, and University of Toronto, as well as individual scientists at several other institutions.



Fermilab to be integrated into the South Pole Telescope camera cryostat. The camera looks like an 8-foot-tall, 2,500-pound optical camera with a telephoto lens on the front, but with the added complication that the lenses must be cooled to just a few degrees above absolute zero. (Even Antarctica isn't that cold, so this special cryostat is required to cool the lenses.)

Finally, the new camera was ready for its 10,000-mile journey to Antarctica by way of land, air and sea. On the final leg, from NSF's McMurdo Station to the South Pole, it flew aboard a specialized LC130 cargo plane outfitted with skis so that it could land on snow near the telescope site, since the station sits atop an ice sheet. The components were carefully unloaded, and a team of more than 30 scientists raced to reassemble the camera during the brief three-month Antarctic summer—since the South Pole is not accessible by plane for most of the year because of temperatures that can drop to –100°F.

The South Pole Telescope's multi-year observing campaign brings together researchers from across North America, Europe and Australia. With the upgraded telescope taking data, the exploration of the cosmic microwave background radiation enters a new era with a powerful collaboration and an extremely sensitive instrument.

Anna Kofman, now a graduate student in physics at University of Pennsylvania, took a year off after receiving her undergraduate degree from the U of I so that she could lead the fabrication of the anti-reflection coatings for the large lenses, which were critical to the overall sensitivity of the new camera.

Kofman acknowledges, "It was an amazing experience to be able to build something that gets sent to the end of the Earth to observe the beginning of the universe. I am so fortunate to have had that opportunity at Illinois."

The South Pole Telescope is funded primarily by the National Science Foundation's Office of Polar Programs and the U.S. Department of Energy Office of Science. Partial support also is provided by the NSF-funded Physics Frontier Center at the KICP, the Kavli Foundation, and the Gordon and Betty Moore Foundation.

African School on Electronic Structure Methods and Applications goes to Ethiopia

ASESMA, a biennial two-week intensive workshop in condensed matter theory, is cultivating the practice of advanced computational science in Africa. The program—co-founded by Illinois Physics Emeritus Professor Richard Martin and Illinois Physics alumnus, Professor Nithaya Chetty of the University of Pretoria—has strong Urbana roots.

SIV SCHWINK
for Illinois Physics Condensate

The 5th African School on Electronic Structure Methods and Applications (ASESMA), an intensive advanced-science workshop held October 22 through November 2, 2018, at the Addis Ababa Science and Technology University, Ethiopia, gave 49 early-career scientists and doctoral students from 13 countries in Africa the opportunity to learn advanced computational research methods in condensed matter physics.

ASESMA is a biennial school, first piloted in 2008 in South Africa. For the last decade, the ASESMA program has been an important part of a larger initiative to develop educational infrastructure, scientific training, and research collaborations in areas critical to the economic interests of mineral-rich African nations. ASESMA draws more applicants than can be accommodated, and prior enrollment has averaged ~40 participants per year.

During the two-week workshop, each day's schedule included about 10 hours of instruction and worktime combined. The first week focused on lectures and hands-on open-source-software tutorials and the second week on projects that address research-level questions. Evening programs covered professional development topics such as writing scholarly papers, giving

Left page: The 2018 5th ASESMA group photo. At the center is the Ethiopian Minister of Science and Technology, who spoke at the opening session.

This page, top down: (1) An ASESMA mentor leading a hands-on tutorial. (2) ASESMA mentors working with participants. (3) An evening session after dinner at the hotel.

Photos by ASESMA mentor Dr. Sinéad Griffin, staff scientist, Lawrence Berkeley National Laboratory

talks, research in Africa, and women in science, among others. Everyone stayed at the same hotel and took all meals together, which provided additional time and opportunities to develop a sense of community.

The workshops have been tremendously successful, according to University of Pretoria Professor of Physics Nithaya Chetty, an Illinois Physics alumnus and co-founder and co-director of ASESMA.

Chetty reports, "The school has helped nucleate research groups in electronic-structure computations at a number of institutions in Africa and has helped network students and young researchers with scientists elsewhere in Africa and with leading researchers abroad. This has enabled ASESMA graduates to continue with their work well after the two-week-long school. One of the biggest challenges facing [ASESMA] graduates returning to their home countries is the isolation. ASESMA has helped counter this by creating a family and a supportive environment for computational materials science to grow in Africa."

By the time this year's school was underway, past ASESMA graduates had contributed to 124 papers published in refereed journals. This is a reflection of the strength and persistence of the ongoing collaborations among program participants, lecturers, and mentors.

"This is the main idea behind ASESMA, that collaborations and cooperation continue well after the school is over," Chetty adds. "There are many

ASESMA's Urbana Roots

Nithaya Chetty

Richard Martin

Nithaya Chetty grew up in rural Natal province in South Africa under the apartheid system of racial segregation. He graduated from the University of Natal (now the University of KwaZulu-Natal) and came to the University of Illinois at Urbana-Champaign in 1985 as a Fulbright scholar. He was Richard Martin's very first doctoral student at the Department of Physics, University of Illinois at Urbana-Champaign.

Chetty shares, "I attended the University of Natal at a time when only seven percent of the student population could be people of color, and even then I had to get special permission from the central government on an annual basis to attend. I was fortunate to secure a Fulbright Fellowship that got me to the U of I. I think that I shall always remember that Illinois, and more specifically the Department of Physics, gave me the first chance to feel human, to feel that I could compete with other students irrespective of my race, and that I could be judged on my abilities alone."

The resolve to initiate a school for talented up-and-coming African scientists—to offer advanced instruction by leading experts in condensed matter physics on African soil—grew out of Martin and Chetty's late-night conversations years later. In 2004, Chetty, then a professor at the University of KwaZulu-Natal, returned to Urbana for a six-month sabbatical on a second Fulbright award, to work with Martin.

Chetty remembers, "We chatted about Richard's keen interests in contributing to the development of electronic structure work in Africa post his retirement. Of course, there were many reasons why and how ASESMA became a reality, involving an international coalition of support. But, I credit Richard and his deep interests in advancing human development in Africa as being the inspiration behind ASESMA."

The two teamed up with Sandro Scandolo of the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy, and together made the first school a reality. Additional funding for a biennial school to be held five times over the next decade was secured based on the successes of the first school. The ICTP has served as the administrative home for ASESMA, and the International Union for Pure and Applied Physics, where Chetty currently serves as vice president, has been its principal sponsor.

Chetty's efforts to make science on the African continent equally accessible to underrepresented groups extend well beyond ASESMA. Asked what it has meant to him to be a leader in this broad effort, he replied, "It is so inspiring for me to meet with young African students and faculty, many of whom are talented and are just yearning for opportunity. So many—especially their families—have sacrificed so much to get to where they are. With so little they have come such a long way. This has undoubtedly made me more appreciative of the talent that exists out there, and has strengthened my resolve to contribute to developing physics in Africa."

ASESMA Workshops Since 2008

A total of 191 early-career scientists and doctoral students from 22 African countries have enrolled in ASESMA or its precursor school since 2008. Among those, 26 graduates returned to the program two or more times as advanced students. In all, 25 women scientists enrolled. A total of 35 lecturers and 33 mentors have served at the schools. Well over a third of ASESMA's lecturers and mentors hail from the African continent.

2008, precursor school, African Institute of Mathematical Sciences (AIMS), Cape Town, South Africa
2010, 1st ASESMA, also at AIMS in Cape Town
2012, 2nd ASESMA, Chepkoilel University College (now University of Eldoret), Kenya
2015, 3rd ASESMA, University of the Witwatersrand, Johannesburg, South Africa
2016, 4th ASESMA, University of Ghana, Legon, Ghana
2018, 5th ASESMA, Addis Ababa Science and Technology University, Ethiopia

Above: ASESMA participants working together. Below: ASESMA participants enjoying after-dinner coffee Ethiopian style. Photos by ASESMA mentor Dr. Sinéad Griffin, staff scientist, Lawrence Berkeley National Laboratory

successful cases, for example, of researchers in Kenya collaborating with individuals in Japan and in France and publishing jointly as a direct result of ASESMA. Similarly, a group in Congo-Brazzaville has been working with us at the University of Pretoria, and this collaboration is proving to be productive. There are other examples too. In some instances, we have arranged for access to the Centre for High Performance Computing in Cape Town for researchers in need of computing resources."

Chetty's doctoral adviser, University of Illinois at Urbana-Champaign Emeritus Professor of Physics Richard Martin, co-founded and co-directs ASESMA. Martin agrees, the schools have helped to cultivate an open intellectual culture among a growing community of promising African scientists. Martin attributes ASESMA's success to its providing early-career interactions with world-leading experts and its establishing lasting collaborations across national lines—these two factors have made a profound difference in the trajectory of ASESMA graduates' scientific careers.

"The ASESMA Schools Series is based on theory and computational methods for predicting and understanding properties of materials through calculations at the fundamental level of electronic structure," comments Martin. "There is an important focus on real applications. This is a growing field in which scientists with limited resources can have a large impact. A personal workstation is sufficient for many problems and the internet is making possible productive use of large computational facilities. It is within reach to create a vibrant electronic structure community in Africa, working on forefront international research."

Mentors play a key role in the accomplishments of ASESMA participants. Mentors are advanced students and postdoctoral fellows who advise on both science and computing subjects. During the program, they deliver portions of lectures or lead hands-on tutorials. After the program, they continue to work with ASESMA graduates through email and other electronic correspondence. According to Martin the mentorship program this year received additional financial support, making it stronger than ever.

A number of factors set this year's school apart from prior schools.

"At this year's school, the number of advanced participants went up significantly, which contributed to a higher level of interactions among all of the participants. These more advanced participants were tutors for the less experienced ones in the first week, and in the second week they did more advanced projects," states Martin.

In 2018, the school's curriculum included more research topics in other fields of computational science.

"This year marked the start of a new direction," Martin reports, "with lectures and a tutorial for all students on molecular dynamics and soft matter and an introductory lecture on biological applications. This expansion of the scope of ASESMA into other areas of computational materials and biological sciences goes along with the emphasis on electronic structure of solids—this is important for the goal of increased collaboration across disciplines that is needed for the research community in Africa."

Martin stresses, research projects are designed not as one-week efforts, but as introductory efforts on take-home research subjects having the potential for publication in scholarly journals.

"In each case participants learn about finding previous work in the area, carrying out reliable calculations, and drawing conclusions," Martin describes. "This year there were seven projects—three in different areas of density functional theory, one in calculations of optical properties, and two types of projects done for the first time this year, molecular dynamics of large polyelectrolytes with effective potentials and a pen-and-paper project of developing functionals.

"The challenge now is to keep up the momentum and to provide opportunities for the participants to have collaborations and interactions within Africa and on a global scale. There was very positive feedback from all the participants, who want to continue the projects started at the school and increase their interactions within Africa and beyond."

Martin notes, "The spirit at ASESMA schools and the social interactions far exceed any schools I know of in the U.S. or Europe, and it is manifested at each school in different ways. This year there were spontaneous songs by participants

From the top (1) Mentor Yusuf Shaidu lectures on crystal structure. (2) Richard Martin (right) visits with a participant during a coffee break. (3) An ASESMA mentor provides one-on-one tutoring to participants. Photos by ASESMA mentor Dr. Sinéad Griffin, staff scientist, Lawrence Berkeley National Laboratory

and a mentor, especially on the last evening when there no technical talks."

ASESMA is supported by sponsors around the globe. After a successful pilot school in South Africa in 2008, the primary funding for the five ASESMA schools starting in 2010 represented a decade-long commitment that has now expired. ASESMA organizers are currently assessing the program's future and planning additional bids for funding, to carry ASESMA's momentum and impact into the future.

Martin shares, "The scope of ASESMA and the number of active, experienced research groups has grown to the point where there can be new opportunities. It is time now for a new, broader vision, one that builds on the recognized success of ASESMA. The emphasis this year on molecular dynamics and biological applications was a step in the direction of that new vision. There are many possibilities and still much to discuss and to plan, but we already have our sights on a strong candidate for the location of ASESMA 2020, the new East African Institute for Fundamental Physics in Rwanda, which is supported by the ICTP."

A 33-member International Advisory Panel provides input on ASESMA's schools. Of special note, Illinois Physics Professor Anthony Leggett, winner of the 2003 Nobel Prize in Physics, is an active member of the panel. ■

For more information, please visit http://asesma.org/ .

Contributors to the 2018 ASESMA

Hosts and local organizers: Getachew Adam, Garu Gebreyesus Hagoss, and Yohannes Teketel.

Program Committee: Richard Martin, Nicola Marzari, Shobhana Narasimhan, Sandro Scandolo, Nicola Seriani

Other Organizers: Omololu Akin-Ojo (East Africa Institute for Fundamental Research, Rwanda) and George Amolo (Technical University of Kenya)

Lecturers: Omololu Akin-Ojo (Rwanda), George Amolo (Kenya), Mark Casida (France), Matteo Gatti (France), Erik Luijten (USA), Ryo Maezono (Japan). Liliana Mammen (South Africa), Andrea Marini (Italy), Richard Martin (USA), Shobhana Narasimhan (India), Lucia Reining (France), Sandro Scandolo (Italy), Nicola Seriani (Italy), Cedric Weber (UK)

Mentors: Felix Dusabirane (Rwanda), Sinead Griffin (USA), Aditi Krishnapriyan (USA), Carla Lupo (UK), Ian Madden (USA), Dennis Magero (Kenya), Nishi Mammen (India, now postdoc in Finland), Yusuf Shaidu (Nigeria, now at ICTP), Azima Seidu (Ghana, now postdoc in Finland), Evan Sheridan (UK), Florian Thole (Switzerland), Joshua Vita (USA), and Nobuya Watanabe (Japan)

Sponsors of the 2018 ASESMA

International Union of Pure and Applied Physics (IUPAP)
The ASESMA series has been endorsed by IUPAP through the Commission of Physics for Development (C13), Commission on Physics Education (C14), and the Commission of Computational Physics (C20). The Commission on the Structure and Dynamics of Condensed Matter (C10) also supported the School. Grants from IUPAP Commission of Physics for Development (C13) and the U.S. Liaison Committee to IUPAP were important for the 2018 school.

International Centre for Theoretical Physics (ICTP) in Trieste provided travel support for participants from other African countries and other financial and administrative support for the school. Scientists from the ICTP are critical for planning and organizing the schools: this year they were Sandro Scandolo and Nicola Seriani.

The Center of Excellence for Sustainable Energy of Addis Ababa Science and Technology University

The Ministry of Science and Technology of Ethiopia

The Ministry of Water, Irrigation and Electricity of Ethiopia

U.S. National Science Foundation provided travel support for 2 lecturers, 3 mentors, and 1 participant.

MARVEL Centre on Computational Design and Discovery of Novel Materials in Switzerland provided travel support for 3 mentors.

Thomas Young Centre and Kings College provided travel support for 1 lecturer and 2 mentors.

Individual travel support was provided for many of the lecturers by institutions or grants.

New CRISPR technique skips over portions of genes that can cause disease

LIZ AHLBERG
for Illinois News Bureau

In a new study in cells, University of Illinois researchers have adapted CRISPR gene-editing technology to cause the cell's internal machinery to skip over a small portion of a gene when transcribing it into a template for protein building. This gives researchers a way not only to eliminate a mutated gene sequence, but also to influence how the gene is expressed and regulated.

Such targeted editing could one day be useful for treating genetic diseases caused by mutations in the genome, such as Duchenne's muscular dystrophy, Huntington's disease or some cancers.

CRISPR technologies typically turn off genes by breaking the DNA at the start of a targeted gene, inducing mutations when the DNA binds back together. This approach can cause problems, such as the DNA breaking in places other than the intended target and the broken DNA reattaching to different chromosomes.

The new CRISPR-SKIP technique, described in the August 15, 2018 issue of the journal *Genome Biology*, does not break the DNA strands but instead alters a single point in the targeted DNA sequence.

"Given the problems with traditional gene editing by breaking the DNA, we have to find ways of optimizing tools to accomplish gene modification. This is a good one because we can regulate a gene without breaking genomic DNA," said Illinois bioengineering professor Pablo Perez-Pinera, who led the study with Illinois physics professor Jun Song. Both are affiliated with the Carl R. Woese Institute for Genomic Biology at the U of I.

In mammal cells, genes are broken up into segments called exons that are interspersed with regions of DNA that don't appear to code for anything. When the cell's machinery transcribes a gene into RNA to be translated into a protein, there are signals in the DNA sequence indicating which portions are exons and which are not part of the gene. The cell splices together the RNA transcribed from the coding portions to get one continuous RNA template that is used to make proteins.

Pictured left to right, Professor Pablo Perez-Pinera, graduate student Alan Luu, Professor Jun Song and graduate student Michael Gapinske pose in the Perez-Pinera research lab. The researchers adapted CRISPR gene-editing technology to help a cell skip over mutated portions of genes. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

CRISPR-SKIP alters a single base before the beginning of an exon, causing the cell to read it as a non-coding portion.

"When the cell treats the exon as non-coding DNA, that exon is not included in mature RNA, effectively removing the corresponding amino acids from the protein," said Michael Gapinske, a bioengineering graduate student and first author of the paper.

While skipping exons results in proteins that are missing a few amino acids, the resulting truncated proteins often retain partial or full activity – which may be enough to restore function in some genetic diseases, said Perez-Pinera, who also is a professor in the Carle Illinois College of Medicine.

There are other approaches to skipping exons or eliminating amino acids, but since they don't permanently alter the DNA, they provide only a temporary benefit and require repeated administrations over the lifetime of the patient, the researchers said.

"By editing a single base in genomic DNA using CRISPR-SKIP, we can eliminate exons permanently and, therefore, achieve a long-lasting correction of the disease with a single treatment," said Alan Luu, a physics graduate student and co-first author of the study. "The process is also reversible if we would need to turn an exon back on."

The researchers tested the technique in multiple cell lines from mice and humans, both healthy and cancerous.

"We tested it in three different mammalian cell lines to demonstrate that it can be applied to different types of cells. We also demonstrated it in cancer cell lines because we wanted to show that we could target oncogenes," Song said. "We haven't used it *in vivo*; that will be the next step."

The researchers sequenced the DNA and RNA from the treated cells and found that the CRISPR-SKIP system could target specific bases and skip exons with high efficiency, and also demonstrated that differently targeted CRISPR-SKIPs can be combined to skip multiple exons in one gene if necessary. The researchers hope to test its efficiency in live animals – the first step toward assessing its therapeutic potential.

"In Duchenne's muscular dystrophy, for example, just correcting 5 to 10 percent of the cells is enough to achieve a therapeutic benefit. With CRISPR-SKIP, we have seen modification rates of more than 20 to 30 percent in many of the cell lines we have studied," Perez-Pinera said.

The group built a web tool allowing other researchers to search whether an exon could be targeted with the CRISPR-SKIP technique while minimizing chances of it binding to similar sites in the genome.

Since the researchers saw some mutations at off-target sites, they are working to make CRISPR-SKIP even more efficient and specific.

"Biology is complex. The human genome is more than three billion bases. So the chance of landing at a location that's similar to the intended region is not negligible and is something to be aware of with any gene editing technique," Song said. "The reason we spent so much time sequencing extensively to look for off-target mutations is that it could be a major barrier to medical applications. We hope that future improvements to gene editing technologies will increase the specificity of CRISPR-SKIP so we can begin to address some of the problems that have kept gene therapy from being widely applied in the clinic." ■

This research was funded by the National Institutes of Health, the National Science Foundation and the American Heart Association. The conclusions presented are those of the researchers and not necessarily those of the funding agencies.

The Grainger Foundation is matching all donations to the Physics Engineering Visionary Scholarship dollar for dollar through the end of 2019.

The Engineering Visionary Scholarship Initiative brings the best students to Illinois Engineering by making college more affordable. Gifts to the initiative have a direct impact on society. They enable Illinois Engineering students—including Engineering Physics majors—to fuse their talent and passion with the skills needed to solve the world's greatest challenges.

Engineering Visionary Scholarships help students leave campus better prepared, more driven, and with less financial burden than those who came before them.

Since 2013, scholarships supported by the Engineering Visionary Scholarship Initiative have had a significant impact on the makeup of Illinois Engineering's student body.

- The number of women in the freshman class has nearly doubled.
- The number of freshmen from underrepresented groups has also nearly doubled.
- The number of first-generation college students offered a scholarship is six times greater.
- ACT scores and graduation rates have increased annually.

Samuel Qunell

Engineering Physics Class of '21
2017 Engineering Visionary Scholarship recipient

"This scholarship made Illinois much more affordable for my family. Illinois had always been a top choice, and with the help of this scholarship, my decision was much easier."

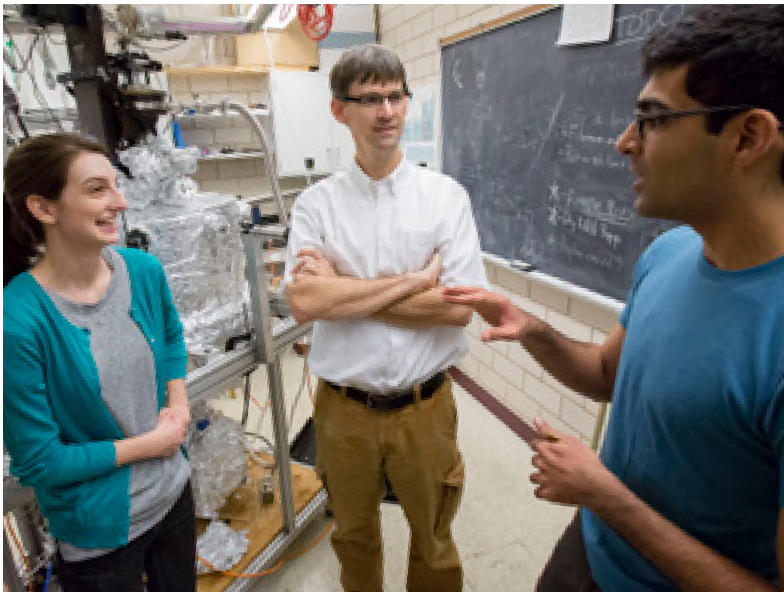
Make an Exponential Impact!

There has never been a better opportunity to support the future of Illinois Physics. Thanks to a generous gift matching offer presented by The Grainger Foundation, any gift you make to the Engineering Visionary Scholarship Initiative will be matched (up to $25 million). We are still $22.5 million away from the College of Engineering's fundraising goal of $100 million. Here's how you can help Illinois Physics be a part of this important campaign:

1. Donate now and have your donation matched.
2. Utilize your corporate match—your donation + the corporate donation will be matched.
3. If you make a 5-year pledge to Engineering Visionary Scholarship in 2019, the entire amount will be matched immediately by the Grainger Foundation. A donation of $25,000 over 5 years ($5,000 per year) pledged in 2019 will be matched $25,000 this year (even before the pledge is paid off).

For more information about the Physics Engineering Visionary Scholarship, contact Amber Lannert, alannert@illinois.edu or (217) 300-7175.

Peter Abbamonte named Fox Family Engineering Professor



Professor Peter Abbamonte in his laboratory with graduate students Mindy Rak (left) and Anshul Kogar, in the Frederick Seitz Materials Research Laboratory in Urbana. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

Professor Peter Abbamonte has been named the Fox Family Professor in Engineering at the University of Illinois at Urbana-Champaign. Named faculty appointments signify a distinction beyond that of professorial rank, recognizing distinguished scholars for their prominence in research, teaching, and service.

Abbamonte, an experimental condensed matter physicist, is known for developing the technique of resonant soft x-ray scattering, now in use at every major synchrotron facility in the world, and for his solution to the phase problem for inelastic x-ray scattering, permitting real-time imaging of electron motion with attosecond time resolution. In recent years, his group is best known for developing the technique of momentum-resolved electron energy-loss spectroscopy, which is the first technique capable of measuring the meV dynamic charge susceptibility of materials with quantitative momentum control.

In 2012, Abbamonte founded Inprentus, a high-tech manufacturing start-up, to address a shortfall in diffraction-grating manufacturing that was adversely affecting researchers in his field. These high-precision optics are required for research at synchrotron radiation facilities. Today, Inprentus x-ray and euv diffraction gratings are used in a variety of scientific and commercial applications in industry, at government laboratories, and at academic institutions around the world.

Inprentus was incubated at the EnterpriseWorks Research Park on the U of I campus. In February 2017, Inprentus announced it had raised $1.5 million in venture capital to build a new manufacturing facility in Champaign and "graduate" from the Research Park. Abbamonte is the tech company's chief scientific officer.

Abbamonte is a Fellow of the American Physical Society. He has been selected for numerous honors, including a Xerox Award for Faculty Research (2010). He was named a University Scholar (2014) and a Moore Foundation EPiQS Investigator (2014–2019). He received his doctoral degree from the U of I in 1999. He completed an NSF Fellowship at University of Groningen in The Netherlands, before returning to the U.S. in 2001 as a postdoc in biophysics at Cornell University. Starting in 2003, he worked as a staff scientist at Brookhaven National Laboratory. He joined the faculty at Illinois Physics in 2005.

Fox Family Professorships support faculty members whose business experience adds value to the university and the Champaign-Urbana community. Peter B. Fox is founder of Fox Development Corp., a real-estate firm. Its subsidiary Fox Ventures has provided startup capital for technology firms at the U of I Research Park. Fox also serves as manager of Fox/Atkins Development, LLC, the developer and manager of the Research Park. Together, Fox and his wife Kim Fox work to promote Champaign County's economic development and to support its community organizations. By supporting University of Illinois faculty and research, the Fox family also helps to create job opportunities for the outstanding graduates the university produces.

The next great scientific and technological revolution: quantum information science

Paul Kwiat

Brian DeMarco

Dale Van Harlingen

University of Illinois at Urbana-Champaign poised to play leading role in national QIS research and development efforts

SIV SCHWINK
for Illinois Physics Condensate

Researchers collaborating across physics, engineering, and computer science have shown that quantum mechanics—one of the most successful theories of physics that explains nature at all scales, from electrons, to atoms, to neutron stars, to the big bang—can be a powerful platform for information processing, data storage, and secure communications. Quantum information science (QIS) has emerged as a rapidly growing and exciting multidisciplinary field having implications for a broad range of astounding advancements to today's technologies. A recent surge in global QIS research efforts is signaling the next great scientific and technological revolution.

Scientists and engineers at research institutions and in the tech-industry are putting large stakes on what's to come. In 2016, China launched the Micius "quantum satellite" and by 2018 had successfully run quantum communications experiments in space—an important first step toward the eventual creation of a global quantum communications network. In 2018, Israel allocated $80 million for the development of quantum computing technology, and in the U.S., every major research funding agency launched special programs to support QIS. By the end of the year, the U.S. National Quantum Initiative Act had passed both the House and the Senate and was signed into law by President Donald Trump on December 21, 2018. This legislation, intended to secure the U.S.'s leadership in QIS, commits $1.2 billion in funding over a five-year period toward the development of QIS technologies and the training of a QIS-smart workforce.

It will likely be some years before the first quantum processors capable of performing large-scale computations are brought online. Many fundamental questions remain on how to optimally incorporate the marvelous, completely unintuitive properties of quantum mechanics in proposed new technologies. But it's evident that a quantum revolution is coming, bringing progress we can't even imagine. After all, before the first laser was invented in the 1960s, who could have dreamed of today's ubiquitous applications of amplified light? Lasers are used in grocery-store scanners, CD and DVD players, laser printers, surgical tools, medical and scientific spectroscopy, firearm and munitions targeting, traffic enforcement, internet fiberoptics, and more. It's fair to say that quantum technologies likewise hold great surprises in store.

New multi-disciplinary center to accelerate QIS research

With faculty members in several departments already doing QIS-related research, the University of Illinois at Urbana-Champaign is in a good position to help lead the coming revolution. On October 29, 2018, the U of I announced that it would invest $15 million to establish a new research center that would draw on and expand Illinois' expertise in QIS. The Illinois Quantum Information Science and Technology Center (IQUIST) will bring together quantum-science experts across multiple Illinois Engineering departments and other units on campus.

IQUIST's newly named director, Physics Professor Paul Kwiat, is a pioneer in QIS research, especially noted for his groundbreaking quantum-communication experiments using entangled and hyperentangled photons. Kwiat says the new center is exactly what's needed to accelerate progress in the development of QIS technologies and QIS education at the U of I.

"To make quick progress, we need a broad spectrum of scientists and engineers to converge and learn one another's languages so that we may effectively work together across our different research paradigms," says Kwiat. "We need computer scientists, materials engineers, electrical engineers, and others with a strong interest in developing technologies using the unique, powerful capabilities of quantum mechanics. Each discipline has its own way of tackling problems, its own methods and tools, and its own strengths. IQUIST will enable QIS researchers at Illinois to collaborate across disciplines to better exploit those strengths, to explore promising new ideas more rigorously, and to benefit more immediately from one another's work."

Physics Professors Dale Van Harlingen and Brian DeMarco have been appointed IQUIST's new executive associate director and associate director for educational programs, respectively. Van Harlingen brings expertise in superconductivity and its potential applications in quantum technologies, and DeMarco brings expertise in trapped ion experiments, which they will apply toward the development of IQUIST's planned quantum processor testbed.

DeMarco asserts, "Illinois is positioned to have a strong impact on QIS research, including algorithm development, creating key technologies such as quantum repeaters and communication channels, and research into the materials needed for next-generation qubits [quantum bits]."

The center will also develop a focused program to educate the next-generation quantum workforce. DeMarco, who also serves as Illinois Physics' associate head for undergraduate programs, comments, "Illinois Physics is one of the largest and top-ranked physics departments in the U.S., and we are working to solve the quantum workforce challenge by developing new undergraduate and master's degree programs in QIS."

In the U of I press release, Chancellor Robert Jones commented, "Our campus has a legacy of groundbreaking contributions to fundamental science and the development of technologies that have shaped society over the past century, including the first automatic computer, magnetic resonance imaging, light-emitting diodes, and the first modern internet browser—not to mention the first computer built and owned by an educational institution. Today, we are pleased to announce near-term concrete actions that will advance this critical area of national need and importance."

The three key organizers wasted no time in making the center a reality. By the end of the calendar year, they had acquired administrative offices in the Frederick Seitz Materials Research Laboratory and research space in the basement of the Engineering Sciences Building for the development of the quantum processor testbed. The testbed is expected to involve trapped ion qubits, conventional and topological superconducting qubits, and possibly semiconductor-defect-state qubits, with photonic interconnects coupling them. IQUIST will acquire state-of-the-art equipment for the fabrication of quantum materials and devices, including an electron-beam writer, thin-film growth and processing equipment, a dry dilution refrigerator, and microwave electronics.

The three key IQUIST organizers have also already outlined the new center's administrative structure and governance; assembled its inaugural membership of 24 U of I scholars from the Departments of Physics (17), Electrical and Computer Engineering (3), Computer Science (2), Mechanical Engineering (1) and Mathematics (1); formed the IQUIST Scientific Advisory Committee comprising eight of its members; and invited thirteen U of I researchers from College of Engineering units to join IQUIST as affiliates, including six from Illinois Physics.

An IQUIST retreat for members and affiliates will take place on Martin Luther King Jr. Day, on January 21, 2018, at the I-Hotel and Conference Center in Champaign. The agenda includes opportunities to discuss future plans for the center, as well as research and funding opportunities.

In conjunction with the new center, the university has authorized at least eight QIS faculty lines. Searches to fill these positions are already underway within the Departments of Physics, Electrical and Computer Engineering, and Computer Science.

Van Harlingen notes, "We expect the number of members and affiliates to grow significantly as we hire new faculty and as more faculty start projects and obtain funding in QIS. We also expect the immediate hiring of postdocs and/or technical staff for designing and engineering the testbed and for advanced thin-film and device fabrication. We will also soon hire a managing director, to handle the day-to-day administrative operations of the center."

Plans are also underway to establish an internal IQUIST Executive Advisory Committee composed of department heads and laboratory directors in the College of Engineering, in addition to an IQUIST External Advisory Board composed of academic, national lab, and industrial leaders in QIS. Part of IQUIST's mission will be to foster and expand collaborations with industry, national labs, and other academic institutions, such as the University of Chicago, Argonne National Laboratory and Fermilab. As a participant in the Discovery Partners Institute's Illinois Innovation Network, IQUIST will contribute to strengthening Illinois' economy through high-tech workforce and next-generation technology development.

New QIS partnerships

On October 30, 2018, the University of Illinois at Urbana-Champaign announced it had joined the Chicago Quantum Exchange (CQE) as its final core member, making it one of the largest QIS collaborations in the world. The CQE was formed last year as an alliance between the University of Chicago and the two Illinois-based national laboratories, Argonne and Fermilab. Van Harlingen serves as the U of I representative on the CQE steering committee, which has one member from each of the four core-member institutions.

Van Harlingen comments, "The CQE is a collaboration designed to bring academic, national lab, and industrial institutions together to take advantage of Chicago's visibility and opportunities in QIS. CQE will focus first on attracting funding through the National Quantum Initiative—that planning has already started. There will also be collaborative projects, educational programs, and industrial partnerships and internships. Eventually, we expect to have research laboratories, office space, and faculty, postdocs, and students located in Chicago."

According to the U of I's October 30 press release, the initiative is a major step in an expanded series of collaborations between UChicago and the Urbana campus, deepening their connections in the Discovery Partners Institute and the Illinois Innovation Network.

The CQE already has multiple projects underway, including plans to develop one of the world's longest quantum communication links to test technology that one day could be the basis for an unhackable network and distributed quantum sensors. It will stretch 30 miles between Argonne in Lemont and Fermilab in Batavia, with a new link to connect to U of I's Urbana campus.

Illinois Physics represented at QIS summits and congressional briefings

Two Illinois Physics faculty members were invited to attend the Advancing American Leadership in QIS Summit, held at the White House in Washington, D.C., on September 24, 2018. DeMarco was joined by the University of Illinois System Vice President for Economic Development and Innovation, Founder Professor of Physics Ed Seidel. Seidel is the former director of the National Center for Supercomputing Applications in Urbana. Prior to that, he served as co-chair of the National Science and Technology Council's Subcommittee on Quantum Information Science while he led the Directorate for Mathematical and Physical Sciences at the National Science Foundation. Top scientists and U.S. officials at the summit coordinated a long-term competitive approach to QIS research and infrastructure development across America, with strong collaboration among private and public efforts.

Illinois Physics was also represented at the inaugural two-day Chicago Quantum Summit, which took place November 8-9, 2018, and was hosted by the CQE. Representing the U of I at the summit were DeMarco, Kwiat, and Van Harlingen. Van Harlingen served as a panelist.

This summit brought together leading experts in quantum information science, representatives of pertinent government agencies, and tech-industry leaders to advance U.S. efforts in QIS—and to position Illinois at the forefront of that race.

DeMarco returned to D.C. for two congressional briefings in January, as part of an Illinois delegation that included representation from UChicago, Northwestern, Fermilab, and Argonne.

"We met with House and Senate staffers in two separate one-hour meetings to educate their respective congressional members about QIS—what's exciting, where opportunities lie, and what strengths the State of Illinois brings—so they can appreciate and advocate for our QIS programs," states DeMarco.

Separating the hype from the vital scientific and technological endeavor

Media attention on esoteric QIS research and its implications for future technologies will inevitably result in some misinterpretations. So what will we use quantum computers for?

DeMarco explains, "The future of many activities central to human life, including transportation, medicine, and manufacturing, will be transformed by improvements in computing, networking, and sensing over the next century. However, computers, networks, and devices based on conventional technology are inherently limited in their ability to tackle some of the most important problems we will face.

"Quantum computers and networks would leverage the physics of quantum mechanics to tackle these problems at a magnitude much larger than any future supercomputer. For example, a large-scale quantum computer could determine the properties of chemical bonds key to new pharmaceuticals for complexes larger than any supercomputer could ever deal with. Beyond medicine, this may also be a route to optimizing artificial photosynthesis for carbon management, which may be central to preventing disaster from climate change."

But will quantum computers someday completely replace classical computers? According to Kwiat, that's unlikely given the laws of quantum mechanics.

Kwiat explains, "Most of what most people do on classical computers—watching cat videos, doing a calculation of something, or writing an email to someone and cc'ing someone else—involves copying information. You can copy classical information, but you can't copy quantum information—that's what makes quantum cryptography secure.

"A classical computer is also more robust against certain encoding errors, and it would be very expensive to achieve the same in a quantum computer. Because of the way a classical computer can do error correction, the parts don't need to be that good. Any bit that's close to a 1 is called a 1, and any bit that's close to a 0 is called a 0. Therefore, if there's a little bit of fluctuation in the data, it's self-correcting. But in quantum computing, all of those fluctuations are totally different quantum states, so those little fluctuations would become big errors. A qubit is non-binary—it can host near limitless states, which is what makes it so powerful."

What will quantum computers do better than classical computers? Researchers have already demonstrated that they can use quantum emulators to solve quantum mechanics problems and to simulate molecular problems. At Illinois Physics, a growing team of atomic, molecular, and optical physicists is doing just that.

Kwiat notes, "Quantum mechanics problems include things like figuring out how proteins could fold up or how medicines might work, or how you could design a better biodegradable chemical fertilizer for maximum crop yields. These kinds of results would have huge impact all over the world. Quantum computers would also be better at optimization problems than classical computers—they could make myriad processes instantly and responsively faster and more efficient, including internet services.

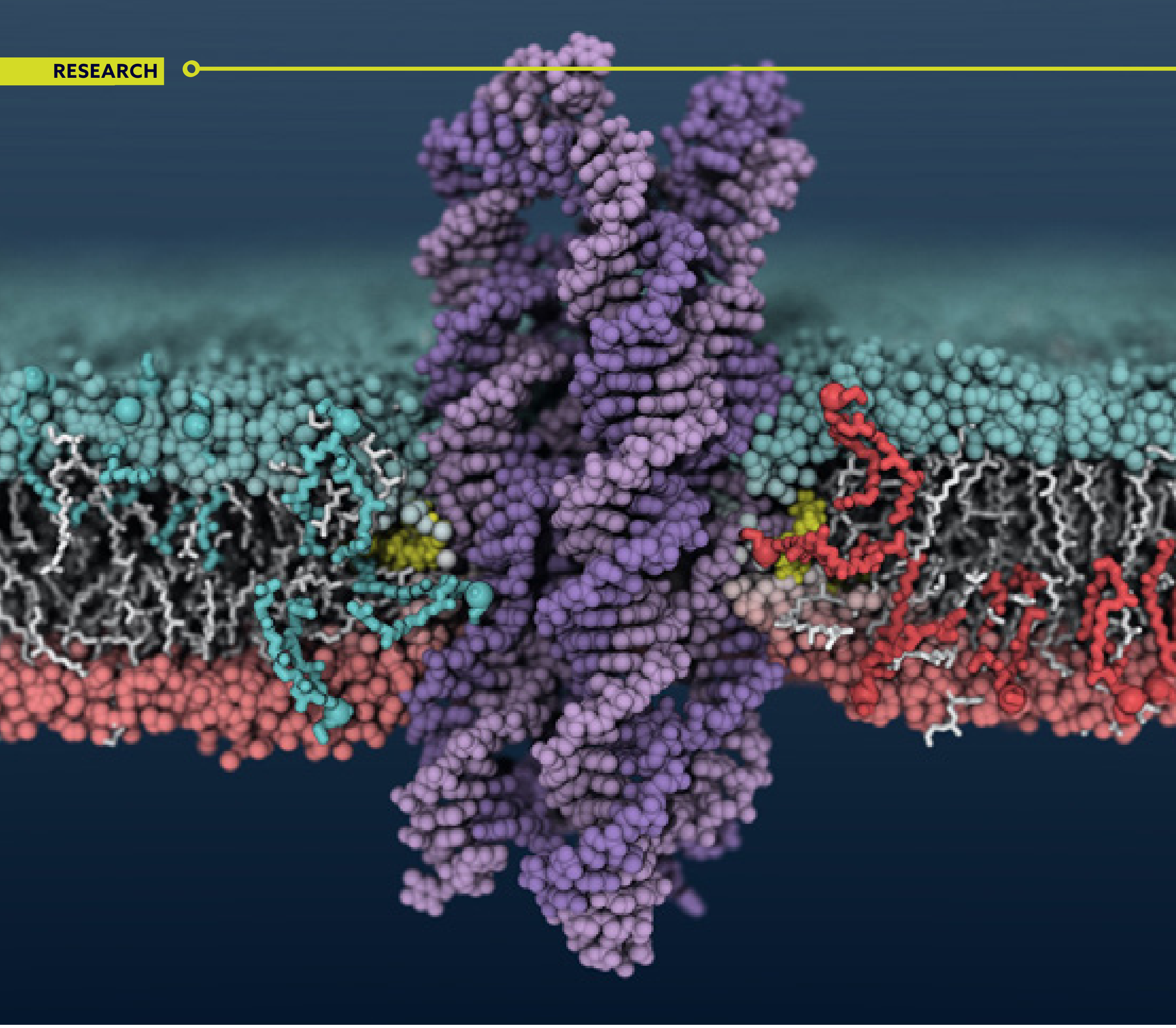
"On the other hand, a case where quantum computing would not serve as well as classical computing, at least for now, is in modeling and forecasting weather, which requires more bits than we currently have the ability to produce in terms of qubits. For now, a quantum computer is good when there is one right answer."

That said, Kwiat says it's impossible to predict all of the possible future applications of quantum technologies, and we should expect the unexpected.

"Take for example the idea of a quantum network, which would have several potential applications, not only for encrypted communications," Kwiat notes, "It's been proposed that we could someday use a quantum network as a telescope, with each node acting as an eye on the sky. The combined effect would be a telescope equivalent to the size of the Earth. With that kind of resolution and magnification, we could see things in deep space far surpassing what we ever believed possible before."

DeMarco and Kwiat are each involved in separate NASA missions that bring QIS research to space. DeMarco chairs the NASA Fundamental Physical Sciences review board, which has oversight responsibility for the recently launched Cold Atom Laboratory (CAL). CAL scientists are currently conducting ultracold atom experiments in microgravity conditions on the International Space Station to learn more about the fundamental properties and interactions of matter at near-absolute zero temperature.

Kwiat is the lead investigator on a NASA mission involving researchers from MIT Lincoln Laboratories, the Jet Propulsion Laboratory, and Oak Ridge National Laboratory, to develop advanced space-based quantum communication capabilities. The initial goal is to transmit entangled and hyperentangled photons between the International Space Station and Earth, which could enable unhackable communication and eventual long-distance quantum networks. ■



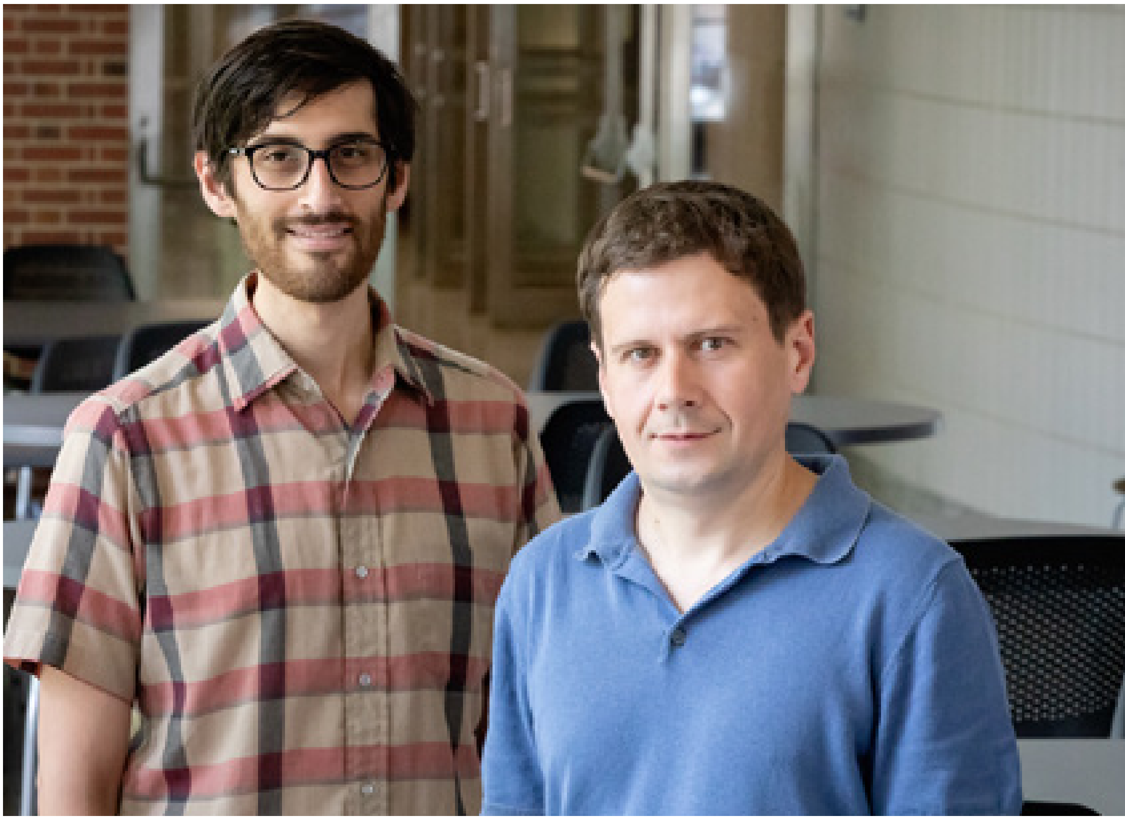
DNA enzyme shuffles cell membranes a thousand times faster than its natural counterpart

LIZ AHLBERG
for Illinois News Bureau

A new synthetic enzyme, crafted from DNA rather than protein, flips lipid molecules within the cell membrane, triggering a signal pathway that could be harnessed to induce cell death in cancer cells.

Researchers at University of Illinois at Urbana-Champaign and the University of Cambridge say their lipid-scrambling DNA enzyme is the first in its class to outperform naturally occurring enzymes—and does so by three orders of magnitude. They published their findings in the June 21, 2018 issue of the journal *Nature Communications*.

"Cell membranes are lined with a different set of molecules on the inside and outside, and cells devote a lot of resources to maintaining this," explains study leader Aleksei Aksimentiev, a professor of physics at Illinois. "But at some points in a cell's life, the asymmetry has to be dismantled. Then the markers that were inside become outside, which sends signals for certain processes, such as cell death. There are enzymes in nature that do that, called scramblases. However, in some diseases where scramblases are deficient, this doesn't happen correctly. Our synthetic scramblase could be an avenue for therapeutics."



Left page: A synthetic DNA enzyme inserts into a cell membrane, causing lipids to shuffle between the inner and outer membrane layers. Image courtesy of Christopher Maffeo, University of Illinois at Urbana-Champaign

Right: Postdoctoral researcher Christopher Maffeo (left) and physics professor Aleksei Aksimentiev pose in the Loomis Laboratory of Physics in Urbana. The team used the Blue Waters supercomputer to model synthetic DNA enzymes. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

Aksimentiev's group came upon DNA's scramblase activity when looking at DNA structures that form pores and channels in cell membranes. They used the Blue Waters supercomputer at the National Center for Supercomputing Applications at Illinois to model the systems at the atomic level. They saw that when certain DNA structures insert into the membrane—in this case, a bundle of eight strands of DNA with cholesterol at the ends of two of the strands—lipids in the membrane around the DNA begin to shuffle between the inner and outer membrane layers.

To verify the scramblase activity predicted by the computer models, Aksimentiev's group at Illinois partnered with Professor Ulrich Keyser's group at Cambridge. The Cambridge group synthesized the DNA enzyme and tested it in model membrane bubbles, called vesicles, and then in human breast cancer cells.

"The results show very conclusively that our DNA nanostructure indeed facilitates rapid lipid scrambling," comments Alexander Ohmann, a graduate student at Cambridge and a co-first author of the paper along with Illinois graduate student Chen-Yu Li. "Most interestingly, the high flipping rate indicated by the molecular dynamics simulations seems to be of the same order of magnitude in experiments: up to a thousandfold faster than what has previously been shown for natural scramblases."

On its own, the DNA scramblase produces cell death indiscriminately, according to Aksimentiev. The next step is to couple it with targeting systems that specifically seek out certain cell types, a number of which have already been developed for other DNA agents.

"We are also working to make these scramblase structures activated by light or some other stimulus, so they can be activated only on demand and can be turned off," Aksimentiev says.

"Although we have still a long way to go, this work highlights the enormous potential of synthetic DNA nanostructures with possible applications for personalized drugs and therapeutics for a variety of health conditions in the future," Ohmann notes.

The National Science Foundation and the National Institutes of Health supported this work. The conclusions presented are those of the researchers and not necessarily those of the funding agencies.

New Slichter Fellowship established for graduate students

Family, friends, and colleagues of the late Professor Charles P. Slichter have established a physics graduate student fellowship in his memory at the University of Illinois at Urbana-Champaign. The Charles P. Slichter Fellowship will provide stipends without a teaching requirement, enabling promising graduate students to place more of their focus on original research earlier in their programs.

Head of Department and Professor Matthias Grosse Perdekamp comments, "Charlie was a cherished member of our faculty for 57 years. Everyone loved Charlie. He was among his generation's most talented and insightful condensed matter experimentalists. But for those of us who worked with Charlie, it was his kindness and love of life mixed with that great intellect, that great creativity, that impacted us so profoundly.

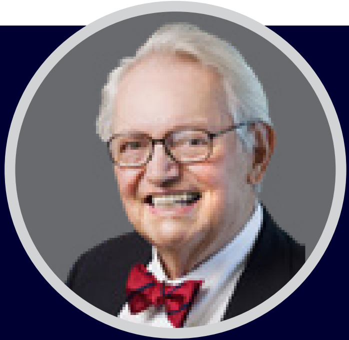
"Charlie's commitment to the academic enterprise—to teaching and to research—left a tremendous legacy. We want this fellowship to extend Charlie's legacy into future generations of stellar students. Our highly competitive graduate program at Illinois Physics is one of the largest in the nation and it attracts promising students from around the world. The fellowship support will help us to recruit and retain the best and brightest young minds, regardless of means."

Slichter's former student Po-Kang "Po" Wang remembers how Slichter was always in high demand, serving in numerous advisory roles in government, academia, and industry, but all the while never failing to demonstrate a deep and steadfast loyalty to his students and colleagues at Illinois.

"In the early 1980s, Charlie traveled often to D.C. and other places to attend meetings of the National Science Board and other boards, including IBM, Polaroid, and Harvard. It was always fun when he returned and showed up at the lab at lunch time, full of energy and eager to share with us his stories, his new ideas jotted down while on the plane, often with some back-of-the-envelope calculations. He was eager to hear about the latest in the lab.

"We would all sit on tall lab stools in a circle with him having one extra stool as his cutting board, where he would use his Swiss Army knife to cut off slices of cheese and ham to make his sandwiches. For him, it seemed, coming home to the small labs, chatting with his students, and puzzling together over the experimental results was the best the world had to offer. And for us, the students, with the passing of many lunches with Charlie, we slowly learned to look beyond the travail of our experiments and to be proud of belonging to the great family of physicists."

The goal for the Charles P. Slichter Fellowship is to support several research fellowships annually. Each full-year fellowship valued at $25,000 requires a $600,000 principal investment. Donations to the endowed fund are tax deductible and will be invested and managed in accordance with donor intent by the University of Illinois Foundation, an independent not-for-profit corporation whose mission is to advance the interests and welfare of the university.



Professor of Physics and Chemistry Charles P. Slichter was a pioneer in the development and application of nuclear magnetic resonance (NMR) spectroscopy to elucidate the structure and behavior of matter at the atomic scale and a renowned expert on superconductivity. Slichter's seminal contributions to the fields of condensed matter physics and chemistry have been recognized with numerous awards, including the 2007 National Medal of Science. His impact is also evident in the successful careers and scientific contributions of those he taught. At Illinois, Slichter directed the research of 63 doctoral students and more than 15 postdoctoral researchers, including Nobel Laureate Sir Peter Mansfield.

Slichter exemplified and fostered the "Urbana style"—a way of tackling longstanding scientific problems through close interdisciplinary collaboration among theorists and experimentalists—which continues to define the culture of the department today. Known by everyone for his brilliant smiles, infectious enthusiasm, and trademark bow ties, Slichter represented science at its finest: creative, rigorous, curious, and scrupulously honest.

For more information about this fund and how it will be awarded, please contact Ross Williams at rwilli@illinois.edu or 217.244.2296.

NADYA MASON ELECTED APS FELLOW

Professor Nadya Mason has been elected a Fellow of the American Physical Society (APS) "for seminal contributions to the understanding of electronic transport in low dimensional conductors, mesoscopic superconducting systems, and topological quantum materials."

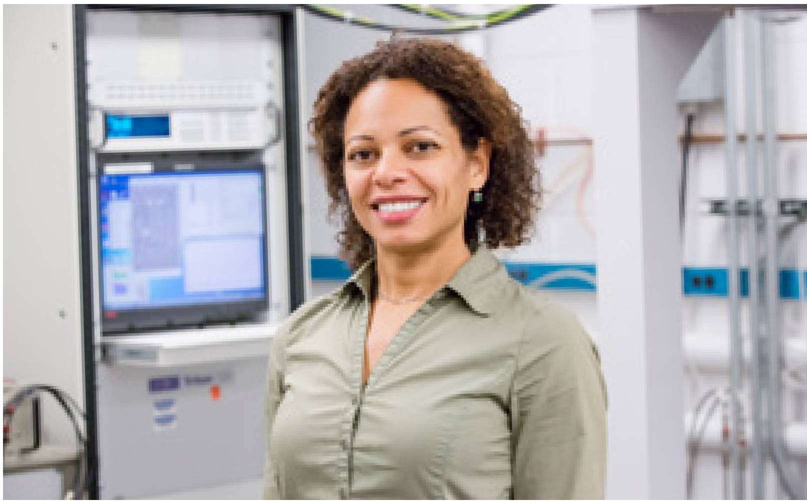
Mason is an experimental condensed matter physicist who has earned a reputation for her deep insights and thorough lines of attack on the most pressing problems in strongly correlated nanoscale physics.

Early in her career, Mason developed innovative new methods to fabricate and control quantum dots in carbon nanotubes. She then turned her focus to the study of correlations in carbon nanotubes and graphene; her findings, most significantly the non-equilibrium Kondo effect demonstrated in 2006 and the determination of individual superconducting bound states in graphene-based systems in 2011, have opened up new areas of research.

More recently, Mason's work has focused on electronic transport in graphene, nanostructured superconductors and semiconductors, and other novel 1D, 2D, and 3D systems. In 2013, in collaboration with colleagues at Brookhaven National Laboratory, Mason was among the first to measure superconducting surface states in topological insulators that were not confounded by interference from sample impurities. Most recently, with colleagues in the Department of Physics, the Materials Research Laboratory, and the Department of Electrical and Computer Engineering at the U of I, she is the first to experimentally elucidate the origin of finite momentum Cooper pairing in 3D topological insulator Josephson junctions.

Mason serves her scientific community in several roles. She is the director of the Illinois Materials Research Science and Engineering Center (I-MRSEC) on the Urbana campus. Funded by the National Science Foundation with additional support from the University of Illinois at Urbana-Champaign and the Frederick Seitz Materials Research Laboratory, the center is dedicated to performing fundamental, innovative materials research with applications to societal needs and to supporting interdisciplinary education and training of students in materials design.

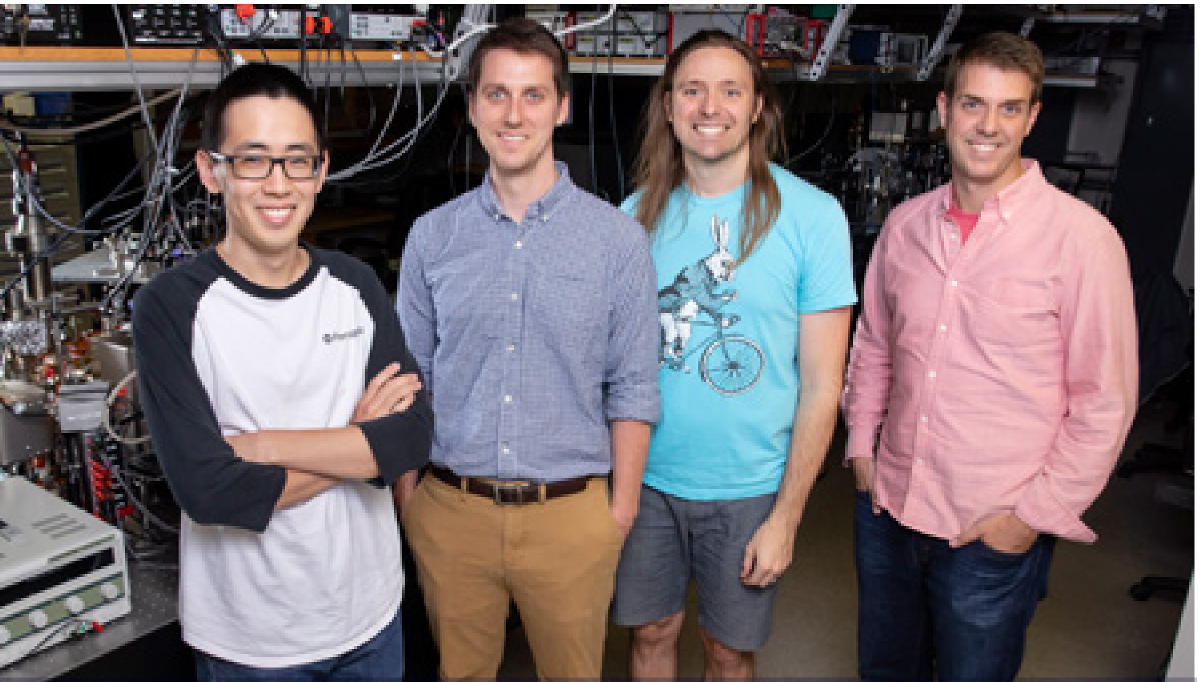
Additionally, Mason is a member of the 2018/19 class of the Defense Science Study Group, a program of education and study in national defense and security challenges directed by the non-profit Institute for Defense Analyses and sponsored by the Defense Advanced Research Projects Agency.



From 2014 through 2017, Mason served as a general councilor of the APS. Mason has long been an avid spokesperson for diversity, inclusion, and equity in the sciences and as such served as chair of the APS Committee on Minorities. She also served as one of the theme leaders for the DOE Basic Energy Sciences cluster on quantum materials and nanoarchitectures (2013).

Mason is the John Bardeen Faculty Scholar in Physics at the U of I (2014–). She is also the recipient of the U of I College of Engineering Dean's Award for Excellence in Research, the Maria Goeppert Mayer Award of the APS (2012), a Center for Advanced Study Fellowship (2011-2012), the Denice Denton Emerging Leader Award (2009), a Woodrow Wilson Career Enhancement Fellowship (2008-2009), and a National Science Foundation CAREER Award (2007).

Mason received a bachelor's degree in physics from Harvard University in 1995 and a doctoral degree in physics from Stanford University in 2001. She returned to Harvard for postdoctoral training, where she was elected junior fellow in the Harvard Society of Fellows. She joined the faculty at Illinois Physics in 2005.



Professors Bryce Gadway (far right) and Taylor Hughes (second from right) pose with graduate students Alex An (far left) and Eric Meier, in Gadway's lab at the Loomis Laboratory of Physics. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

Disorder induces topological Anderson insulator

In experiments using ultracold atoms trapped and driven by lasers, researchers have created a new disorder-induced topological state previously predicted to occur in electronic materials.

SIV SCHWINK
for Illinois Physics Condensate

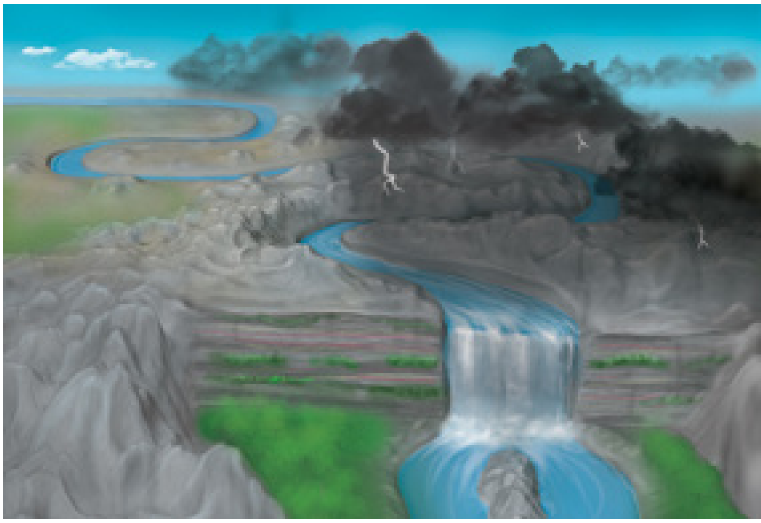
Topological insulators (TIs) host exotic physics that could shed new light on the fundamental laws of nature. What's more, the unusual properties of TIs hold tremendous promise for technological applications, including quantum computing, next-generation miniaturized data storage, and spintronics. Scientists around the globe are working to understand the microscopic properties of these materials that freely conduct electricity along their edges even though their bulk is an insulator.

Now a team of experimental physicists at the University of Illinois at Urbana-Champaign have made the first observation of a specific type of TI that's induced by disorder. Professor Bryce Gadway and his graduate students Eric Meier and Alex An used atomic quantum simulation, an experimental technique employing finely tuned lasers and ultracold atoms about a billion times colder than room temperature, to mimic the physical properties of one-dimensional electronic wires having precisely tunable disorder. The system starts with trivial topology just outside the regime of a topological insulator; adding disorder nudges the system into the nontrivial topological phase.

This type of topological insulator induced by disorder is called the topological Anderson insulator, named after the noted theoretical physicist and Nobel laureate Philip Anderson, an alumnus of University Laboratory High School on the U of I campus. Surprisingly, while disorder typically inhibits transport and destroys nontrivial topology, in this system it helps to stabilize a topological phase.

The observation was made possible through close collaboration with an international team of theoretical physicists at the U of I, at the Institute of Photonic Sciences (ICFO), and at the Universitat Politècnica de Catalunya (UPC) in Spain, who elucidated the quantum physics at work and identified the key signature the experimentalists should look for in the system.

Artist's depiction of a disorder-induced transition to the topological Anderson insulator phase. A river flowing along a straight path is altered by disorder in the underlying landscape. After going through a transition (waterfall), the river forms a closed loop—a shape having a different topology from that of the initially straight path. In the topological Anderson insulator phase, the trivial band structure of a normal material is transformed into a topologically nontrivial band structure from disorder and disruptions in the tunnel couplings between lattice sites. The winding number in the topological Anderson insulator phase is distinct from that of the normal case without disorder. Image by Lachina Creative, copyright Bryce Gadway, University of Illinois at Urbana-Champaign



Theoretical physicist Pietro Massignan of UPC and ICFO comments, "Intuitively, one would think that disorder should play against conductance. For example, running is easy in an open field, but gets harder and harder as one moves through an increasingly denser forest. But here we show that suitably tailored disorder can actually trigger some peculiar conducting excitations, called topologically protected edge modes."

Meier is lead author on the paper. "Interestingly," he adds, "in a 3D or 2D topological system, those edge states would be characterized by freely flowing electrons. But in a 1D system like ours, the edge states simply sit there, at either end of the wire. In any TI, the boundary states have the dimensionality of your system minus 1. In our 1D topological Anderson insulator, the boundary states are basically just points. While the boundary physics is actually a bit boring in this system, there is rich dynamics going on in the bulk of the system that is directly related to the same topology—this is what we studied."

The group's experimental observation validates the concept of topological Anderson insulators that was worked out roughly a decade ago. The topological Anderson insulator phase was first described theoretically by J. Li et al. in 2009, and its origin was further explained by C. W. Groth, et al. that same year. Five years later, a pair of works, one by A. Altland et al. and one by the group of Taylor Hughes at the U of I working with the group of Emil Prodan at Yeshiva University, predicted the occurrence of the topological Anderson insulator in one-dimensional wires, as realized in the new experiments from the Gadway group.

Gadway emphasizes, "Our taking on this research was really inspired by the 2014 prediction of Taylor Hughes and his graduate student Ian Mondragon-Shem at the U of I. Taylor was a key collaborator. Likewise, our colleagues in Spain made a tremendous contribution in introducing the concept of mean chiral displacement, which allows us to measure the topology directly in the bulk of the material."

"Working with Taylor," Gadway adds, "our Spanish colleagues found that the mean chiral displacement is essentially equivalent to the topological invariant of such a 1-D system, something called the winding number. This was critical to our being able to take the data on the system and relate what we saw in experiment to the system's topology. This was one project where having a bevy of theorists around was a big help, both for performing the right measurements and for understanding what it all meant."

"This is an exciting result in terms of potential applications," Gadway affirms. "This suggests we may be able to find real materials that are almost topological that we could manipulate through doping to imbue them with these topological properties. This is where quantum simulation offers a tremendous advantage over real materials—it's good for seeing physical effects that are very subtle. Our designer disorder is precisely controllable, where in real materials, disorder is as messy as it sounds—it's uncontrollable."

"Gadway's experimental setup is a theorist's dream," Massignan adds. "It was like playing with LEGO: the model we envisaged could be built step-by-step, in a real laboratory. Every single element of the Hamiltonian we had in mind could be implemented in a very careful way, and changed in real time."

ICFO postdoctoral researcher Alexandre Dauphin adds, "This platform is also very promising for studying the effects of both interaction and disorder in topological systems, which could lead to exciting new physics."

NSF Program Director Alex Cronin oversees the funding program that supported this experimental effort. He points out the importance of this fundamental research that successfully employs engineered quantum systems to uncover new physics: "Before we get full-scale quantum computers to study a broad range of exotic systems, we already have quantum simulators like this one that are producing results right now. It is exciting to see new discoveries made with quantum simulators like this."

These results were published online by the journal Science on Thursday, October 11, 2018. After submitting their work to the journal, the researchers of this study learned of the parallel observation of this same phenomenon by another research team at the University of Rostock, Germany.

"Their team used photonic waveguides to mimic the physical properties of this same kind of system, and they studied properties at the boundary of the system. We used cold atoms and observed bulk properties to get at a really clear visualization of the topology," Gadway states. "These two works were complementary and together they illustrate how diverse physical systems can be controlled and made to exhibit the same kind of interesting phenomena."

This research was supported by the National Science Foundation, by the Office of Naval Research, and by the Spanish MINECO, the Generalitat de Catalunya, the EU, and the Fundació Privada Cellex. The results are those of the researchers and not necessarily those of the funding agencies.

CAMPUS NEWS, EXPERT VIEWPOINTS:

What are neutrinos and why do they matter?

Scientists recently announced the discovery of a subatomic particle that made its way to Earth from an event that occurred 3.7 billion light-years away. Sensors buried within Antarctic ice detected the ghostly cosmic particle, called a neutrino, and traced its origin to a rapidly spinning galactic nucleus known as a blazar. Illinois News Bureau physical sciences editor Lois Yoksoulian spoke with physics professor Liang Yang about the significance of the discovery.

LOIS YOKSOULIAN
for Illinois News Bureau

What is a neutrino?

Neutrinos are the second most abundant elementary particles in the universe after photons. Even though billions of them pass through us every second, we would not notice them because they rarely interact with matter. This property makes them one of the most elusive and mysterious elementary particles. On the other hand, they can traverse a vast distance without bumping into anything, which makes them an excellent probe for astrophysical phenomena deep in the universe.

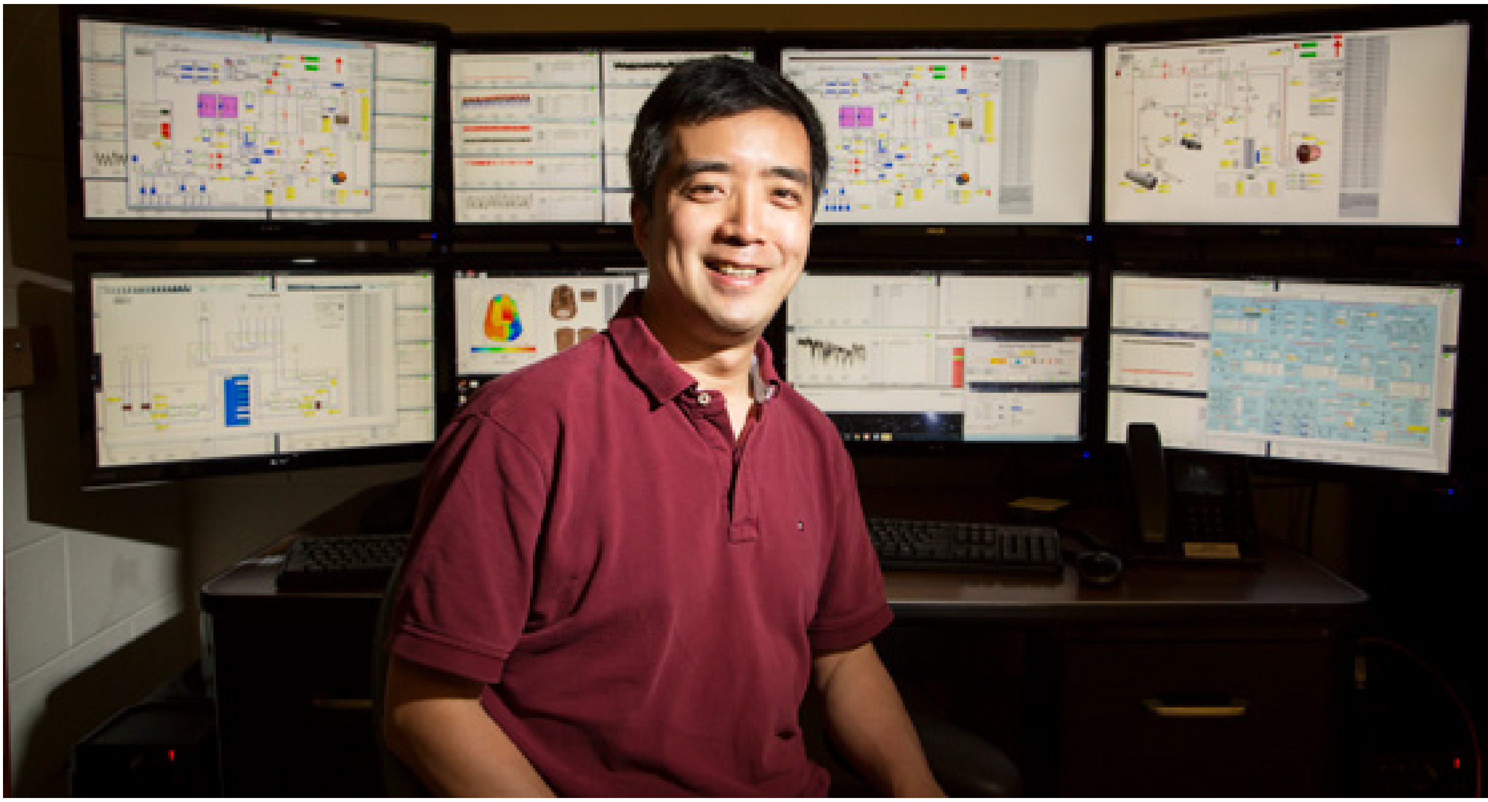
Much of the news coverage about this discovery discusses how this will advance our understanding of cosmic rays.

What are cosmic rays and how are they related to the neutrinos?

Cosmic rays are the energetic particles constantly bombarding Earth's atmosphere. They mostly consist of protons and can have energies more than a million times greater than what scientists can produce even in the most powerful accelerators on earth.

We knew that the ultra-high energy cosmic rays come from outside our galaxy, but we did not know where they came from because they do not travel in straight lines. This question has puzzled scientists since the first observation of cosmic rays more than 100 years ago. However, it is very likely that the processes responsible for the acceleration of cosmic rays are also responsible for the creation of ultra-high energy neutrinos. Because neutrinos travel in straight lines, we can determine the direction of their sources.

Shortly after the IceCube Neutrino Observatory detected the high-energy neutrino in 2017, telescopes were able to locate a distant gamma source called a blazar in the same direction. Furthermore, by analyzing recorded data in the past, more neutrino and gamma events were identified from the same blazar. Since high-energy neutrinos are created from proton collisions with gas, determining



Physics Professor Liang Yang discusses the significance of the recent neutrino detection in Antarctica and what it means for the future of observational astronomy. Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

the blazar as the source of the high-energy neutrinos tells us that the blazar is also a source of high-energy protons, i.e., the cosmic rays. This marks the first time that scientists have been able to pinpoint a source of ultra-high-energy cosmic rays.

What is the IceCube Neutrino Observatory and how does it detect neutrinos?

The IceCube Neutrino Observatory is the largest particle detector ever built. It consists of one cubic kilometer of ice in Antarctica and 86 strings of light sensors buried inside the ice. When, by chance, a high-energy neutrino crashes into a nucleus of one of the atoms that make up the ice, it can generate a stream of secondary particles. These secondary particles, in turn, create a burst of blue light detected by the light sensors. From the energy and direction of the secondary particles, we can infer the energy and direction of the original high-energy neutrino.

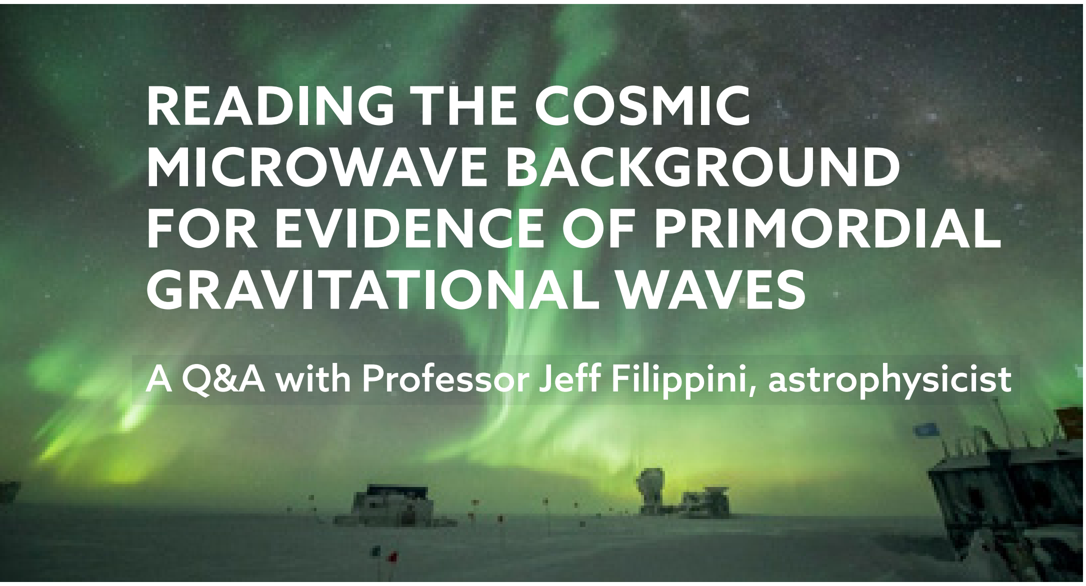
Why is the detector located in Antarctica under ice?

Because neutrinos interact very weakly with matter, we need gigantic detectors to “see” them. The polar ice cap turns out to be a perfect medium for such a detector. Unlike regular ice, polar ice has almost no impurities or gas bubbles when under enormous pressure deep inside the ice cap, allowing the light signals to travel a long distance with minimal interference. Such an ideal condition is available only in Antarctica. Meanwhile, scientists are looking at other creative ways to detect ultra-high energy neutrinos.

What are the major implications of this discovery?

The recent discoveries made by IceCube and other instruments like the Fermi Gamma-ray and MAGIC telescopes demonstrate the power of observational astronomy. It is only through the observation of both neutrinos and high-energy photons that scientists are able to uncover the mystery of cosmic rays. Astronomers are now armed not just with optical telescopes for photons across the entire electromagnetic spectrum, but also gravitational wave detectors and neutrino telescopes. Together, they will help us tackle big questions such as the origin and evolution of the universe and the nature of dark matter and dark energy. Many exciting discoveries await.

This expert viewpoint was originally published July 18, 2018, on the Illinois News Bureau website.



READING THE COSMIC MICROWAVE BACKGROUND FOR EVIDENCE OF PRIMORDIAL GRAVITATIONAL WAVES

A Q&A with Professor Jeff Filippini, astrophysicist

Over the past 12 years, the BICEP (Background Imaging of Cosmic Extragalactic Polarization) collaboration has deployed four generations of increasingly powerful instruments to observe the early universe from the Amundsen-Scott South Pole Station. BICEP1, BICEP2, the Keck Array, and BICEP3 were designed to measure the polarization of the cosmic microwave background in search of the faint signature of primordial gravitational waves. The collaboration is currently constructing an even more ambitious instrument called the BICEP Array.

The collaboration recently published findings based on all data taken through the 2015 season, providing the most stringent constraint to date on the amplitude of primordial gravitational waves in our universe. Professor Jeff Filippini is an astrophysicist at the University of Illinois at Urbana-Champaign, interested in observational searches for signatures of new fundamental physics. He joined the BICEP collaboration while BICEP2 was being developed and contributed to its superconducting detectors and readout systems. Filippini is a coauthor on the BICEP collaboration's latest result.

What generally has the BICEP collaboration achieved in this latest published research?

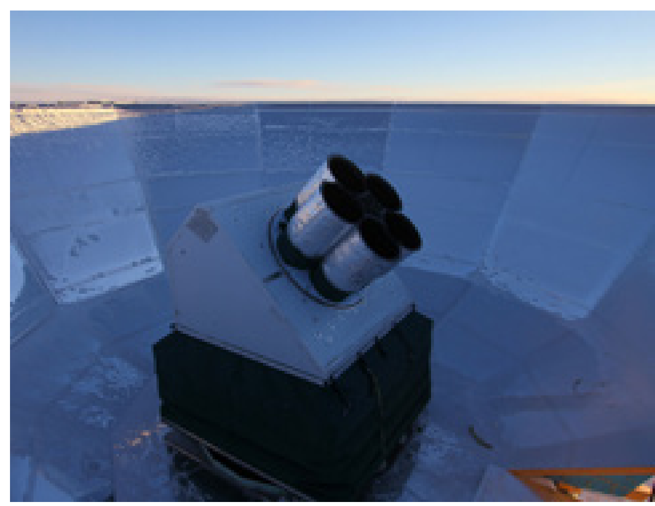
Through several years of observation with BICEP2 and the Keck Array, the collaboration has made the most precise (lowest noise) map to date of the polarization of the cosmic microwave background (CMB). The map covers about 1 percent of the sky, chosen to be relatively (though not completely!) free of contaminating polarized emission from our own galaxy. The remaining galaxy glow is cleaned from the data by combining maps made at multiple observing frequencies (90, 150, and 220 GHz), as well as noisier maps at 23 GHz–353 GHz from the WMAP and Planck satellites. The main result is a new world-leading upper limit on the amplitude of primordial gravitational waves in the early universe, a key prediction of the theory of cosmic inflation.

Why is it important to study the CMB?

The CMB has proven to be an incredibly versatile probe of cosmology, teaching us an enormous amount about the contents, history, and workings of our universe. The CMB is the black-body glow of the hot early universe, emitted about 380,000 years after the big bang, when the universe transitioned from opaque plasma to transparent neutral gas. The faint anisotropies in this glow—about 1 part in 100,000—carry the imprint of sound waves in the primordial plasma, and through those, information about the universe's contents and geometry. The CMB radiation also carries information about subsequent cosmic history, through the absorption and gravitational lensing it experienced on its long journey to our telescopes.

What is *B*-mode polarization, and how does it relate to primordial gravitational waves?

Doppler shifts within the plasma imprint a weak polarization on the CMB via Thomson scattering. By symmetry, sound waves can generate only a "curl-free" (*E*-mode) pattern of polarization. Gravitational waves have no such restriction, however, and generate a mix of *E*-modes and twisty *B*-modes. If such *B*-mode polarization



Images of the South Pole Telescope by astrophicist Robert Schwarz, BICEP staffmember and the South Pole Telescope's "Iceman"

were observed it would be evidence that our universe was born with a primordial hum of gravitational waves, imperceptibly faint in the modern era, but detectable via their effect on the CMB.

What does this measurement mean for the theory of cosmic inflation?

Cosmic inflation postulates that the universe expanded extremely rapidly in its early moments, and that this epoch seeded spacetime with quantum "noise" in the form of both sound waves and gravitational waves. The sound waves are detectable in the CMB—they formed the seeds of the vast cosmic structures we see through our telescopes. The gravitational waves remain undetected, and this result constrains their power to be no more than 6 percent of that in the sound waves. Different specific models for the physics behind inflation predict different amounts of gravitational and sound waves, so this measurement disfavors certain models while leaving others viable.

In what ways has the instrumentation of the BICEP experiment improved over the years?

Each new iteration of the program adds more sensitivity by cramming in more detectors, as well as fanning out to new observing frequencies to better characterize galactic contamination. BICEP1 observed with 98 individually wired bolometric detectors, maintained at 300 mK using a ^{3}He refrigerator. BICEP2 brought that count to 512 detectors using monolithic arrays of superconducting transition-edge sensors (TESs) and multiplexed SQUID readout. Keck Array consisted of five such telescopes spanning several observing frequencies. BICEP3 pioneered a new 2500-sensor receiver design, which BICEP Array will deploy in quantity at several frequencies.

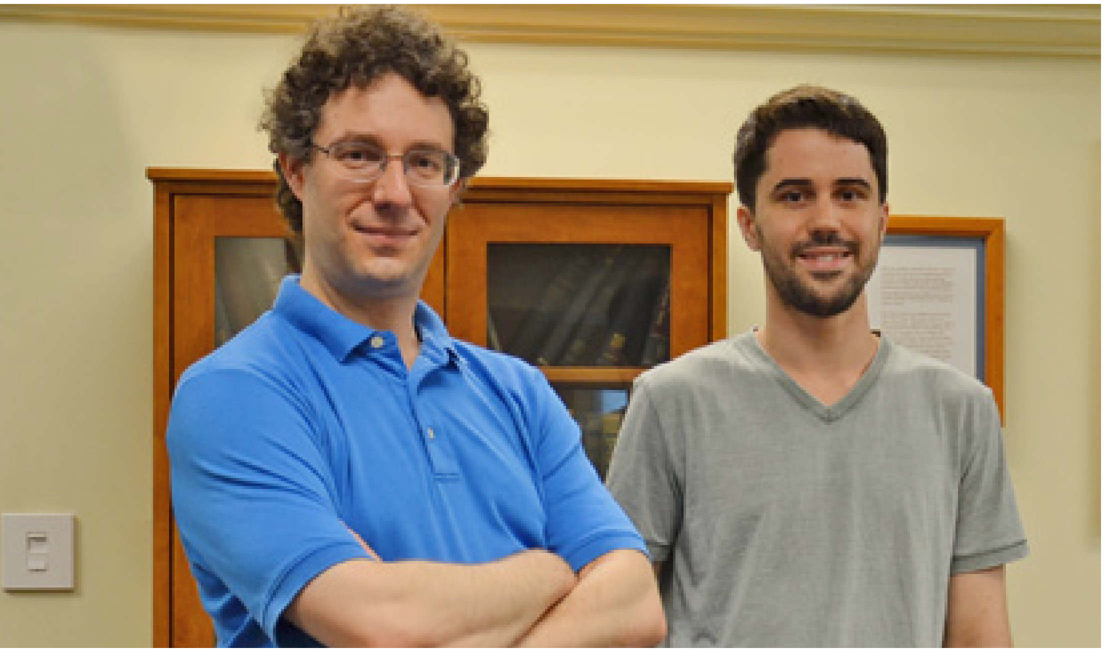
You said the new measurement has improved only slightly over the team's previous result —why is it important?

The key advance is the addition of new Keck Array data at 220 GHz, which map galactic dust emission with a sensitivity similar to Planck's. Removing this dust contamination accurately is currently the key limiting factor on the analysis. Right now the Keck map gives only an incremental improvement over using Planck's dust map alone, but it's a turning point: in coming seasons we'll be doing a lot better.

What are the next steps for the collaboration and the field?

BICEP is completing another big analysis of more recent data, including first observations from BICEP3. Starting next year, the team will begin fielding BICEP Array, a massive new instrument with more than 30,000 detectors. In parallel, I'm excited about observations from SPIDER, an instrument pursuing similar science with observations from a stratospheric balloon over Antarctica. My group at the U of I is working hard to analyze data from SPIDER's 2015 flight and to prepare new telescopes for a second flight in 2019. On a longer time horizon, we and CMB scientists worldwide are developing technologies for a future generation of instruments on the ground (CMB Stage IV), from balloons, and from space. ■

The BICEP collaboration's latest results are published in the November 27, 2018 issue of Physical Review Letters. This work is supported by the National Science Foundation and by the Keck Foundation. Additional support came from the JPL Research Technology Development Fund, NASA, the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the U.K. Science & Technology Facilities Council, and member institutions. The conclusions presented are those of the researchers and not necessarily those of the funding agencies.



Professor Bryan Clark (left) and graduate student Eli Chertkov pose in the common room of the Institute for Condensed Matter Theory. Photo by Siv Schwink for Illinois Physics Condensate

New algorithm could help find new physics

Inverse method takes wave functions and solves for Hamiltonians

SIV SCHWINK
for Illinois Physics Condensate

Scientists at the University of Illinois at Urbana-Champaign have developed an algorithm that could provide meaningful answers to condensed matter physicists in their searches for novel and emergent properties in materials. The algorithm, invented by Illinois Physics Professor Bryan Clark and his graduate student Eli Chertkov, inverts the typical mathematical process condensed matter physicists use to search for interesting physics. Their new method starts with the answer—what kinds of physical properties would be interesting to find—and works backward to the question—what class of materials would host such properties?

Inverse problem solving isn't a new technique in classical physics, but this algorithm represents one of the first successful examples of an inverse problem-solving method with quantum materials. And it could make searching for interesting physics a more streamlined and deliberate process for many scientists. More physicists are working in condensed matter than any other subfield of physics—the rich diversity of condensed matter systems and phenomena provide ample unsolved problems to explore, from superconductivity and superfluidity to magnetism and topology. Experimentalists probe the macro- and microscopic properties of materials to observe the behavior and interactions of particles in materials under a strict set of controls. Theoretical condensed matter physicists, on the other hand, work to develop mathematical models that predict or explain the fundamental laws that govern these behaviors and interactions.

The field of theoretical condensed matter physics has the well-earned reputation for being esoteric and difficult for the lay person to decipher, with its focus on understanding the quantum mechanics of materials. The process of writing and solving condensed matter equations is extremely intricate and meticulous. That process generally starts with a Hamiltonian—a mathematical model that sums up the energies of all the particles in the system.

Clark explains, "For a typical condensed matter problem, you start with a model, which comes out as a Hamiltonian, then you solve it, and you end up with a wave function—and you can see the properties of that wave function and see whether there is anything interesting. This algorithm inverts that process. Now, if you know the desired type of physics you would like to study, you can represent that in a wave function, and the algorithm will generate all of the Hamiltonians—or the specific models—for which we would get that set of properties. To be more exact, the algorithm gives us Hamiltonians with that wave function as an energy eigenstate."

Clark says the algorithm gives a new way to study physical phenomena such as superconductivity.

"Typically, you would guess Hamiltonians that are likely to be superconducting and then try to solve them. What this algorithm—in theory—will allow us to do is to write down a wave function that we know superconducts and then automatically generate all of the Hamiltonians or the specific models that give that wave function as their solution. Once you have the Hamiltonians, in some sense, that gives you all the other properties of the system—the excitation spectrum, all the finite temperature properties. That requires some more steps once you have the Hamiltonian, so we didn't improve that part of the research process. But what we did, we found a way to find interesting models, interesting Hamiltonians."

Chertkov adds, "There are lots of wave functions people have written down for which there are no known Hamiltonians—maybe 50 years' worth. Now we can take any of these wave functions and ask if any Hamiltonians give those as eigenstates and you may end up with one model, no models, or many. For example, we are interested in spin-liquid wave functions, highly entangled quantum states with interesting topological properties. Theorists have constructed many spin-liquid wave functions, but don't know which Hamiltonians give them. In the future, our algorithm should let us find these Hamiltonians."

Clark and Chertkov tested the algorithm on wave functions related to frustrated magnetism, a topic that presents interesting physics with many open questions. Frustrated magnetism occurs in a class of materials that is insulating, so the electrons don't move around, but their spins interact. Clark explains one such wave function they tested, "The electron spins in a frustrated magnet want to be anti-aligned, like the north and south on a magnet, but can't because they live on triangles. So we make a wave function out of a linear superposition of all of these frustrated states. Then we turn the crank of this algorithm and ask, given this wavefunction—which is an interesting quantum state on a frustrated magnet—are there Hamiltonians that would give it. And we found some."

Chertkov says the results of the algorithm could point experimentalists in the right direction to find interesting new physics: "That would hopefully be one way it would be used. You pick a wave function that has some kind of physics that you care about and you see what sort of interactions can give you that sort of physics, and hopefully then the models you find through this method can be looked for in experiments. And it turns out you find many models with our method."

Clark sums up, "This has inverted the part of the process where we were sort of hunting in the dark. Before, you could say, we're going to try lots of models until we find something interesting. Now you can say, this is the interesting thing we want, let's turn the crank on this algorithm and find a model that gives that." ■

This work was supported by the U.S. Department of Energy Office of Science's SciDAC program and is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation and the State of Illinois. The conclusions presented are those of the researchers and not necessarily those of the funding agencies.

ALUMNI RECEPTION

Mark your calendar for the annual gala Physics alumni reunion! Tuesday, March 5, 6:00–8:00 P.M., at the Westin Boston Waterfront Hotel, Ballroom C.

The gala Physics alumni reunion is held annually in conjunction with the American Physical Society's March meeting. Sponsored by the Department of Physics and the Physics Alumni Association, the Illinois reunion has long been known as the best party at the March Meeting. Please join us and help us maintain that reputation of warmth and collegiality. It's a great chance to renew old acquaintances and learn about the exciting new initiatives for Illinois Physics!

You need not be an APS member or registered for the meeting to attend—we are also extending an invitation to all our alumni living in the greater Boston area. Great refreshments and door prizes!

Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

Faulkner receives DOE Early Career Award

Professor Thomas Faulkner has been selected by the U.S. Department of Energy (DOE) Office of Science to receive an Early Career Award. The DOE Early Career Research Program, now in its ninth year, provides award recipients with significant funding over a five-year period. Faulkner is among 84 scientists at U.S. universities and DOE-supported national laboratories to be selected this year. He is one of only two scientists at the University of Illinois at Urbana-Champaign to receive the honor this year.

The Early Career Award recognizes promising scientists within 10 years of having earned their doctoral degrees, working in research areas supported by the DOE Office of Science. Faulkner's research proposal in theoretical high-energy physics is entitled, "New perspectives on QFT and gravity from quantum entanglement."

Faulkner will use the grant to study fundamental aspects of quantum field theory (QFT) and the nature of spacetime and gravity via the patterns of quantum entanglement present in these theories. These patterns will be harnessed to find new constraints on the dynamics of QFT and quantum gravity.

According to Faulkner, these topics find a natural home within the holographic duality, a deep mathematical correspondence discovered in string theory where a gravitational system can be described by a quantum system without gravity. By studying the spatial distribution of quantum correlation in various quantum systems, Faulkner hopes to directly observe the holographic emergence of quantum gravity within this setting and to characterize the spacetime structure that emerges along with it.

With this research, Faulkner aims to shed new light on the thermodynamic nature of gravity and to explore the implications of this paradigm for our understanding of the unification of gravity with quantum mechanics. He intends to develop new tools for studying the structure of quantum entanglement in QFT. In so doing, the powerful constraints satisfied by entanglement and its generalizations will place bounds on the basic data of the QFT. In turn these bounds will be related to causality constraints and quantum energy conditions, which are local and non-local bounds on the energy density for arbitrary out-of-equilibrium states of the QFT.

Faulkner received his bachelor's degree in physics from the University of Melbourne in 2003 and his doctoral degree from MIT in 2009. He held postdoctoral positions at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara (2009–2012) and at the Institute for Advanced Studies at Princeton University (2012–2013). He joined the faculty at Illinois Physics in 2014. He is also a recipient of the DARPA Young Faculty Award (2015). ■

DeMarco selected University Scholar

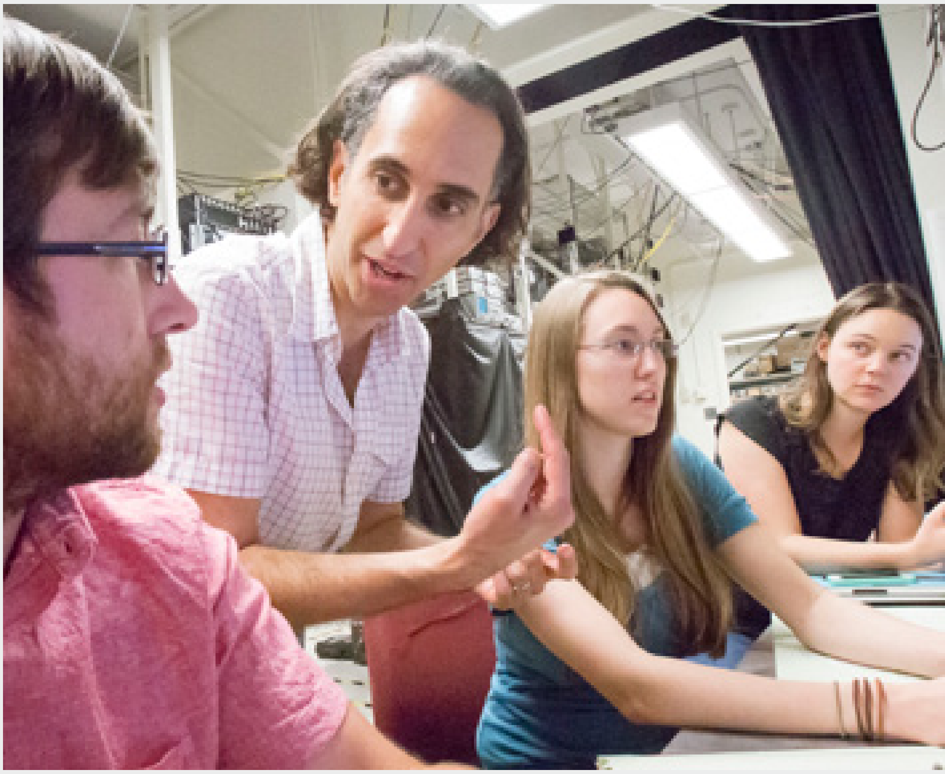


Photo by L. Brian Stauffer, University of Illinois at Urbana-Champaign

Professor and Associate Head for Undergraduate Programs Brian DeMarco has been named a University Scholar by the Office of the Vice President for Academic Affairs at the University of Illinois at Urbana-Champaign. The award recognizes faculty who have made significant contributions to research and teaching in line with the university's reputation for leading-edge innovation and excellence. DeMarco is among five faculty members on the Urbana campus to be named to this honor in this selection round.

"The University Scholars program honors the best of the best and showcases the leading-edge scholarship and teaching that help transform students' lives and drive progress for our state and nation," notes Barbara Wilson, the executive vice president and vice president for academic affairs for the U of I System.

DeMarco is an experimental physicist who works at the intersection of atomic, molecular, and optical physics and condensed matter physics. His research group at the Loomis Laboratory of Physics is using quantum simulation—experiments that involve ultracold atoms trapped in optical lattices that simulate models of strongly correlated electronic solids—to solve outstanding problems in condensed matter physics. His 1999 experiment that resulted in a degenerate Fermi gas launched a new frontier in atomic, molecular, and optical physics.

DeMarco is the recipient of numerous honors, most notably an NSF CAREER Award, an ONR Young Investigator Award, and a Sloan Foundation Fellowship. He has served on the APS Panel on Public Affairs (POPA) and the National Academy of Sciences Intelligence Science and Technology Experts Group (ISTEG). He is currently Chair of the NASA Fundamental Physical Sciences Standing Review Board and was in the 2016–2017 class of the Defense Sciences Study Group.

DeMarco received his bachelor's degree in physics with a mathematics minor from the State University of New York at Geneseo in 1996, graduating *summa cum laude*. He received his doctoral degree in physics from the University of Colorado at Boulder in 2001. He joined the faculty at Illinois Physics in 2003, following a postdoc at the National Institute of Standards and Technology in Boulder.

Illinois Physics is well represented on the list of prior recipients of this honor. Since it was first conferred in 1985, 17 physics faculty members have been named University Scholars, including Peter Abbamonte (2014), Kevin Pitts (2013), Taekjip Ha (2009), Paul Selvin (2006), Philip Phillips (2003), Douglas Beck (2001), David Hertzog (2000), Tony Liss, (1999), Dale Van Harlingen (1998), Paul Goldbart (1996), Klaus Schulten (1996), Donald Ginsberg (1994), Steven Errede (1991), Miles Klein (1989), Stephen Wolfram (1988), Gordon Baym (1987), and Ralph Simmons (1986). ■

University of Illinois part of $25 million software institute to enable discoveries in high-energy physics

On September 4, 2018, the National Science Foundation (NSF) announced its launch of the Institute for Research and Innovation in Software for High-Energy Physics (IRIS-HEP). The $25 million software-focused institute will tackle the unprecedented torrent of data that will come from the high-luminosity running of the Large Hadron Collider (LHC), the world's most powerful particle accelerator located at CERN near Geneva, Switzerland. The High-Luminosity LHC (HL-LHC) will provide scientists with a unique window into the subatomic world to search for new phenomena and to study the properties of the Higgs boson in great detail. The 2012 discovery at the LHC of the Higgs boson—a particle central to our fundamental theory of nature—led to the Nobel Prize in physics a year later and has provided scientists with a new tool for further discovery.

The HL-LHC will begin operations around 2026, continuing into the 2030s. It will produce more than 1 billion particle collisions every second, of which only a tiny fraction will reveal new science—the phenomena of greatest interest to physicists have a very low probability per collision of occurring. The HL-LHC's tenfold increase in luminosity—a measure of the number of particle collisions occurring in a given amount of time—will enable physicists to study familiar processes at an unprecedented level of detail and observe rare new phenomena present in nature.

But the increased luminosity also leads to more complex collision data. A tenfold increase in the required data processing and storage can't be achieved without new software tools for intelligent data filtering that record only the most interesting collision events, to enable scientists to analyze the data more efficiently.

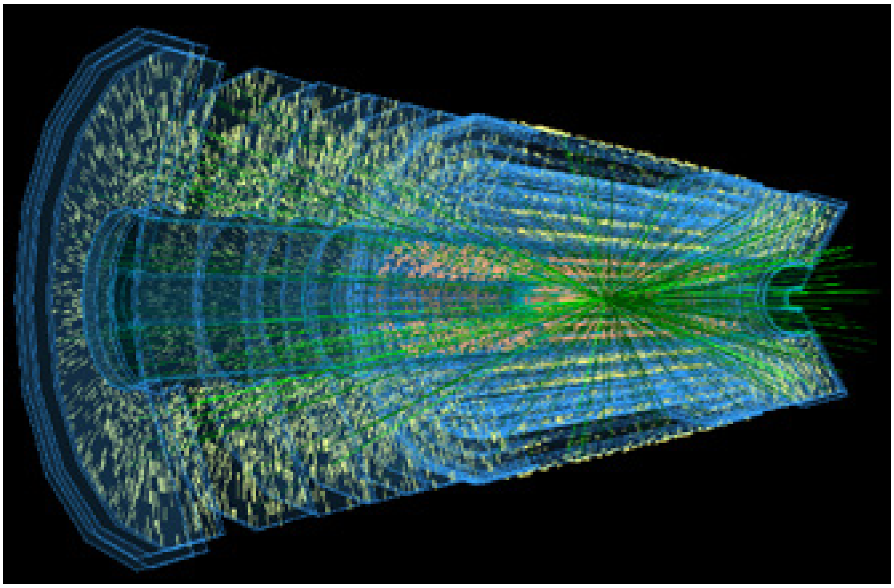
Over the next five years, IRIS-HEP will focus on developing innovative software for use in particle physics research with the HL-LHC as the key science driver. It will also create opportunities for training and education in related areas of computational and data science and outreach to the general public. The institute will also work to increase participation from women and minorities who are underrepresented in high-energy physics research.

IRIS-HEP brings together multidisciplinary teams of researchers and educators from 17 universities, including Mark Neubauer, a professor of physics at the University of Illinois at Urbana-Champaign and a faculty affiliate with the National Center for Supercomputing Applications (NCSA) in Urbana. Neubauer is a member of the ATLAS Collaboration, which generates and analyzes data from particle collisions at the LHC. Neubauer will serve on the IRIS-HEP executive board and coordinate the institute's activities to develop and evolve its strategic vision.

Neubauer, along with colleagues Peter Elmer (Princeton) and Michael Sokoloff (Cincinnati), led a community-wide effort to conceptualize the institute with funding from the NSF. Neubauer was a key member of the group that developed the IRIS-HEP proposal. Through a conceptualization process involving 18 workshops over the last two years, key national and international partners from high-energy physics, computer science, industry, and data-science were brought together to generate more than eight community position papers, most notably a strategic plan for the institute and a roadmap for HEP software and computing R&D over the next decade. They reviewed two decades of approaches to LHC data processing and analysis and developed strategies to address the challenges and opportunities that lay ahead.

Left: Professor Mark Neubauer

Right: A data visualization from a simulation the collision between two protons that will occur at the High-Luminosity Large Hadron Collider (HL-LHC). On average, up to 200 collisions will be visible in the collider's detectors at the same time. Shown here is a design for the Inner Tracker of the ATLAS detector, one of the hardware upgrades planned for the HL-LHC. Image courtesy of the ATLAS Experiment © 2018 CERN



"IRIS-HEP will serve as a new intellectual hub of software development for the international high-energy physics community," comments Neubauer. "The founding of this institute will do much more than fund software development to support the HL-LHC science; it will provide fertile ground for new ideas and innovation, empower early-career researchers interested in software and computing aspects of data-enabled science through mentoring and training to support their professional development, and will redefine the traditional boundaries of the high-energy physics community."

Neubauer will receive NSF funding through IRIS-HEP to contribute to the institute's efforts in software research and innovation. He plans to collaborate with Daniel S. Katz, NCSA's assistant director for scientific software and applications, to put together a team to research new approaches and systems for data analysis and innovative algorithms that apply machine learning and other approaches to accelerate computation on modern computing architectures.

In related research also beginning in the current fall semester, Neubauer and Katz through a separate NSF award with Kyle Cranmer (NYU), Heiko Mueller (NYU) and Michael Hildreth (Notre Dame) will be collaborating on the Scalable Cyberinfrastructure for Artificial Intelligence and Likelihood-Free Inference (SCAILFIN) project. SCAILFIN aims to maximize the potential of artificial intelligence and machine learning to improve new physics searches at the LHC, while addressing current issues in software and data sustainability by making data analyses more reusable and reproducible.

Katz says he is looking forward to delving into these projects: "How to build tools that make more sense of the data, how to make the software more sustainable so there is less rewriting, how to write software that is portable across different systems and compatible with future hardware changes—these are tremendous challenges. And these questions really are timely. They fit into the greater dialogue that is ongoing in both the computer science and the information science communities. I'm excited for this opportunity to meld the most recent work from these complementary fields together with work in physics."

Neubauer concludes, "The quest to understand the fundamental building blocks of nature and their interactions is one of the oldest and most ambitious of human scientific endeavors. The HL-LHC will represent a big step forward in this quest and is a top priority for the U.S. particle physics community. As is common in frontier-science experiments pushing at the boundaries of knowledge, it comes with daunting challenges. The LHC experiments are making large investments to upgrade their detectors to be able to operate in the challenging HL-LHC environment.

"A significant investment in R&D for software used to acquire, manage, process, and analyze the huge volume of data that will be generated during the HL-LHC era will be critical to maximize the scientific return on investment in the accelerator and detectors. This is not a problem that could be solved by gains from hardware technology evolution or computing resources alone. The institute will support early-career scientists to develop innovative software over the next five to ten years, to get us where we need to be to do our science during the HL-LHC era. I am elated to see such a large investment by the NSF in this area for high-energy physics."

Researchers engineer bacteria to exhibit stochastic Turing patterns

First in-vivo *proof of principle that patterns can be stabilized by noise*

Research image credit: D. Karig, K. M. Martini, T. Lu, N. DeLateur, N. Goldenfeld, R. Weiss

SIV SCHWINK
for Illinois Physics Condensate

How did the zebra get its stripes, or the leopard its spots? Mankind has been trying to answer such questions since our earliest recorded days, and they resonate throughout the extant mythologies and folklores of an earlier world. In modern times, we've looked to mathematical models and most recently to genomic science to uncover the explanation of how patterns form in living tissues, but a full answer has proven particularly hard to get at.

The mechanism of pattern formation in living systems is of paramount interest to bioengineers seeking to develop living tissue in the laboratory. Engineered tissues would have countless potential medical applications, but in order to synthesize living tissues, scientists need to understand the genesis of pattern formation in living systems.

A new study by researchers at the University of Illinois at Urbana-Champaign, the Massachusetts Institute of Technology, and the Applied Physics Laboratory at Johns Hopkins University has brought science one step closer to a molecular-level understanding of how patterns form in living tissue. The researchers engineered bacteria that, when incubated and grown, exhibited stochastic Turing patterns: a "lawn" of synthesized bacteria in a petri dish fluoresced an irregular pattern of red polka dots on a field of green.

What are classic Turing patterns?
Turing patterns can be stripes, spots or spirals that arise naturally out of a uniform state. In 1952, the British mathematician, computer scientist, and theoretical biologist Alan Turing proposed a mechanism for how patterns form, theorizing that it's due to a very general kind of instability, which he worked out mathematically. At that time, biology had not yet uncovered the complexities of gene regulation, and it's now clear that the model Turing proposed is overly simplified to describe the multitude of parameters at work in animal-skin pattern formation.

So while Turing patterns have been observed in certain chemical reactions, such patterns have proven very difficult to demonstrate in biological organisms.

U of I Physics Professor Nigel Goldenfeld illustrates the limitations of classic Turing pattern formation in biology, using a predator-prey analogy.

"The problem with Turing's mechanism," Goldenfeld explains, "is that it hinges on a criterion that isn't satisfied in many biological systems, namely that the inhibitor must be able to move much more quickly than the activator. For example, if instead of chemicals, we were looking at two creatures in an ecosystem, like wolves and sheep, the wolves would need be able to move around much faster than the sheep to get classic Turing patterns. What this would look like, you would first see the sheep grow in number, feeding the wolves, which would then also grow in number. And the wolves would run around and contain the sheep, so that you would get little localized patches of sheep with the wolves on the outside. That's essentially the mechanism in animal terms for what Turing discovered."

The stochastic Turing model driven by randomness
In the current study, the researchers demonstrated both experimentally and theoretically that Turing patterns do in fact occur in living tissues—but with a twist. Where the instability that generates the patterns in Turing's model is defined as a high diffusion ratio between two chemicals, an activator and an inhibitor, in this study, researchers demonstrate that it's actually randomness—which would in most experiments be considered background noise—that generates what Goldenfeld has coined a stochastic Turing pattern.

About a decade ago, Goldenfeld and a former graduate student, Dr. Tom Butler, developed a theory of stochastic Turing patterns, wherein patterns develop not from a high inhibitor-activator ratio, but from the noise of stochastic gene expression. Goldenfeld explains, "About 10 years ago we asked, what happens if there is only a small number of sheep, so that there are large fluctuations in population numbers? Now you get processes where sheep die at random. And we discovered, when you give birth to randomness, that actually drives the formation of stochastic Turing patterns. These are random patterns, but they have a very characteristic structure, and we worked out mathematically what that was.

"The theory of stochastic Turing patterns doesn't require a great difference in speed between the prey and the predator, the activator and the inhibitor. They can be more or less the same, and you still get a pattern. But it won't be a regular pattern. It'll be disordered in some way."

The bioengineering experiments

The bacterial patterning experiments in this study were being performed around the same time Goldenfeld and Butler were developing their theory. The initial motivation for the *in vivo* study was to see whether bacteria could be engineered to produce a Turing instability. The researchers used synthetic biology to engineer bacteria, based on the activation-inhibition idea from Turing. They injected the bacteria with genes that made the bacteria emit and receive two different molecules as signals. The researchers attached fluorescent reporters to the molecules, creating a system where they could view the on-off switch of the genetic circuits through their signaling molecules: the activator fluoresced red and the inhibitor green. The researchers observed that, starting with a homogeneous film, the engineered bacteria formed red dots surrounded by a field of green after incubation for a period of time—but the bacteria formed irregular Turing patterns, like those predicted by the stochastic theory.

The original experimental and modeling work at MIT were led by Ron Weiss and carried out by David Karig, now at the Applied Physics Laboratory, Johns Hopkins University, and Ting Lu, now at the U of I, and later continued by graduate student Nicholas DeLateur at MIT.

Goldenfeld notes, "Serendipity definitely played a role in our connecting our two studies, as it often does in academia—the right place, the right time, and our ideas converged."

Validating the stochastic Turing theory

To test if the experiments really were described by the new theory took several years of work. K. Michael Martini, a graduate student at the Center for the Physics of Living Cells at the U of I, worked with Goldenfeld to build a very detailed stochastic model of what was going on in these synthetic pattern-forming gene circuits, computed the consequences, and then compared the theoretical predictions with what the bioengineers had seen in the petri dishes.

"To really prove that our stochastic patterns work—it was hard. We had made a lot of predictions that had to be verified in experiment," comments Goldenfeld. "Because the mathematics that describe these patterns have many parameters, we had to explore all of the effects of each. It involved a lot of searching in parameter space to reveal what was the mechanism of pattern formation. And there was necessarily a lot of interaction and collaboration with our engineering colleagues.

"What our work shows is that you can in fact get Turing patterns even in situations where you wouldn't expect to be able to see them, but they are disordered patterns—stochastic Turing patterns. And the stochasticity here is not the birth and death of sheep or wolves, but it's the birth and death, the creation and absorption of proteins. This is a very counter-intuitive prediction: it's the noise of stochastic gene expression that generated these patterns. Normally you think of noise wiping out a signal. If you were trying to listen to music on a radio, noise in the signal drowns it out. But in this case, we have a noise-stabilized pattern."

These findings shed new light on an age-old question and begin to pave the way for future efforts in biomedical engineering.

Goldenfeld affirms, "This is really the first proof of principle that you can engineer *in vivo* stochastic Turing patterns, though it's not simple. So now we know that this mechanism really can work, and that these fluctuations can drive patterns. Ultimately, bioengineers would like to use this type of technology to make novel tissues and new functional biological systems. Our study shows that you can do that in a regime where the classical Turing patterns couldn't be used."

These findings were published June 11, 2018, in the *Proceedings of the National Academy of Sciences of the United States of America* (PNAS), in the article "Stochastic Turing patterns in a synthetic bacterial population." ■

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DEPARTMENT OF PHYSICS
University of Illinois at Urbana-Champaign
Loomis Laboratory of Physics
1110 W. Green Street
Urbana, IL 61801-3003

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