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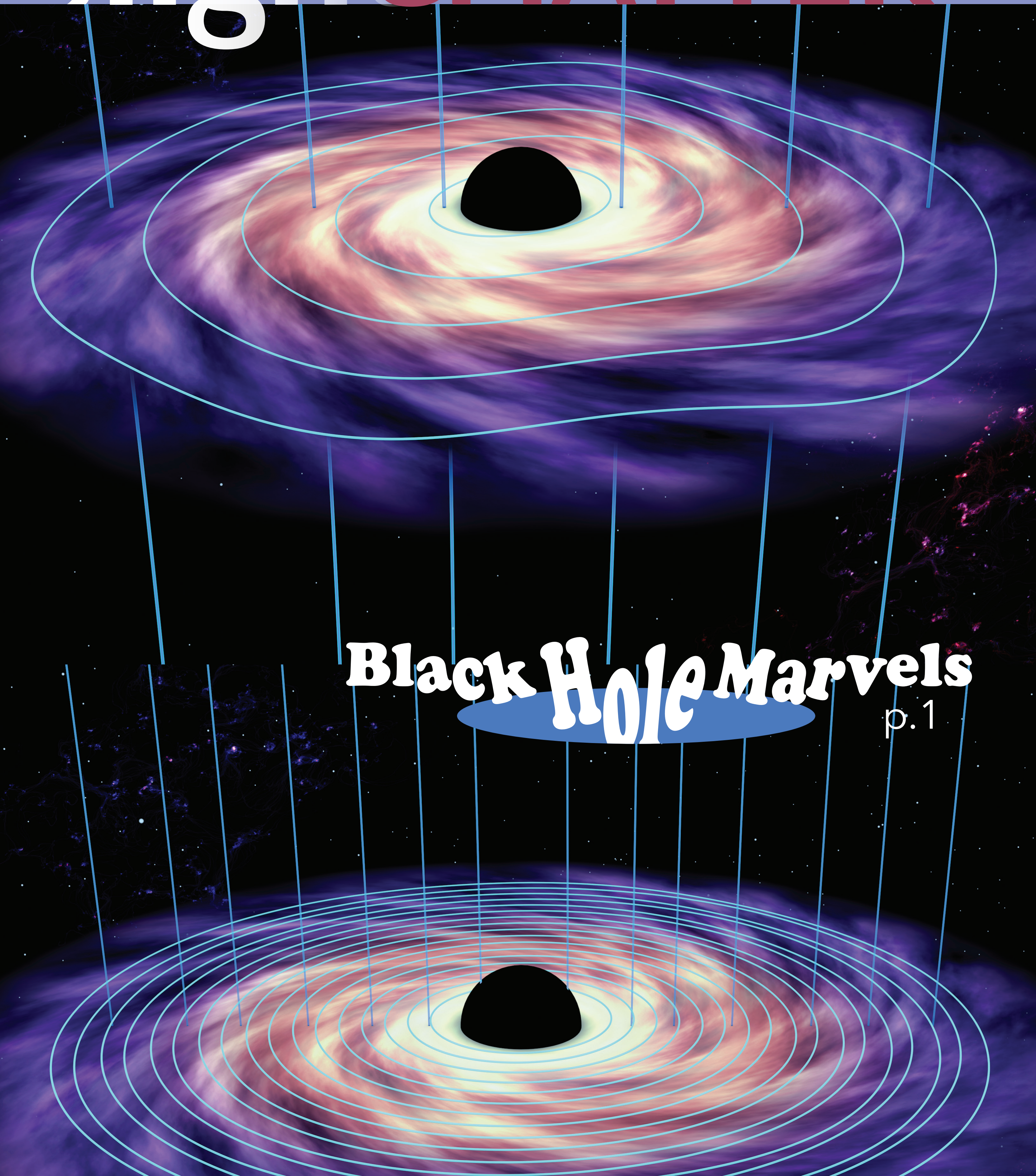
JILA light&MATTER



Black Hole Marvels

p.1

The Keck Lab is an optical metrology laboratory at JILA with advanced capabilities for (1) precision measurement, (2) micro and nano fabrication in a Class 1000 clean room, (3) atomic force, optical, and scanning electron microscopies, and (4) optics education. Credit: Kristin Conrad, JILA

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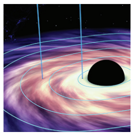
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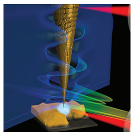
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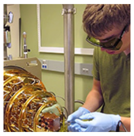
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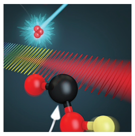
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Black Hole Marvels

Some have magnetized disks of swirling gas that generate super-gale force winds

Graduate student Greg Salvesen, JILA Collaborator Jake Simon (Southwest Research Institute), and Fellows Phil Armitage and Mitch Begelman decided they wanted to figure out why swirling disks of gas (accretion disks) around black holes often appear strongly magnetized. They also wanted to figure out the mechanism that allowed this magnetization to persist over time. In the process, they hoped to explain some intriguing observations of super-gale force winds blown off of some black-hole accretion disks. So the researchers created supercomputer simulations that allowed them to come up with some interesting ideas about the behavior of magnetized disks.

What they learned is that if there is a magnetic field that is poking vertically through the black hole's accretion disk, a wreath-shaped magnetic field will be generated within the accretion disk. And, the stronger the vertical field is, the stronger the magnetic wreath will be inside the gas making up the accretion disk—up to a point.

"What we've shown is that to get a very strongly magnetized disk, the wreath-shaped component is dominant,' said Salvesen. "But you still need that vertical magnetic field, which is subdominant, but very important for the physics that produces and maintains a strong wreath-shaped magnetic field."

Salvesen explained that there are generally two types of black holes that sometimes have accretion disks: supermassive black holes (at the center of each galaxy) with masses of millions to billions of Suns and stellar-sized black holes with masses of about 5 to 30 Suns that are littered throughout every galaxy. Light coming from these accretion disks helps astrophysicists understand both the properties of black holes and the physics of the disks.

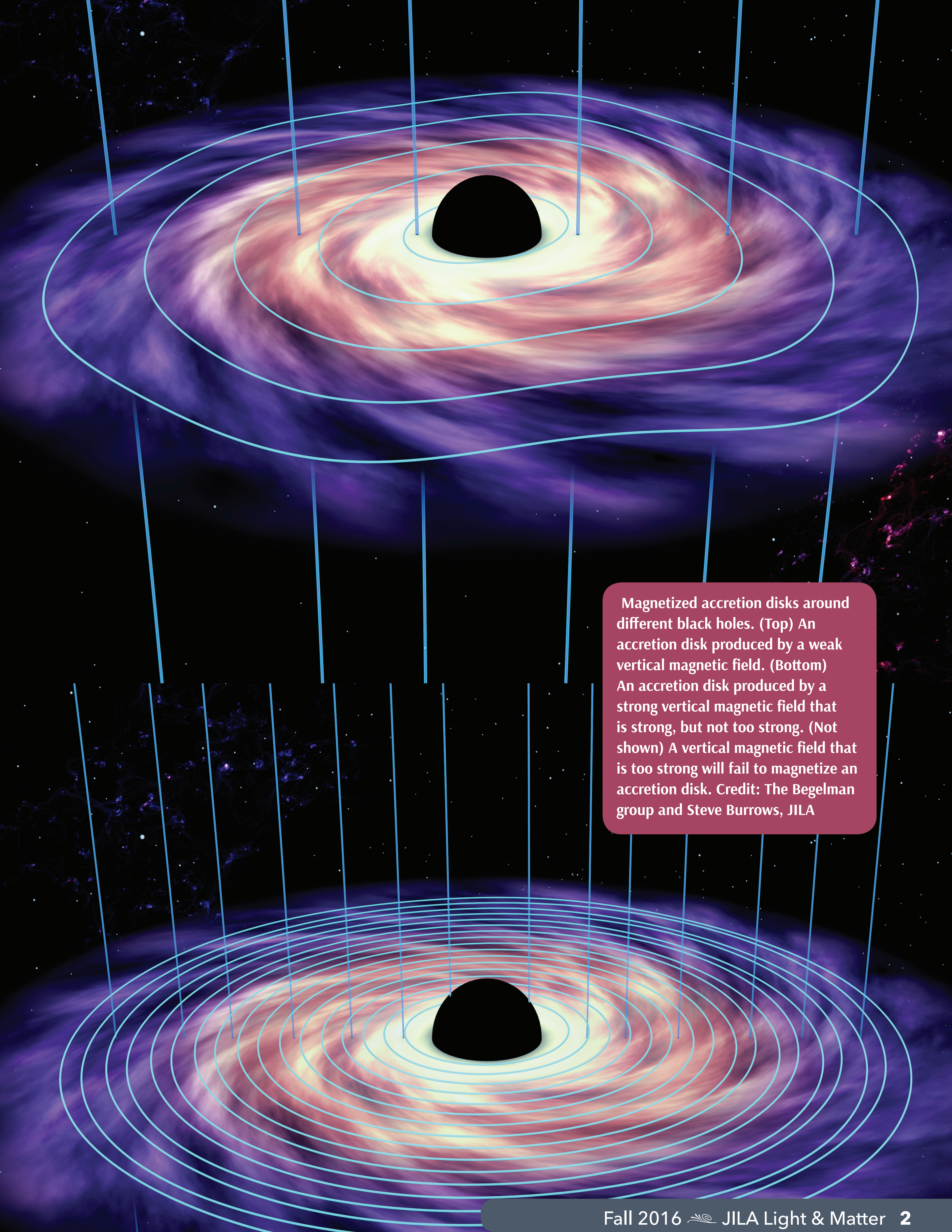
"There have been observations recently that are suggestive of some disks being strongly magnetized," Salvesen explained. "But the most compelling observations are the fast winds we sometimes see coming from the disks. These winds travel at a few percent of the speed of light and are about 10,000 times more powerful than the strongest hurricane winds on Earth!"

The winds must be launched away from the disks by some kind of pressure. There are three possible mechanisms that could create winds: thermal pressure from hot gas; radiation pressure from light; or pressure from magnetic fields. Salvesen is focusing on the pressure from magnetic fields.

"Radiation and thermal pressure often can't cut it, because they can't make a wind powerful enough," he said. "In these cases, the magnetic fields must be responsible for producing the winds we observe coming off the disk."

Consequently, Salvesen decided to further explore the formation of magnetic fields in black hole accretion disks. What he discovered is fascinating.

"If you have a disk that is initially not turbulent and then you thread it with a vertical magnetic field, an instability will generate turbulence within the disk," he said. "Even the very weakest field will cause the disk to become turbulent. But, if that vertical magnetic field is too strong, then this instability won't happen. The vertical magnetic field has to be just right—strong, but not too strong." The vertical field needs to be just strong enough to (continued p. 3)



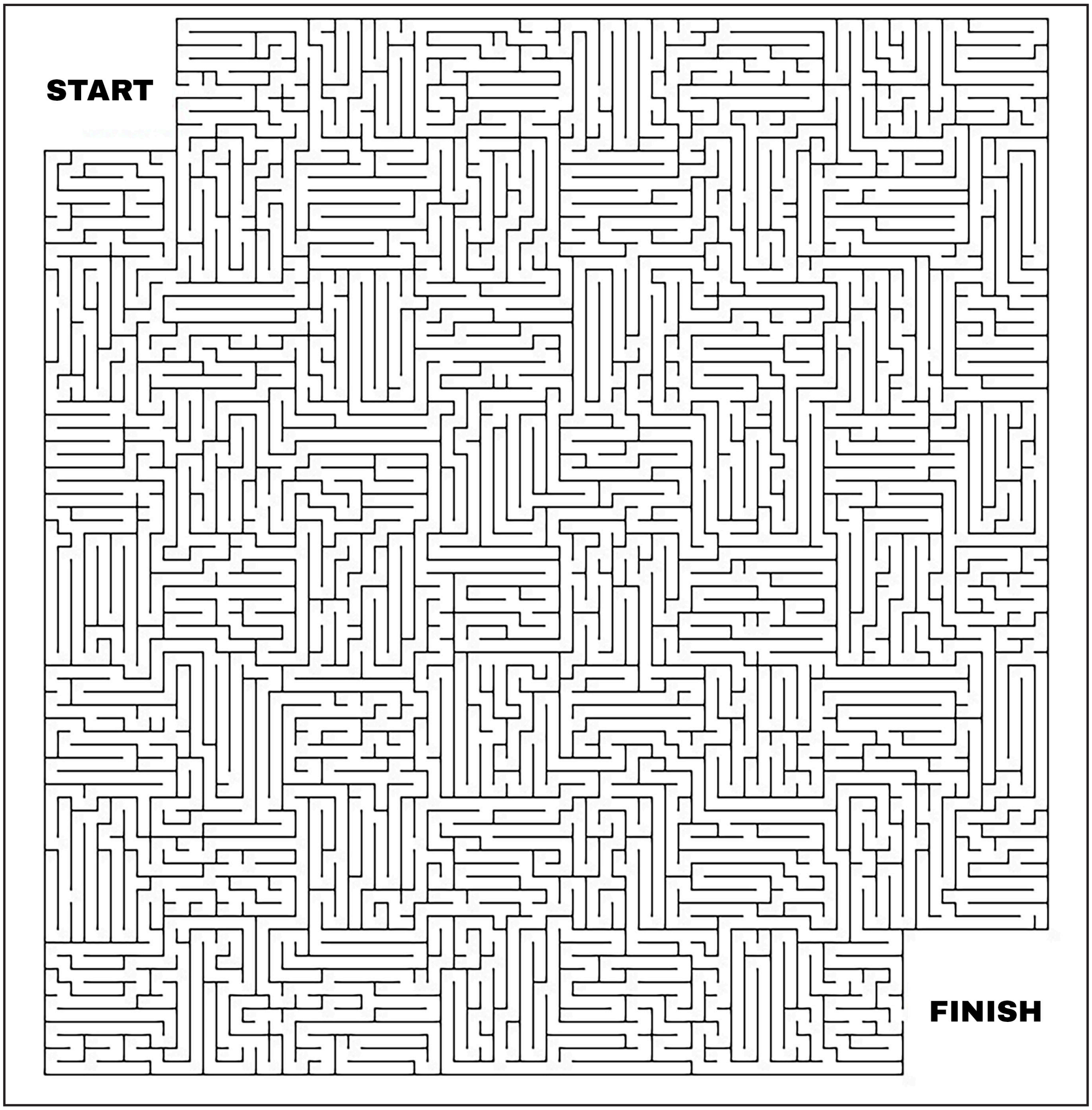
Magnetized accretion disks around different black holes. (Top) An accretion disk produced by a weak vertical magnetic field. (Bottom) An accretion disk produced by a strong vertical magnetic field that is strong, but not too strong. (Not shown) A vertical magnetic field that is too strong will fail to magnetize an accretion disk. Credit: The Begelman group and Steve Burrows, JILA create a very strong magnetic wreath. The magnetic wreath then governs the behavior (and the physics) of the disk from then on, so long as a vertical magnetic field remains in place. In black-hole accretion disks where such conditions can exist, strong magnetic wreaths may play a role in producing extremely fast winds that can be observed by Earthlings hundreds of light years away.

Greg Salvesen, Philip J. Armitage, Jacob B. Simon, and Mitchell C. Begelman, *Monthly Notices of the Royal Astronomical Society*, **460**, 3488–3493 (2016).

Greg Salvesen, Jacob B. Simon, Philip J. Armitage, and Mitchell C. Begelman, *Monthly Notices of the Royal Astronomical Society*, **457**, 857–874 (2016).

Puzzle

The first person to turn in a correctly-completed puzzle to Kristin Conrad, S264 will receive a $25 gift card.



Congratulations to Rabin Paudel & Roman Chapurin for winning the Summer 2016 puzzle contest!

A New Electron Movie, Thanks to the Tip

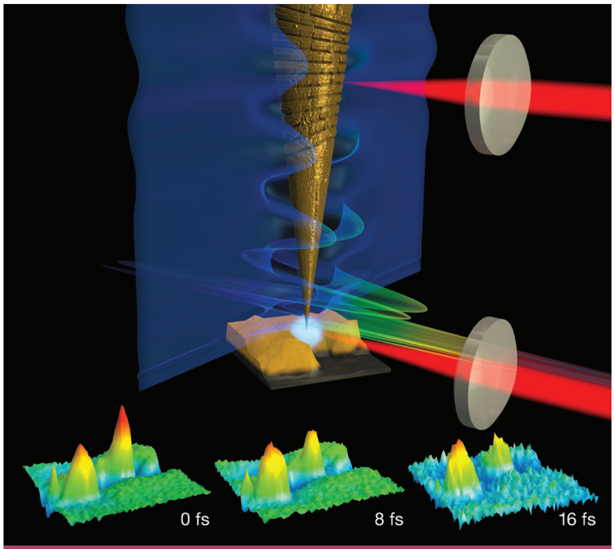
The Raschke group has created an ultrafast optical nanoscope based on a unique way of "nano" focusing the light to image the behavior of electrons on a thin gold film. The nanoscope is 1,000 times more powerful than conventional optical microscopes.

It allows the researchers to investigate matter on its natural time and length scales, which are measured in femtoseconds and nanometers, respectively. This new technique may find application to studies of photosynthesis, solar cells, energy conversion and use, and other phenomena based on the transfer of electrons from molecule to molecule.

The nanoscope can see the motion of atoms and electrons at a speed that is one trillion times faster than the blink of an eye. This rate of image capture allowed the researchers to make a movie of the oscillations of electron clouds in real time and space! The researchers responsible for this amazing feat include graduate student Vasily Kravtsov, research associate Ronald Ulbricht, former research associate Joanna Atkin (University of North Carolina, Chapel Hill), and Fellow Markus Raschke.

Their secret was figuring out how to nanofocus ultrashort light pulses on the tip of the scanning-probe nanoscope. The researchers accomplished this by generating plasmons on the nanometer-sized conical tip surface. In contrast to conventional light waves, plasmons are surface waves of light bound to the metallic tip shaft. They travel down to the tip of the cone. During their journey, they get so compressed that by the time a plasmon wave reaches the nanoscopic tip, its field strength is so large that it creates a rainbow of new colors of light. When the tip is then raster-scanned near the sample, a spatial image is created with individual movie frames that reflect the time delay of the excitation pulses.

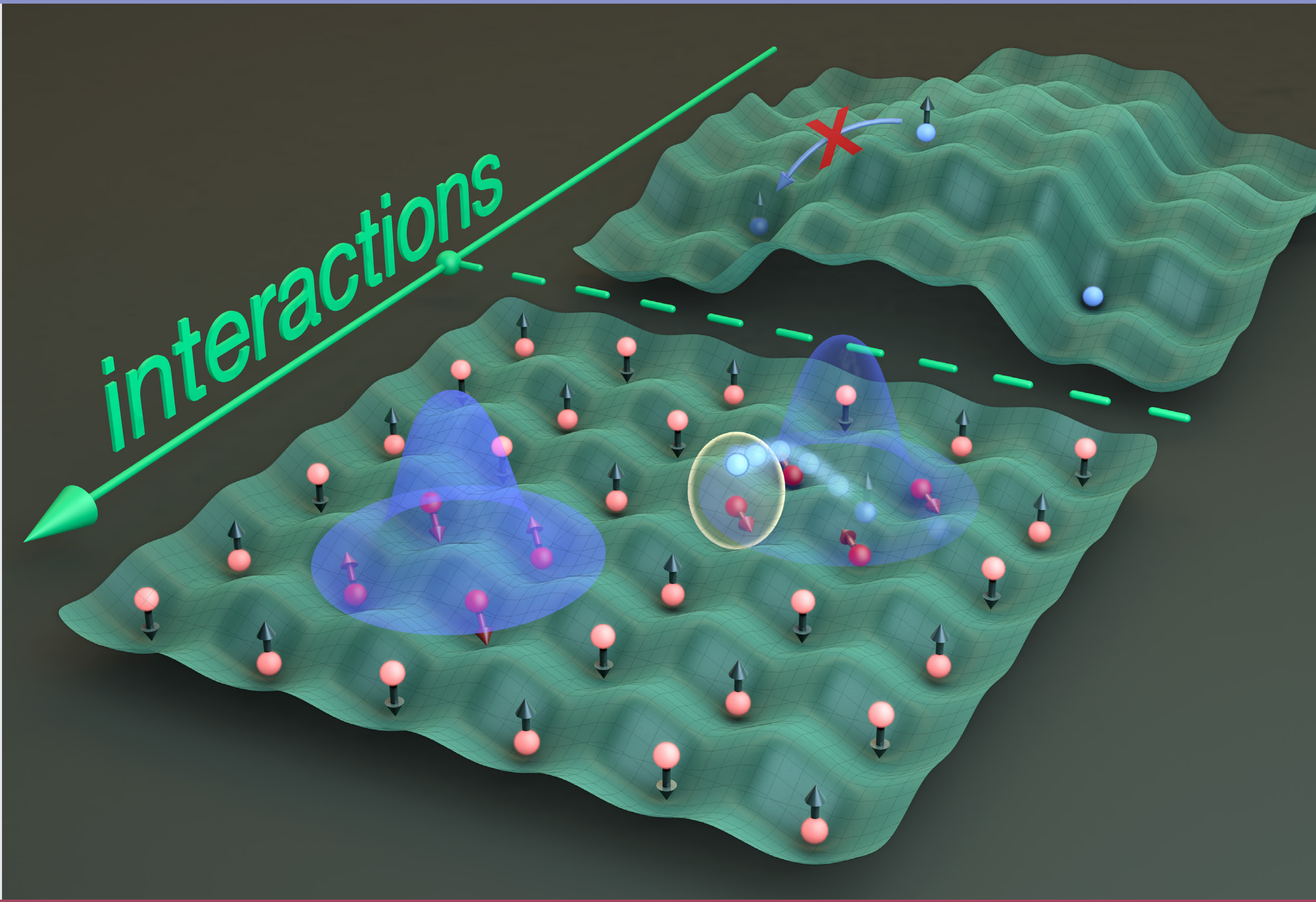
"This work expands the reach of optical microscopes into the ultrafast and ultrasmall," said Raschke. "Using this technique, researchers can image the elementary processes in materials ranging from battery electrodes to solar cells, helping to improve their efficiency and lifetime."



The Raschke group's novel, ultrafast optical nanoscope is capable of focusing extremely short light pulses to image the behavior of electrons in real space and time on a thin gold film. Because the nanoscope can measure time in femtoseconds and length in nanometers, it may be used in studies of photosynthesis as well as solar cells and other energy conversion and storage materials. Credit: The Raschke group and Steve Burrows, JILA

The new technique of ultrafast optical nanoimaging will also help research groups to study charge and energy transport in soft matter, including biological materials.✺

Vasily Kravtsov, Ronald Ulbricht, Joanna M. Atkin, and Markus B. Raschke, *Nature Nanotechnology* **11**, 459–464 (2016).



The behavior of strontium atoms in a crystal of light changes when the atoms interact with each other. The state of the atoms can change from an insulator, where the particles don't move, to a quantum metal with mobile, interacting particles. Credit: The Rey group and Steve Burrows, JILA

A Quantum Metal Model System

Under the right conditions, a strontium-lattice atomic clock becomes a quantum metal

Exciting new theory from the Rey group reveals the profound effects of electron interactions on the flow of electric currents in metals. Controlling currents of strongly interacting electrons is critical to the development of tomorrow's advanced microelectronics systems, including spintronics devices that will process data faster, use less power than today's technology, and operate in conditions where quantum effects predominate.

The new theory explaining the flow of electrons exploits the ability of lasers to couple the spin and velocity of atoms, thereby engineering "spin-orbit" coupling.

The group's secret to better understanding electron interactions comes from controlling arrays of cold strontium (Sr) atoms inside the crystal made of light, or optical lattice, at the heart of the Ye group's Sr-lattice atomic clock. The Ye group's atomic clock should be an ideal simulator of the complex quantum interactions associated with the flow of electrons in metals. Metals themselves are much too complicated and "messy" for understanding novel quantum interactions and their effects.

The new theory explaining the flow of electrons exploits the ability of lasers to couple the spin and velocity of atoms, thereby engineering "spin-orbit" coupling. Spin-orbit coupling occurs in materials like metals where electrons (which have spin) move naturally through crystals of positively charged atoms. In the Sr-lattice clock, two atomic clock states play the role of electrons in either a spin-up or spin-down state. The motion of Sr atoms through the crystal of light simulates the flow of electrons in metals.

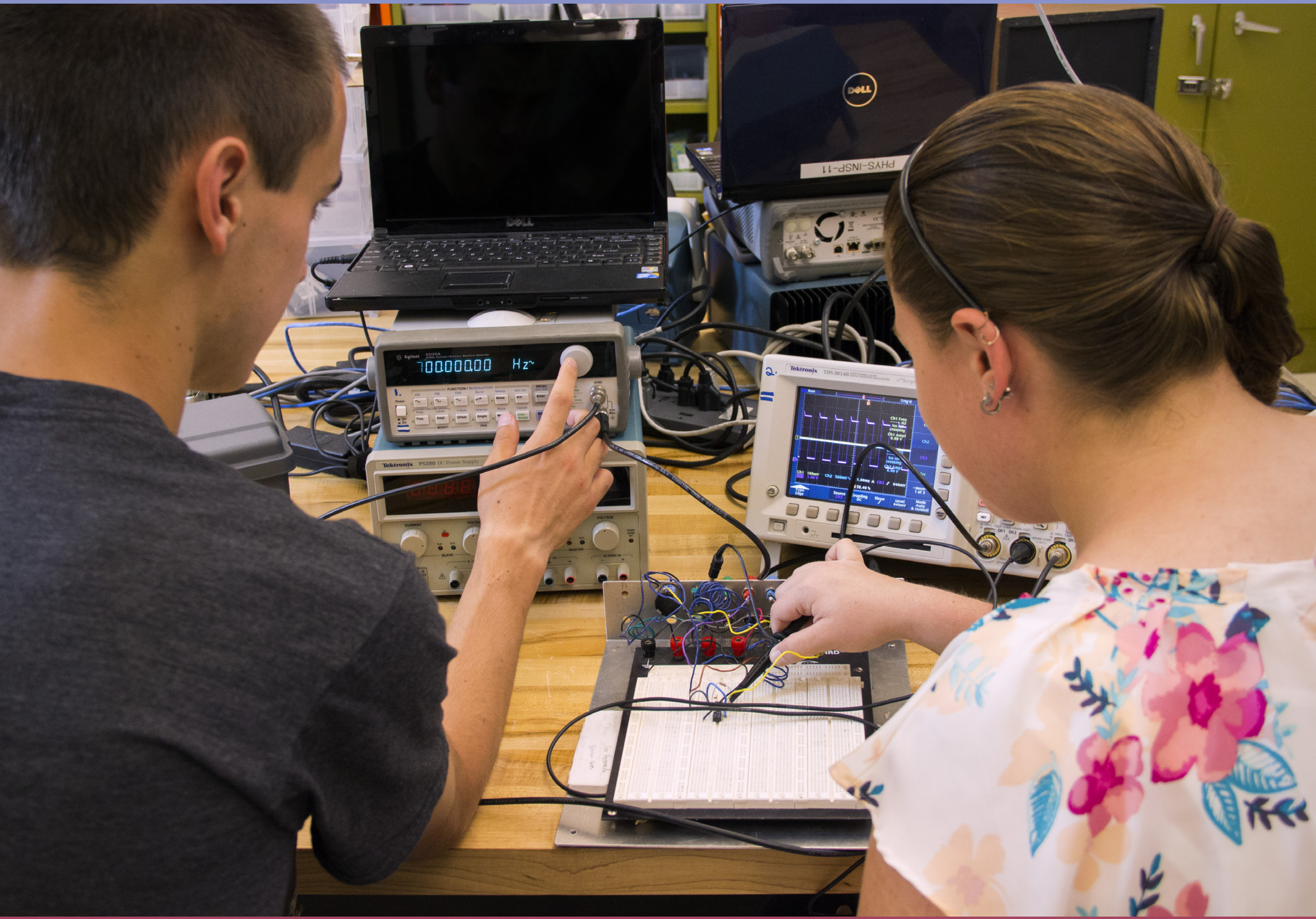
In this work, research associates Leonid Isaev and Johannes Schachenmayer as well as Fellow Ana Maria Rey investigate how the behavior of Sr atoms changes when the atoms are no longer independent, but rather interact with each other. The new theory predicts that the state of the cold Sr atoms can change from an insulator, where the atoms don't move at all, to a quantum metal with mobile, interacting Sr atoms. Changing from an insulating state to a quantum metal is simply a matter of manipulating the intensity of the laser responsible for spin-orbit coupling.

Spin-orbit coupling is just one of three key ingredients for creating the exotic metallic state with Sr atoms. The other two ingredients are atomic spin and strong interatomic interactions.

Here's how all three work together: The spin-orbit coupling generated by the laser creates a landscape of energy barriers that stop all atom movement. However, when the intensity of the laser is "just right," the atoms start moving again, creating a "mass" current. At the same time, a spin current is generated when pairs of atoms in different spin configurations are in a superposition. In a superposition, the atoms can exchange spins with their partners, inducing a spin current. This phenomenon is sensitive to even the slightest variations in laser intensity, which gives researchers a lot of control over the process. This ability to create and control spin transport may be a key ingredient in the development of spintronics.

All that's left to do now is to verify that this theory works in real experiments. Efforts are already underway to do just that in the Ye labs. Results are expected soon. ✺

L. Isaev, J. Schachenmayer, and A. M. Rey, *Physical Review Letters* **117** (13) 135302 (2016).



Setup for students asked to talk aloud as they used modeling to diagnose and repair a malfunctioning electric circuit with two problems. Credit: The Lewandowski group and Steve Burrows, JILA

Modeling Lessons

Physics education researchers from the University of Colorado Boulder and the University of Maine recently showed that students troubleshooting a malfunctioning electric circuit successfully tackled the problem by using models of how the circuit ought to work. The researchers confirmed this approach by analyzing videotapes of eight pairs of students talking aloud about their efforts to diagnose and repair a malfunctioning electric circuit. The circuits had not just one, but two problems. Both problems had to be corrected for the circuit to work properly.

The researchers responsible for this work included Fellow Heather Lewandowski, MacKenzie Stetzer, Assistant Professor of Physics at the University of Maine, research associate Dimitri R. Dounas-Frazer (Colorado), and graduate student Kevin L. Van De Bogart (Maine). Their work was published in *Physical Review Physics Education Research* as an "Editors' Suggestion" on June 15, 2016.

> "Troubleshooting is an integral skill for experimental physics, whether it's electronics or something else that's gone wrong in the lab," Lewandowski said. "And, a student's ability to model systems is integral to being able to troubleshoot successfully."

Lewandowski and Dounas-Frazer designed this study because troubleshooting is an integral part of being successful in both electronics and experimental physics.

"Things never work the first time," Lewandowski observed. "Things always break. A big portion of the lives of students studying experimental physics is troubleshooting. This is a valuable skill." Lewandowski should know. She divides her time between physics education research and experimental research on cold molecules.

The study subjects were pairs of advanced undergraduate students taking similar electronics laboratory courses at the University of Colorado Boulder and at the University of Maine. Lewandowski said she and her colleagues followed a rigorous process of coding the videotaped student conversations as the student pairs were troubleshooting the faulty circuits. In their analysis of the coded conversations, the researchers determined exactly how the students were engaged in modeling. And, they were able to demonstrate that modeling was important for troubleshooting.

"You have to have a model of your system," Lewandowski said, "Because otherwise you don't even know if something is wrong. If you don't have predictions or expectations of various parts of the circuit, it's hard to know if it's working or not, or how to go about fixing the problem."

This research underscores the importance of teaching students that troubleshooting is a process of experimentation. That means expecting that a new experiment isn't necessarily going to work the first time. Often, new experiments become puzzles to solve.

"Troubleshooting is an integral skill for experimental physics, whether it's electronics or something else that's gone wrong in the lab," Lewandowski said. "And, a student's ability to model systems is integral to being able to troubleshoot successfully." ✺

Dimitri R. Dounas-Frazer, Kevin L. Van De Bogart, MacKenzie R. Stetzer, and H. J. Lewandowski, *Physical Review Physics Education Research* **12**, 010137 (2016).

The Lewandowski Group studies how students obtain experimental research skills in the context of upper-divison instructional labs and undergraduate research experiences. In addition, they work to transform these classroom experiences to help students better transition into the research lab environment.

IN THE NEWS

IN THE NEWS

A selection of news, awards, and what is happening around JILA

JILA's Quantum Machine Team Scores!

Fellows Cindy Regal and Konrad Lehnert have won the 2016 Governor's Award for High-Impact Research in Foundational Science and Technology, CO-LABS announced on August 30, 2016. JILA Chair Dana Anderson submitted the nomination of their joint research on building, studying, and using devices that exploit the strange and powerful properties of quantum mechanics. The nomination was entitled, "The JILA Quantum Machine Team: Extending Mastery of Quantum Mechanics from Microscopic Particles to Human-Made Machines."

"This award is well deserved," said JILA's Quantum Physics Division Chief Tom O'Brian. "Konrad Lehnert and Cindy Regal are leading a 21st century revolution by creating the first fully quantum machines. These machines will be the foundation of powerful new 21st century technologies, including ultrasecure quantum communications networks, quantum computers, advanced sensing for defense and intelligence applications as well as novel approaches to making precision measurements in support of both research and manufacturing."

The Lehnert/Regal Quantum Machine Team has already racked up some major accomplishments on the path to these eagerly anticipated 21st century technologies. Their accomplishments include (1) the cooling of a drum made of about 10^{18} aluminum atoms to its quantum ground state, (2) the creation of the world's first efficient two-way converter between electrical and optical signals—an important step along the way to making a fully quantum machine, and (3) the world's first laser cooling of this converter—a human made object—to about 14 millionths of a degree above absolute zero.

Lehnert's and Regal's work represents foundational research and technology development at its best, and CO-LABS clearly agrees. Each year a special committee appointed by the CO-LABS Board of Directors reviews nominations from Colorado labs for the Governor's Award for High-Impact Research and selects projects that have had a significant global, national, or state impact resulting from a scientific breakthrough, change in public policy, or development of a new technology. The Governor's Award for High-Impact Research has honored Colorado scientists and engineers from federally funded research laboratories in Colorado since 2009.

This year's award winners were recognized at a special event held Thursday October 6, 2016, at the Denver Museum of Nature & Science. The event will be presented by The Alliance for Sustainable Energy and hosted by CO-LABS.

CO-LABS is a non-profit consortium of federal laboratories, research institutions, businesses and economic development organizations that provide financial and in-kind support for programs that promote the retention and expansion of Colorado scientific resources.

David Nesbitt Receives E. Bright Wilson Award in Spectroscopy

The American Chemical Society (ACS) has awarded David Nesbitt the 2017 E. Bright Wilson Award in Spectroscopy. The award, sponsored by the ACS Division of Physical Chemistry, recognizes outstanding accomplishments in fundamental or applied spectroscopy in chemistry. It consists of $5,000 and a certificate.

Nesbitt will be honored at an awards ceremony on April 4, 2017, held in conjunction with the 253rd ACS National Meeting in San Francisco. There, he will deliver an award address at the spring awards symposium of the ACS Division of Physical Chemistry. Nesbitt was particularly pleased to be honored with this award.

"Spectroscopy is the way we speak to the Universe, and the way the Universe speaks to us," Nesbitt said. He added that E. B. Wilson was not only a great pioneer of spectroscopy at Harvard, but also a genuinely nice man. "He was a brilliant scholar with a gentle personality; no one's ever said a bad word about E.B."

Nesbitt explained that the E. Bright Wilson Award is typically given to honor a career-long contribution to the field of spectroscopy. He said that over the years his group has made contributions to two areas of molecular spectroscopy: (1) High-resolution infrared spectroscopy and predissociation dynamics of weakly bound complexes and (2) Spectroscopy of highly reactive molecular transients that play a key role in combustion, atmospheric processes as well as chemistry of the interstellar medium.

Maya Fabrikant Wins Journal of Physical Chemistry Poster Prize at 2016 MOLEC Conference

Graduate student Maya Fabrikant has won one of three prizes awarded to the best posters presented by young researchers during the MOLEC 2016 conference held in Toledo, Spain, September 11–16. Both graduate students and postdoctoral researchers were eligible for the prizes, which included a $200 Visa gift card. The three prizes were presented by the *Journal of Physical Chemistry*.

Fabrikant is a graduate student in Heather Lewandowski's Cold Molecule group. Her poster was entitled "Cold Radical Chemistry with Buffer-Gas Beams."

MOLEC 2016 is the XXI edition of the European Conference on the Dynamics of Molecular Systems.

Jun Ye and Deborah Jin Highly Cited Researchers

Fellows Jun Ye and Deborah Jin (1968–2016) have been named Highly Cited Researchers for 2016 by Thomson Reuters. Highly Cited Researchers is an annual list that recognizes leading researchers from around the world based on an analysis of their research publications. The 2016 list recognizes the most-cited authors of research publications in the period 2004 through 2014. Ye and Jin are two of 110 people in the physics category in this year's list.

This is a particularly poignant accolade for JILA, as Deborah Jin passed away on September 15, 2016 (see In Memoriam, page 19).

"This honor reinforces the huge impact Debbie Jin had on science and on people during her career," said Tom O'Brian, Quantum Physics Division chief at JILA. "As Jun well knows, Debbie remained as active as possible in her research over the past year, with wonderful support from him and Eric Cornell. Her inclusion again on the list of most highly cited scientists is bittersweet—demonstrating the enormous impact Debbie had on physics and the great loss we are all feeling."

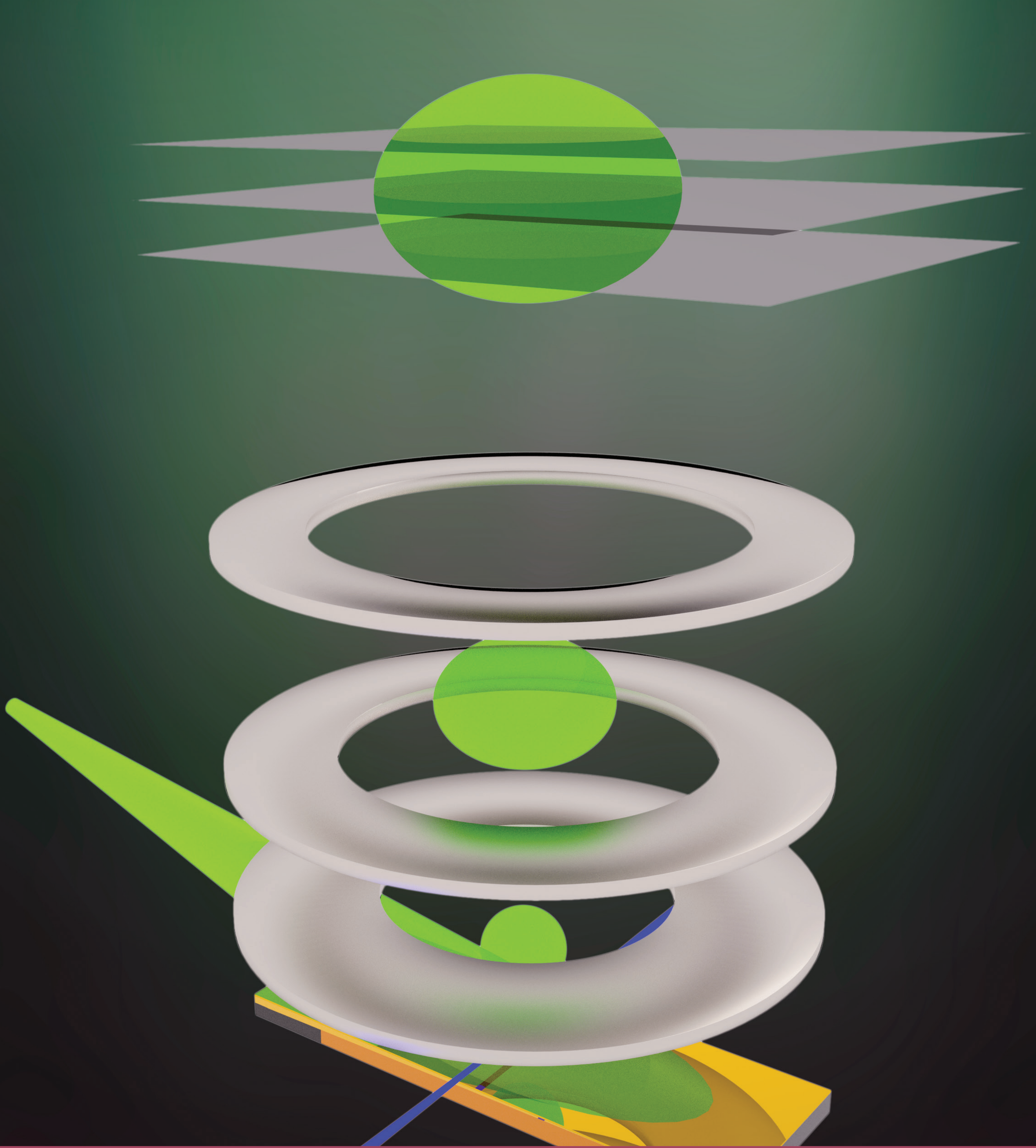
Congratulations to Jun Ye for being a Highly Cited Researcher. Best wishes to him going forward with his work on quantum simulation, the world's most accurate optical atomic clock, and the creation of ultracold potassium-rubidium molecules, a project envisioned in 2002 by the team of Jin and Ye, first achieved in 2008, and followed by years of trend-setting experiments in ultracold chemistry.

Science News Profiles Tenio Popmintchev

Science News has a delightful profile of Senior Research Associate Tenio Popmintchev as part of the magazine's annual feature, "The SN10: Meet the scientists making the next big discoveries" found online at goo.gl/lpjVcz.

The magazine showcases Popmintchev's accomplishments at JILA as a laser physicist, including his having played a key role in the invention of the world's first tabletop x-ray laser. The magazine dubbed this invention a "Swiss army knife made of light."

The goal of Popmintchev's research now is to push the frontiers of the tabletop x-ray laser into higher and higher energies of x-rays. To learn more about how he plans to accomplish this goal, and find out how he came to JILA from Bulgaria, check out his profile at goo.gl/H5SpkB.



The ultimate radar detector (a.k.a. the 3D velocity map-imaging apparatus). The radar detector makes it possible to "see" the quantum states of products of a chemical reaction occurring at the interface of a supersonic beam of gas and a liquid-like surface on a self-assembled monolayer, or SAM. The SAM is grown on the gold-plated bar; the bright green beam on the left is the supersonic beam of 1% HCl; the blue laser at the bottom is used to detect the quantum states of products of chemical reactions that occur between the HCl and molecules on the surface of the SAM; the three grey circles in the center represent electrodes that probe the flight paths and velocities of product molecules in two dimensions (x, y); and the time slices at the top determine velocity and direction of the molecules in the third dimension (z). Credit: Carl Hoffman, JILA

The Ultimate Radar Detector

Essentially all chemistry in the Universe occurs at an interface
–David Nesbitt

The Nesbitt group has invented a nifty technique for exploring the physics and chemistry of a gas interacting with molecules on the surface of a liquid. The group originally envisioned the technique because it's impossible to overestimate the importance of understanding surface chemistry.

For instance, ozone depletion in the atmosphere occurs because of chemical reactions of hydrochloric acid on the surface of ice crystals and aerosols in the upper atmosphere. Interstellar chemistry takes place on the surface of tiny grains of dust. And, any time industrial chemists want to react a gas with a liquid or solid, the secret is getting the gas to touch the surface of whatever they want the gas to react with.

"At the surface of the ocean wave action generates small little liquid droplets that get popped up into the air. This is why it's such a pleasant experience to be near the ocean. And, there's a great deal of chemistry that occurs at the interfaces of these microscopic-to-nanoscopic aerosol particles."

"At the surface of the ocean, for example," explained Fellow David Nesbitt, "wave action generates small little liquid droplets that get popped up into the air. This is why it's such a pleasant experience to be near the ocean, and it's why we smell the ocean. And, there's a great deal of chemistry that occurs at the interfaces of these microscopic-to-nanoscopic aerosol particles." Nesbitt added that it's even possible that life itself may have originated inside microscopic liquid particles formed early in Earth's history.

Back in present time, however, the new technique will help the group investigate the complex chemistry that occurs on the surface of liquids. For instance, the technique (which Nesbitt has dubbed the ultimate radar detector) can identify the quantum states of new molecules produced in chemical reactions that occur when a supersonic jet of gas molecules interacts with a liquid-like surface called a self-assembled monolayer, or SAM.

Some neat things about a SAM are that (1) the SAM sways around like a liquid even though it's attached to a solid anchor at one end and (2) it's possible to link different kinds of molecules to it. Different molecules on the SAM will react differently with the same supersonic jet of gas molecules. The new technique is able to not only identify the products of these chemical reactions, but also detect the flight paths and speed of all the molecules that come flying off the SAM.

The researchers responsible for inventing the new ultimate radar detection system (which they call Quantum-State Resolved 3D Velocity Map Imaging) are graduate student Carl Hoffman and Fellow David Nesbitt. ✺

Carl H. Hoffman and David J. Nesbitt, *The Journal of Physical Chemistry* **120**, 16687–16698 (2016).

How Cold Can a Tiny Drum Get

–With laser cooling, to just 14 μK above absolute zero!

Bob Peterson and his colleagues in the Lehnert-Regal lab recently set out to try something that had never been done before: use laser cooling to systematically reduce the temperature of a tiny drum made of silicon nitride as low as allowed by the laws of quantum mechanics.

Although laser cooling has become commonplace for atoms, researchers have only recently used lasers to cool tiny silicon nitride drums, stretched over a silicon frame, to their quantum ground state. Peterson and his team decided to see just how cold their drum could get via laser cooling.

The lowest drum temperature achieved in the experiment was 14 μK, i.e., 14 millionths of a degree above absolute zero, or –434.47 °F. Without changing the quantum nature of the laser light, there was no way to get the temperature any lower, either. At that temperature, the fundamental quantum fuzziness of the laser heats up the drum just as fast as the laser can cool it. In other words, at 14 μK, the researchers had reached the brick wall known as the quantum backaction limit, which is the formal way of saying quantum mechanics stops additional laser cooling in its tracks. The researchers responsible for this exciting result include graduate student Peterson, former research associate Tom Purdy, research associate Nir Kampel, former graduate students Reed Andrews and Pen-Li Yu as well as Fellows Konrad Lehnert and Cindy Regal.

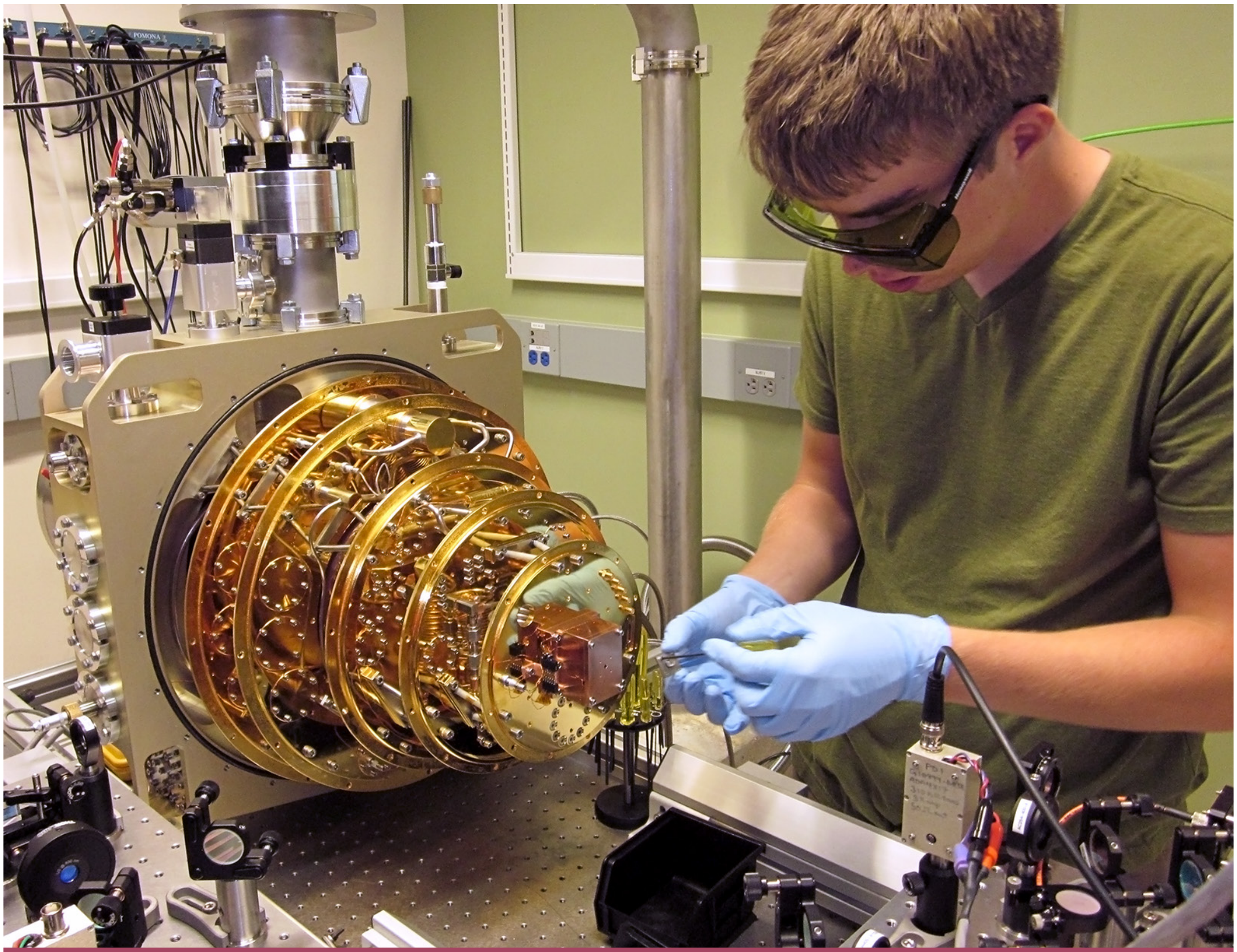
This successful experiment is an important step in the Lehnert-Regal collaboration's goal to use tiny drums to connect the microwave frequencies of electrical circuits with optical frequencies. Reaching this goal may lead to the creation of vast networks of quantum computers linked via fiber-optic cables. Quantum computers will be able to process information much faster than today's fastest computers.

Meanwhile, the collaboration's experiment also provided a demonstration of some exciting new technology! The Lehnert-Regal group's lovely new sideways–oriented 30 mK dilution refrigerator (made with a stack of increasingly colder gold-plated copper plates) meshed seamlessly with the Regal group's state-of-the art optical cavity and laser. Peterson is especially proud of the refrigerator.

"The new refrigerator is exactly the same as other dilution refrigerators in the sense that it has a plate you can screw stuff onto so it gets cold," Peterson said. "But it's very different in that it sits on an optical table, and it's tipped sideways relative to the typical (vertical) configuration to make it easier to get the optics in." Peterson noted that he is the person in the picture screwing the optical cavity onto the refrigerator.

Another big plus is that the new refrigerator cools down to as low as 30 mK. And, the Regal group's optical cavities have never before been cooled below 4 K. The many technological advances coming out of the Lehnert-Regal lab are bringing researchers closer to the goal of using a silicon nitride drum to store and transfer information inside a microwave–to–optical converter. ✷

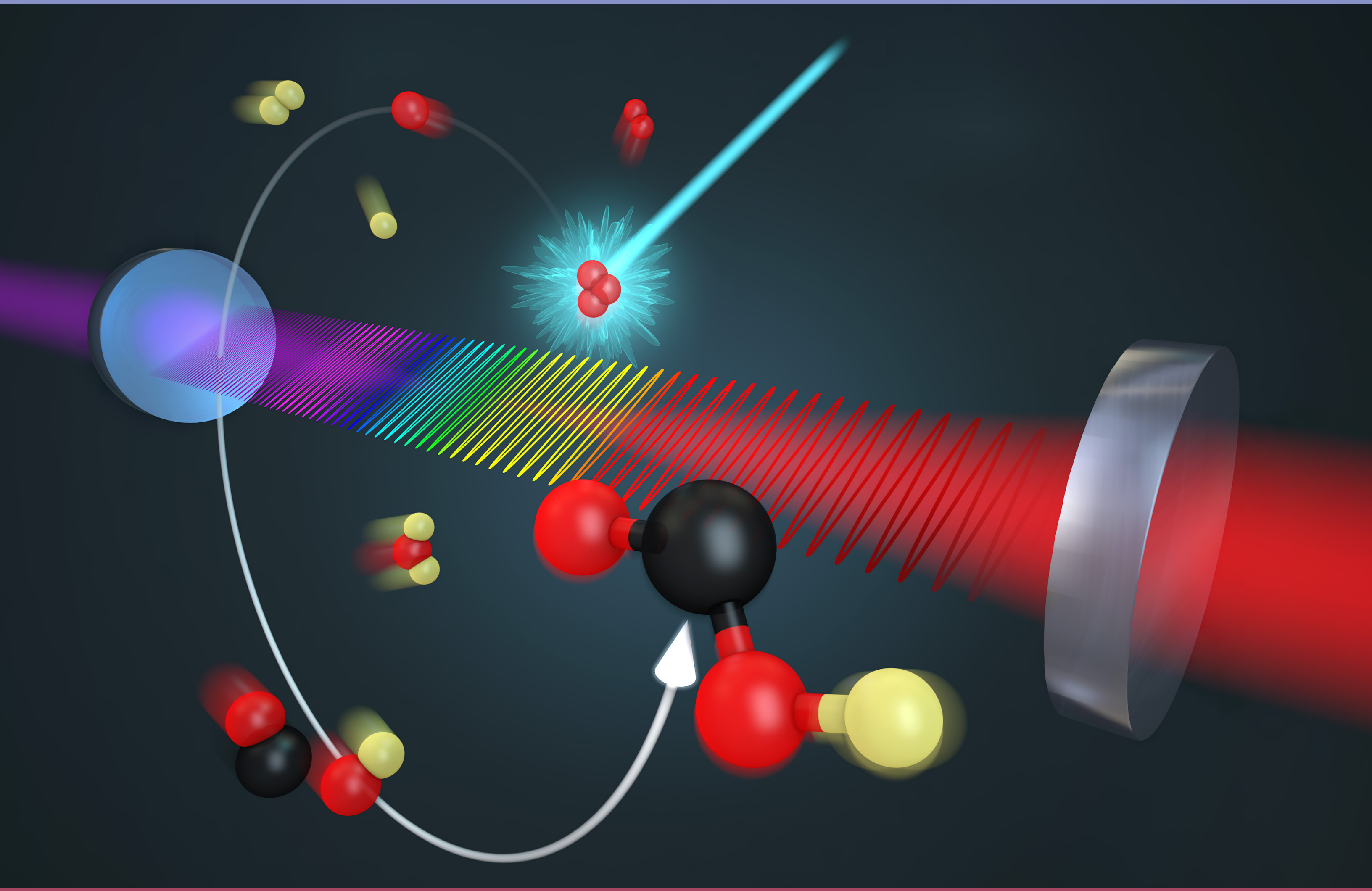
R. W. Peterson, T. P. Purdy, N. S. Kampel, R. W. Andrews, P.-L. Yu, K. W. Lehnert, and C. A. Regal, *Physical Review Letters* **116**, 063601 (2016).



To investigate how cold a tiny drum could get if it were laser cooled down to a limit set by the laws of quantum mechanics, graduate student Bob Peterson (shown here) and his colleagues in the Lehnert-Regal lab used this brand new refrigerator featuring gold plating on copper plates. The device can cool down to as low as 30 mK. Laser cooling then further cools a tiny drum to 14 μK, more than 2,000 times colder. Credit: The Regal group and Tom Purdy, JILA

CO-LABS 2016 Awards Ceremony

L-R: (1) Colorado Governor, John Hickenloooper, addresses the CO-LABS audience on October 6, 2016, at the Denver Museum of Nature & Science; (2) JILA CO-LABS award winners Konrad Lehnert (center) and Cindy Regal (right) with Konrad's wife Kate Houck (left); (3) Governor John Hickenlooper presents the award to Cindy Regal and Konrad Lehnert.



Artist's conception of an infrared frequency comb "watching" the reaction of a molecule of carbon monoxide (CO, red and black) and hydroxyl radical (OD red and yellow) as they form the elusive reaction intermediate DOCO (red/black/red/yellow) before DOCO falls apart. This chemical reaction was seen for the first time under normal atmospheric conditions in the laboratory by the Ye group. Credit: The Ye group and Steve Burrows, JILA

The Radical Comb-Over

Frequency comb spectroscopy is making it possible to watch chemical reactions unfold in real time

Using frequency comb spectroscopy, the Ye group has directly observed transient intermediate steps in a chemical reaction that plays a key role in combustion, atmospheric chemistry, and chemistry in the interstellar medium. The group was able to make this first-ever measurement because frequency combs generate a wide range of laser wavelengths in ultrafast pulses. These pulses made it possible for the researchers to "see" every step in the chemical reaction of $OH + CO \rightarrow HOCO \rightarrow CO_2 + H$.

This reaction is an example of the importance of free radicals such as the hydroxyl radical (OH), which has an unpaired electron that makes it highly reactive. Understanding (and one day controlling) the reaction OH + CO → HOCO → CO_2 + H will lead to a better understanding of combustion processes as well as atmospheric chemistry and greenhouse gases. In the atmosphere, for example, the reaction of OH with CO adds carbon dioxide (CO_2) to the atmosphere when fossil fuels are burned.

Here on Earth, Bryce Bjork, Thinh Bui, and their colleagues in the Ye group used frequency comb spectroscopy to observe the detailed intermediate steps of the full reaction of OH with CO for the first time. The researchers used one trick to make their job easier. They substituted deuterium (D), or heavy hydrogen, for the H in the OH.

Deuterium is easier to distinguish in the measurement of OD reacting with CO to form DOCO, which is the heavy-hydrogen analog of the short-lived HOCO intermediate. Although long predicted to exist, HOCO wasn't identified in conditions seen in nature until this year. Like HOCO, DOCO has so much energy that it rapidly shakes apart to form D and CO_2. That's why DOCO (and HOCO) have been so hard to find in the lab. They come and go in the blink of an eye.

With frequency comb spectroscopy, however, the researchers were able to "see" the formation of DOCO, how much of it was made, and watch DOCO separate into CO_2 and D. They were also able to take 10-microsecond snapshots of the spectra of the atoms and molecules as they interacted and reacted, thus making a complete record of the chemical reaction. The researchers not only observed the chemical reaction from start to finish, but also made a movie of it!

> "What's nice about frequency combs is that you have a broad array of spectral lines to use to unambiguously identify atoms and molecules," Bjork explained, "But you also get to use an optical cavity, which drastically increases the sensitivity. Plus, our camera allows us to take pictures of what's happening—almost in real time. These three components are what enabled us to do this experiment."

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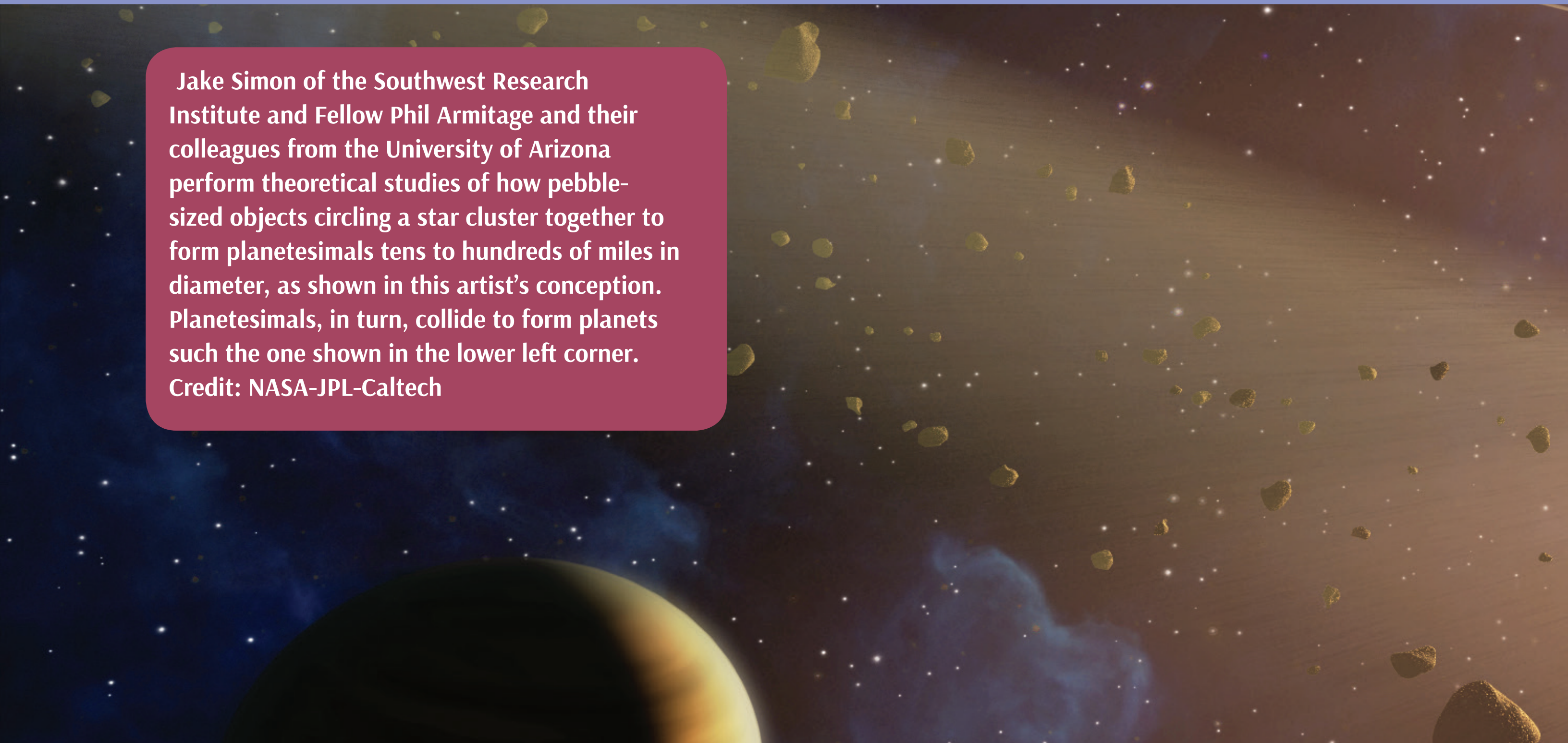
The researchers responsible for putting all this together include graduate students Bryce Bjork and Bryan Changala, research associates Thinh Bui, Oliver Heckl, and Ben Spaun, Fellow Jun Ye, and their colleagues from Crystalline Mirror Solutions, the University of Vienna and the California Institute of Technology. ✺

B. J. Bjork, T. Q. Bui, O. H. Heckl, P. B. Changala, B. Spaun, P. Heu, D. Follman, C. Deutsch, G. D. Cole, M. Aspelmeyer, M. Okumura, J. Ye, *Science* **354**, 444–448 (2016).

Adam J. Fleisher, Bryce J. Bjork, Thinh Q. Bui, Kevin C. Cossel, Mitchio Okumura, and Jun Ye, *The Journal of Physical Chemistry Letters* **5**, 2241–2246 (2014).



Jake Simon of the Southwest Research Institute and Fellow Phil Armitage and their colleagues from the University of Arizona perform theoretical studies of how pebble-sized objects circling a star cluster together to form planetesimals tens to hundreds of miles in diameter, as shown in this artist's conception. Planetesimals, in turn, collide to form planets such the one shown in the lower left corner. Credit: NASA-JPL-Caltech

Some Assembly Required

Fellow Phil Armitage and group collaborator Jacob Simon of the Southwest Research Institute are leading work to answer a central question about planet formation: How do pea- and pebble-sized objects orbiting within a protoplanetary disk evolve into asteroid-sized objects tens to hundreds of kilometers in size? This is an important question to answer because the eventual formation of planets around a star is mainly governed by the gravitational interactions of these primordial asteroids.

The formation of primordial asteroids is likely initiated by the gravity. When you have pebbles in a protoplanetary disk, under the right circumstances, the pebbles cluster into very dense clumps, which collapse into primordial asteroids, or planetesimals.

Armitage prefers to call them planetesimals because the word asteroid conjures up the Solar System's asteroid belt, which is filled with asteroids of all sizes, many of which were likely produced in violent collisions. In other words, most of the asteroids in the asteroid belt are too small (and new) to be considered planetesimals.

However, planetesimals may well exist in the Solar System. The Solar System's outermost region, known as the Kuiper belt, is sparsely populated and far from the Sun. This region has changed little since the Solar System formed. Planetesimals have survived there for billions of years. Because they are so far apart, they almost never collide. Curiously, many Kuiper-belt objects exist as pairs orbiting one another.

The Kuiper belt may offer insights into the creation of the building blocks of the eight major planets. Collisions between planetesimals are thought to have produced the rocky planets (Mercury, Venus, Earth, and Mars) and the cores of the giant planets (Jupiter, Saturn, Neptune, and Uranus).

Since the growth of planetesimals is central to the formation of planets, Armitage and Simon have been working on theoretically modeling this process with the help of National Science Foundation (NSF) supercomputers. In their modeling, the researchers are focusing on how pebble-sized objects clump together to form planetesimals of a wide range of sizes, from a few kilometers up to hundreds of kilometers.

A central focus of this work is the basic process known as the streaming instability. The streaming instability occurs because pebbles orbit faster than the gas around a star. As the pebbles and gas try to move through each other, the pebbles start clumping together.

"One analogy for this process is the formation of a peloton in the Tour de France," Armitage explained. "If you have a bunch of cyclists, and they're cycling against the wind, then they do better if they clump together in a group rather than staying spread out. So there can be an energetic advantage to being close together and clumped up. We think this behavior may be somewhat related to what happens to the pebbles." Armitage cautioned, however, that streaming instability isn't exactly the same thing as what happens to bicycle racers, but serves as an illustrative analogy.

Armitage and Simon plan to continue to probe what happens as clumps of pebbles collapse down to form denser planetesimals. They're particularly interested in learning how to accurately model the process in a real protoplanetary disk where the density of gas and solid material is quite low.

The researchers involved in this continuing quest to understand the formation of planetesimals include Rixin Li and former JILA senior research associate Andrew Youdin, both of the University of Arizona, JILA group collaborator Jacob Simon of the Southwest Research Institute, and Fellow Phil Armitage. ✺

Jacob B. Simon, Philip J. Armitage, Rixin Li, and Andrew N. Youdin, *The Astrophysical Journal*, 822:55 (18pp) 2016.

Deborah Jin (1969–2016)

Deborah Jin passed away September 15, 2016, after a courageous battle with cancer. She was 47. Jin was an internationally renowned physicist and Fellow with the National Institute of Standards and Technology (NIST), Professor Adjunct in the Department of Physics at the University of Colorado Boulder, and a Fellow of JILA, a joint institute of NIST and the University of Colorado.

A bright light at JILA has gone dim much too soon. For more than two decades, Deborah Jin was a friend and mentor to her JILA colleagues, young scientists in training, and JILA staff members. She was a role model and inspiration for women scientists, and hopefully the future will bring more women like her into science. JILA is grieving her loss.

"Debbie was an incredible scientist, outstanding mentor, valued friend, and loving spouse and mother," said Tom O'Brian, Quantum Physics Division Chief at JILA. "Her passing leaves a void at JILA, in the world-wide scientific community, and in the hearts of her family and friends that cannot be filled. Our deepest sympathies and thoughts are with Debbie's family, and her friends and colleagues at JILA and across the world."

Jin had many accomplishments and received much recognition for her work during an unusually productive career. She was a pioneer in polar molecule quantum chemistry. From 1995–1997, she worked with Eric Cornell and Carl Wieman at JILA on some of the earliest studies of dilute gas Bose-Einstein condensates, which form when particles known as bosons are cooled to just a few millionths of a degree above absolute zero (-459.67 °F). Since then she had continued to explore the physics of atomic gases at ultracold temperatures and investigates the link between superconductivity and Bose-Einstein condensation

Jin subsequently developed innovative technical systems to study the behavior of ultracold Fermi gases, whose atoms are particles known as fermions and can form a superfluid or Bose condensate, if they become correlated atom pairs. In 2003, her group made the first ultracold fermionic condensate, a new form of matter. Since 2004, her group has conducted detailed studies of the behavior of Fermi gases in the regime of strong interactions, or correlations.

In 2008, Jin collaborated with Fellow Jun Ye at JILA to create the first ultracold gas of polar molecules in the quantum regime. Using these ground-state potassium-rubidium (KRb) molecules, Jin and Ye began exploring ultracold chemistry in 2009. The team went on to use ultracold KRb molecules in a quantum simulator to investigate quantum behaviors.

"Debbie has forever changed my life with her friendship and scientific mind, and I am only one of many who were touched by her," said Jun Ye. "No words can describe the deepest sense of void left by Debbie's passing. She was the best friend, the best colleague, and the best critic, all in one."

Dana Anderson, Chair of the JILA Institute, added "As a scholar and educator Debbie leaves

The Jin Research Group, 2016

behind an indelible legacy of achievement at the University."

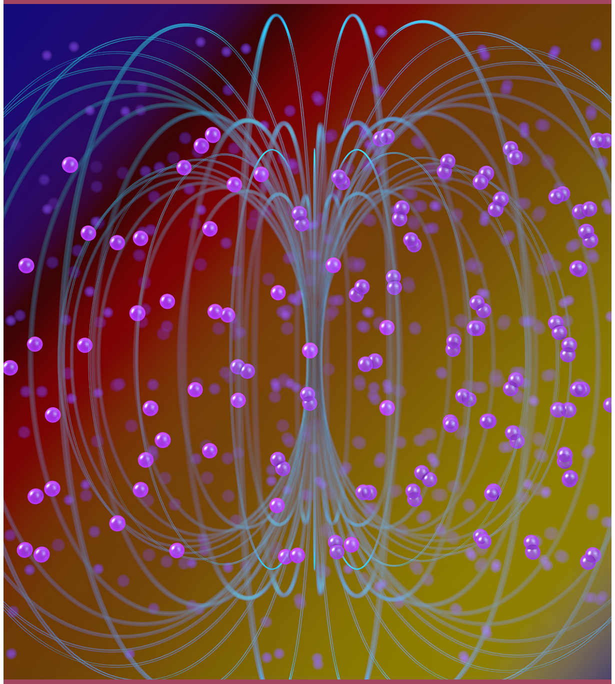
In 2003, Jin received a MacArthur Fellowship (commonly known as a "genius grant") from the John D. and Catherine T. MacArthur Foundation. In 2013, she was named the L'Oreal-UNESCO For Women in Science Laureate for North America. Her other prestigious awards include a 2002 Maria Goeppert Mayer Award, a 2004 Scientific American "Research Leader of the Year," a 2008 Benjamin Franklin Medal in Physics, a 2014 Institute of Physics Isaac Newton Medal, and the 2014 Comstock Prize in Physics. At the time of her election in 2005 and for several years afterward, Jin was the youngest member of the National Academy of Sciences.

"Deborah Jin was the definition of world-class faculty," said CU Boulder Chancellor Philip P. DiStefano. "The international scientific community has lost a giant, and our campus has lost a mentor to young scientists and an inspiration to female scientists. She will be deeply missed in many quarters. Our thoughts and prayers go out to her family."

Jin earned an A.B. in physics from Princeton in 1990 and a Ph.D. in physics from the University of Chicago in 1995. From 1995 to 1997, she was a National Research Council research associate at JILA, where she was hired in 1997 as a NIST physicist and assistant professor adjoint at the University of Colorado Boulder.

Deborah Jin is survived by her husband, JILA Fellow John Bohn, their daughter Jaclyn Bohn, siblings Laural Jin O'Dowd and Craig Jin, and mother Shirley Jin.

Deborah Jin, JILA Fellow. Credit: Steven Burrows, JILA



Strongly-acting fermions. Credit: Steven Burrows, JILA

JILA is a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology

University of Colorado **Boulder**

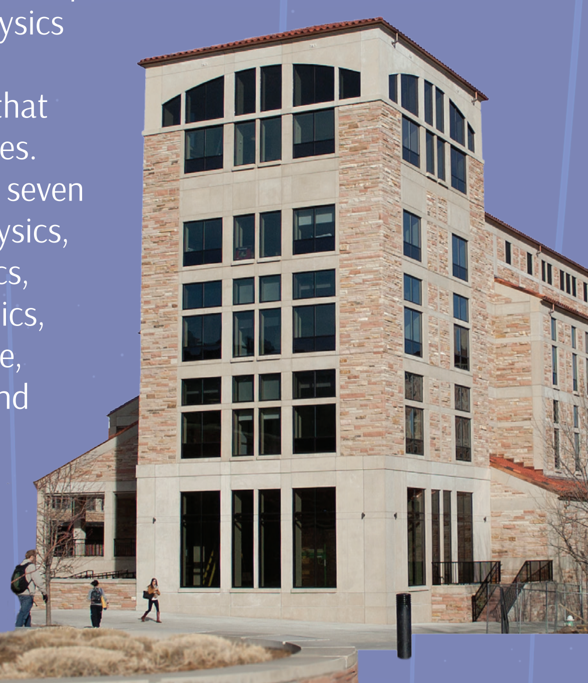
NIST National Institute of Standards and Technology
U.S. Department of Commerce

About JILA

JILA was founded in 1962 as a joint institute of CU-Boulder and NIST. JILA is located at the base of the Rocky Mountains on the CU-Boulder campus in the Duane Physics complex.

JILA's faculty currently includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Astrophysical & Planetary Science; Chemistry and Biochemistry; and Molecular, Cellular, and Developmental Biology as well as in the School of Engineering. NIST's Quantum Physics Division members hold adjoint faculty appointments at CU in the same departments.

The wide-ranging interests of our scientists have made JILA one of the nation's leading research institutes in the physical sciences. They explore some of today's most challenging and fundamental scientific questions about quantum physics, the design of precision optical and X-ray lasers, the fundamental principles underlying the interaction of light and matter, and processes that have governed the evolution of the Universe for nearly 14 billion years. Research topics range from the small, frigid world governed by the laws of quantum mechanics through the physics of biological and chemical systems to the processes that shape the stars and galaxies. JILA science encompasses seven broad categories: Astrophysics, Atomic & Molecular physics, Biophysics, Chemical physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information.



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