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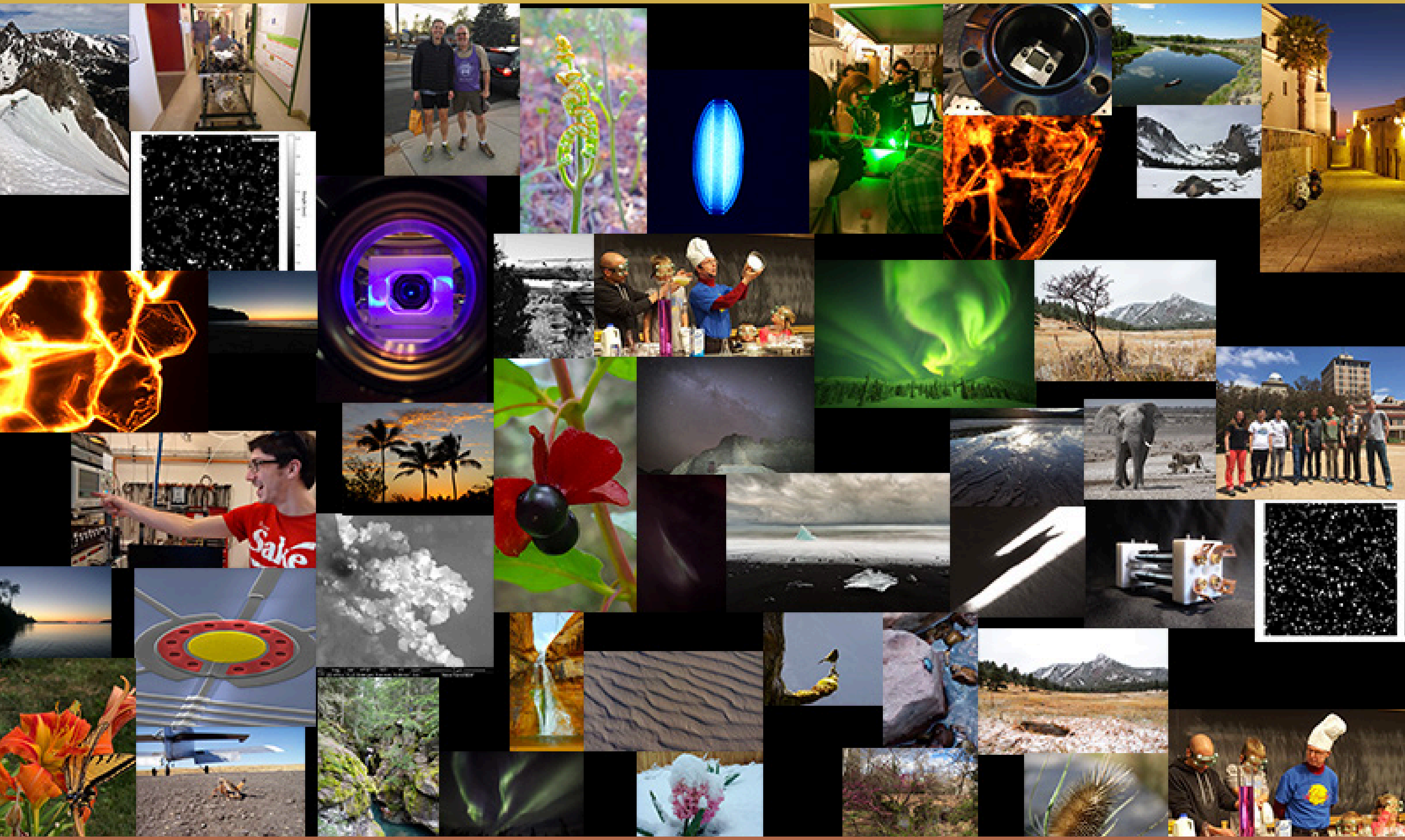
JILA light & MATTER

The Sharpest Images p.1



In May 2017, JILAns submitted photos in the 3rd Annual JILA Photo Contest. The four categories were JILA Science, Nanoscale Imagery, JILA People, and Nature Photography.

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The JLM staff do their best to track down recently published journal articles and great research photos and graphics. If you have an image or a recent paper that you'd like to see featured, contact us at: communications@jila.colorado.edu.

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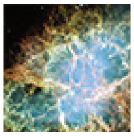
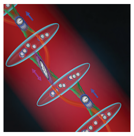
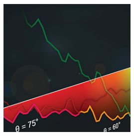
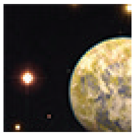
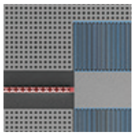
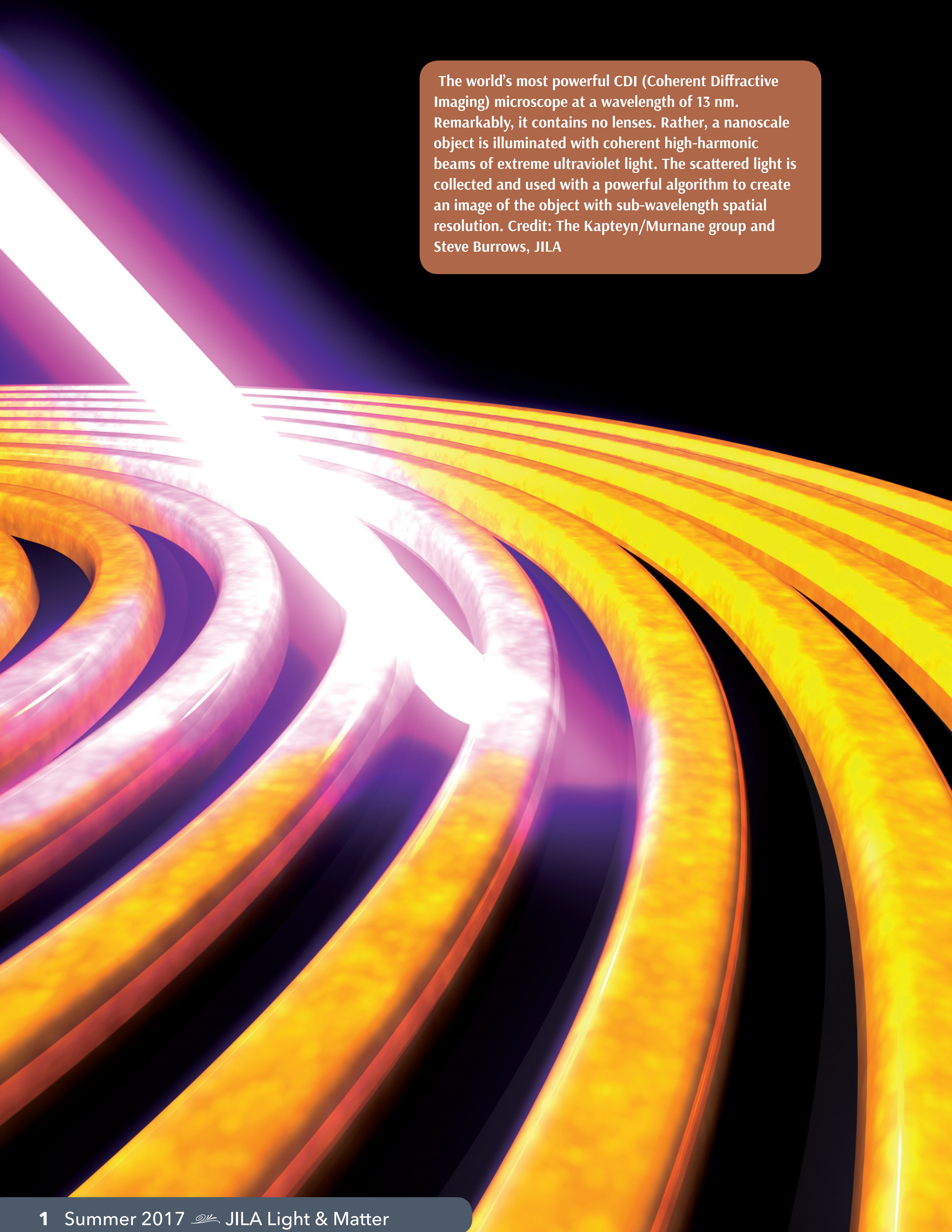






Features



The world's most powerful CDI (Coherent Diffractive Imaging) microscope at a wavelength of 13 nm. Remarkably, it contains no lenses. Rather, a nanoscale object is illuminated with coherent high-harmonic beams of extreme ultraviolet light. The scattered light is collected and used with a powerful algorithm to create an image of the object with sub-wavelength spatial resolution. Credit: The Kapteyn/Murnane group and Steve Burrows, JILA

The Sharpest Images

New X-ray Microscope Probes the Nano World—without Optics!

Dennis Gardner and his coworkers in the Kapteyn-Murnane group accomplished two major breakthroughs in imaging tiny structures much too small to be seen with visible light microscopes: (1) for the first time in the extreme ultraviolet (EUV) or soft X-ray region, they achieved a resolution smaller than the wavelength of the light; and (2) for the first time, they obtained high-resolution quantitative imaging of near-periodic tiny objects (structures with repetitive features).

To accomplish these breakthroughs, the team used coherent diffractive imaging (CDI), which amazingly does not require any optical components such as lenses or mirrors. At EUV wavelengths, optical components are difficult to make and typically cause substantial loss of EUV light. The team also surpassed results typically available only at enormous and expensive research facilities, such as synchrotrons and free electron lasers, by using only tabletop lasers and imaging systems. EUV imaging can provide simultaneous information about chemical composition and structure, which are crucial to understanding nanoelectronic devices, advanced materials, and biological samples. The Kapteyn-Murnane group has just made EUV imaging potentially more powerful using imaging systems orders of magnitude smaller and less expensive than the previously required synchrotrons and free electron lasers.

The Kapteyn-Murnane group's CDI technology provides a new tabletop imaging capability that is complementary to scanning electron microscopes, but without having to bombard the object with potentially damaging high-energy charged particles. To image with such high resolution, it is necessary to use light with wavelength shorter than the size of the object. In this case, the researchers used light in the EUV region of the electromagnetic spectrum. This work shows that, with the right type of illumination, i.e., a laser beam, previous limitations of X-ray microscopy can be overcome. This breakthrough will be critical for imaging and designing the next generation of nano-engineered devices.

The secret of making CDI work well began with innovative basic research on high-harmonic generation (HHG) in the K/M group for more than 20 years. In HHG, a strong laser field rips an electron from an atom such as argon or some other noble gas. The electrons then smash back into these atoms in a way that retains their coherence and produces coherent EUV or soft-X-ray beams. This process is essentially a quantum version of the ubiquitous X-ray tube.

Getting the highest resolution CDI images requires very stable illumination for a coherent microscope. Fortunately, KMLabs had recently developed a robust tabletop device that reliably produces ultra-stable coherent beams with a 13.5 nm wavelength. This EUV light is about 50 times shorter than visible light.

KMLabs allowed JILA to test the newest version of its device in a research project to produce the sharpest images ever. The device made it possible for the JILA-KMLabs team to create the first sub-wavelength spatial resolution X-ray microscope from any light source—whether tabletop scale or in a large facility. Consequently, CDI is revolutionizing X-ray imaging because it is simple to implement and extremely powerful—almost magical.

One simply shines an EUV or X-ray laser onto an object, which scatters the light and creates a speckle pattern. By directly recording this speckle pattern and then using a computer (cont. page 3)

(cont. from page 2) algorithm, the computer constructs an image. This technique is well suited for an X-ray microscope because X-ray lenses are not only very expensive, but also don't work very well. In contrast, CDI has much better resolution because there are no lenses between the sample and the detector—thus the image is distortion-free.

At JILA, the K/M group used a CDI technique called "ptychography" in which multiple diffraction patterns were collected using a detector to record the scatter from overlapping areas of the sample. This technique provided enough information for the computer algorithm to reconstruct the amplitude and phase of the light coming off the sample plus the amplitude and phase of the focused beam that illuminated the sample.

The result was the highest resolution ever measured for a tabletop-scale microscope using light, rather than electrons, for illumination. This is a particularly important advance because electrons cannot be used to image many types of samples because of the accumulation of charge and sample damage.

The researchers responsible for this breakthrough study include recently minted JILA Ph.D. Dennis Gardner; graduate students Michael Tanksalvala, Elisabeth Shanblatt, Benjamin Galloway, Christina Porter, Robert Karl, Jr., and Charles Bevis; JILA Ph.D. Xiaoshi Zhang now at KMLabs; University of Colorado Boulder Research Professor Dan Adams; Fellows Henry Kapteyn and Margaret Murnane; and research associate Guilia Mancini.✺

D.F. Gardner, Tanksalvala, M., Shanblatt, E.R., Zhang, X., Galloway, B.R., Porter, C.L., Karl Jr., R.M., Bevis, C., Adams, D.E., Kapteyn, H.C., Murnane, M.M., and Mancini, G.F., *Nature Photonics* **11**, 259–263 (2017).

IN THE NEWS

JILA FOUNDING FELLOW STEPHEN J. SMITH DEAD AT 92

Dr. Stephen J. Smith, Founding Fellow of JILA, passed away on June 10, 2017, at the age of 92. He is survived by his wife of 66 years, three of his five sons, and four grandchildren.

Smith was one of seven NIST scientists who relocated to Boulder, Colorado, in 1962, to found the Joint Institute for Laboratory Astrophysics (JILA) with the University of Colorado Boulder Physics Department. The joint institute was officially launched April 13, 1962. Fifty years later, Smith contributed a delightful introduction entitled "Genesis: Inspiration for an institute" to the web book *JILA: The First 50 Years*.

In his introduction, Smith recounted how he worked with Lewis Branscomb at the National Bureau of Standards (NBS) to refine Branscomb's research apparatus and institute the use of radiometric standards. The accuracy of their data improved to a level where it provided support for the Chandrasekhar model of the solar visible spectrum.

"Thus, in my mind, was born the field of laboratory astrophysics," Smith recalled more than 50 years later. This was "laboratory work in atomic physics closely related to theoretical issues faced by astronomers. Though it didn't yet have a name, laboratory astrophysics was about to run headlong into the space race."

In 1958, Branscomb and Smith began working with Michael Seaton of University College London and met Richard N. Thomas, a theoretical astrophysicist from Boulder, Colorado. The three began talking about ideas for an institute that would bring together atomic physics, astrophysics, and a theory of energy transfer through the very hot gases in stars. These conversations began just a year after the launch of Sputnik 1.

By 1960–1961, the search was on for the "right university." After CU Boulder was selected, six NBS scientists,

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

including Smith and Branscomb, were appointed Professors Adjoint at CU. At the time, Branscomb was the Chief of the NBS Atomic Physics Division and Smith led the Atomic Physics Section (1960–1962).

In 1962, CU President Quigg Newton and Wesley Brittin, Chair of CU's Physics Department, agreed to partner with NBS to form the Joint Institute for Laboratory Astrophysics. The question then became: Who was going to move to Boulder?

"Of course, nothing was going to keep Branscomb and me from coming out to Boulder to launch JILA," Smith remembered. He and his family moved to Boulder in 1962. Smith served as Chair of JILA in 1971–1972. He was Deputy Chief, the Chief of the Laboratory Astrophysics Division of NBS from 1966 to 1977. He was Adjoint Professor of Physics at CU Boulder from 1966 through 1995.

Donations may be made to the JILA Fund (https://giving.cu.edu/fund/jila-fund) "In memory of JILA Fellow Stephen J. Smith."

DAMOP THESIS AWARD RENAMED TO HONOR DEBORAH JIN

The American Physical Society is memorializing Fellow Deborah Jin by renaming the APS Division of Atomic, Molecular and Optical Physics (DAMOP) Award for "Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics." Henceforward, the award will be called the Deborah Jin Award for Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics.

On April 27, 2017, the Deborah Jin Memorial Endowment Campaign reached its goal of raising $100,000 to supplement the award's existing endowment fund. The income from this endowment will help with travel expenses for finalists and provide funding to make it possible for a more diverse group of students to attend the annual DAMOP meeting.

The Deborah Jin Award for Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics recognizes thesis research of outstanding quality and achievement in these areas of physics. The award consists of a $2,500 stipend, a certificate citing the achievements of the recipient, and a travel allowance of $1,000 for finalists to attend the DAMOP annual meeting. At this meeting, the recipient of each year's award is selected and presented with the award.

M Squared Lasers generously sponsors the DAMOP award, which will now honor Deborah Jin in perpetuity while recognizing young researchers.

MARKUS RASCHKE RECEIVES A FRIEDRICH WILHELM BESSEL RESEARCH AWARD

Markus Raschke has been given a Friedrich Wilhelm Bessel Research Award by the Humboldt Foundation. The award is given in recognition of lifetime achievements in research. Award winners are invited to conduct reseach projects of their choice in cooperation with colleagues in Germany, with the goal of promoting international scientific cooperation. The Humboldt Foundation annually grants about 20 of these awards, which are valued at 45,000 Euros. Award winners are invited to spend up to one year collaborating on a long-term research project with colleagues at a research institution in Germany. This period of collaboration may be divided into blocks of time.

Raschke was nominated for this prestigeous award by Prof. Dr. Martin Wolf of the Fritz Haber Institute of the Max Planck Society (FHI), Berlin, Germany. Raschke joins other young scientists who completed their doctorates less than 18 years ago and who have also become internationally renowned in their field. In bestowing this award, the Humboldt Foundation expects the awardees to continue producing cutting-edge research achievements that have influence well beyond their immediate field of work.

Nominations for this award come from established academics in Germany. Congratulations Markus!

The Fast and the Furious

The lovely Crab Nebula was created by a supernova, and its spinning-neutron-star remnant is known as a pulsar. Pulsar wind nebulae, accretion disks, and jets emanating from black holes are made of plasmas of charged particles, such as electrons and protons, traveling at near the speed of light.

A key question in astrophysics has long been: What process accelerates some of the charged particles in plasmas to energies much higher than the average particle energy, giving them near light speeds? It can't be collisions because the particles are simply too far apart to run into each other. It can't just be high temperature, because cold plasma can also contain a small population of particles that move at a significant fraction of the speed of light. But, it must be something fairly ordinary, because relativistic plasmas are not uncommon.

Research associate Vladimir Zhdankin, Fellow Mitch Begelman and their University of Colorado Boulder colleagues believe they have found the answer.

"The physical mechanism responsible for accelerating these particles may have been hiding in plain sight," Zhdankin explained. "The turbulence that inevitably forms in astrophysical plasmas can be an efficient particle accelerator."

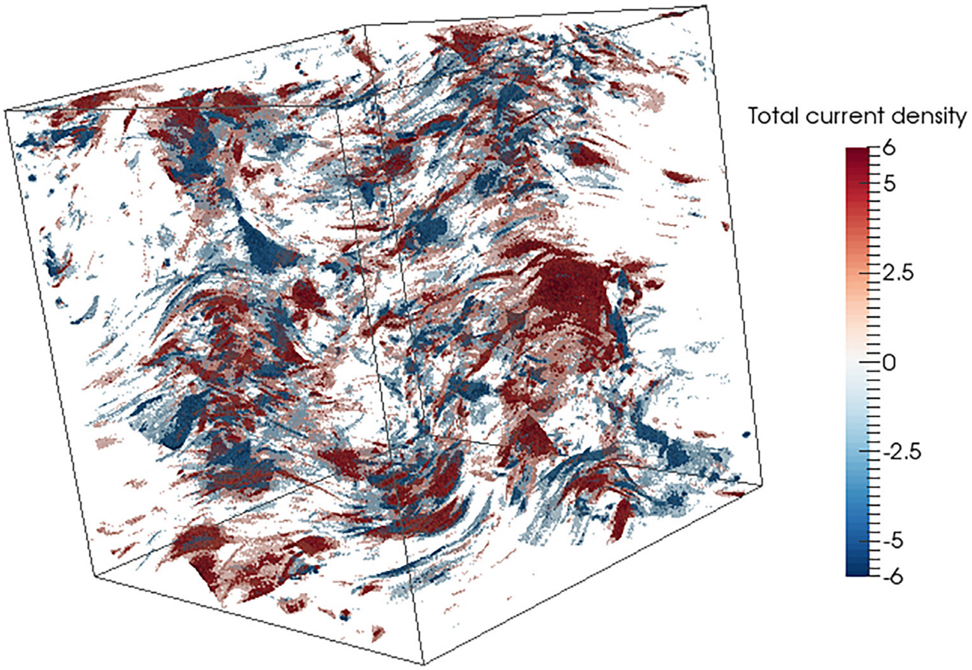
To test this idea, the researchers performed a massive supercomputer-based simulation of the effects of turbulence on relativistic plasmas in which the particles do not collide, but rather interact through their mutual electric and magnetic fields. The simulation showed how the energy of large-scale motions and magnetic fields starts a process that leads to a fraction of the particles gaining a massive amount of energy. As the turbulent motions approach relativistic speeds, particle acceleration becomes more efficient–sufficiently efficient to explain the acceleration of the charged particles in the plasma to near light speeds.

The researchers also found evidence that particle acceleration may also be the result of the random scattering of particles between turbulent magnetic structures, a mechanism originally proposed by Enrico Fermi in 1949. This mechanism suggests that turbulence may produce energetic particles in a variety of high-energy astrophysical systems.

Either way, Zhdankin says that turbulence has a big advantage over other proposed mechanisms, such as shockwaves and magnetic reconnection, as the main mechanism for accelerating charged particles to relativistic speeds in plasmas. Turbulence is likely to be inevitable in astrophysical plasmas. In contrast, the alternatives mechanisms, shockwaves and magnetic reconnection, require specific large-scale configurations that may not be always present. ✺

Vladimir Zhdankin, Gregory R. Werner, Dmitri A. Uzdensky, and Mitchell C. Begelman, *Physical Review Letters* **118**, 055103 (2017).

The Crab Nebula (shown here) was created by a supernova and its spinning-neutron star remnant known as a pulsar. Pulsar wind nebulae, accretion disks, and black-hole jets are made of plasmas of charged particles traveling at near the speed of light. Acceleration of these particles is likely caused by turbulence in the plasmas. Credit: Hubble Space Telescope mosaic image assembled from 24 individual Wide Field and Planetary Camera 2 exposures taken in October 1999, January 2000, and December 2000 (NASA).



Electric current density in a simulation of turbulence in relativistic plasmas. Credit: Vladimir Zhedankin, JILA

Quantum Leaps

Research associate Shimon Kolkowitz and his colleagues in the Ye group and Rey theory group have developed a powerful new way to experimentally simulate the complex behavior of electrons in solids.

In these experiments, the team uses its strontium-lattice optical clock not to track time, but to take advantage of the ultracold atoms in the clock mimicking the quantum behavior of electrons in a lattice of metal atoms. Because the ultracold atoms in the clock can be controlled and measured so much more precisely than electrons in a solid, the electron simulator based on the clock can provide information that cannot be obtained directly from the solids or electrons. The team's secret is coupling the motion and internal states of strontium atoms via their interactions with laser light. These innovative clock experiments will not only improve traditional timekeeping applications, but also could one day lead to brand new materials or contribute to the design of reliable and robust quantum computers.

The advantages of the clock setup for reaching such long-term goals include not only precision control of the quantum states in each atom, but also novel measurement techniques and the ability to perform experiments without heating up and losing atoms—processes that could mask interesting physics. The use of the clock is expected to make it possible for the group to investigate the physics of single strontium atoms as well as the complex phenomena that occur when interactions between those atoms are introduced into the experiment.

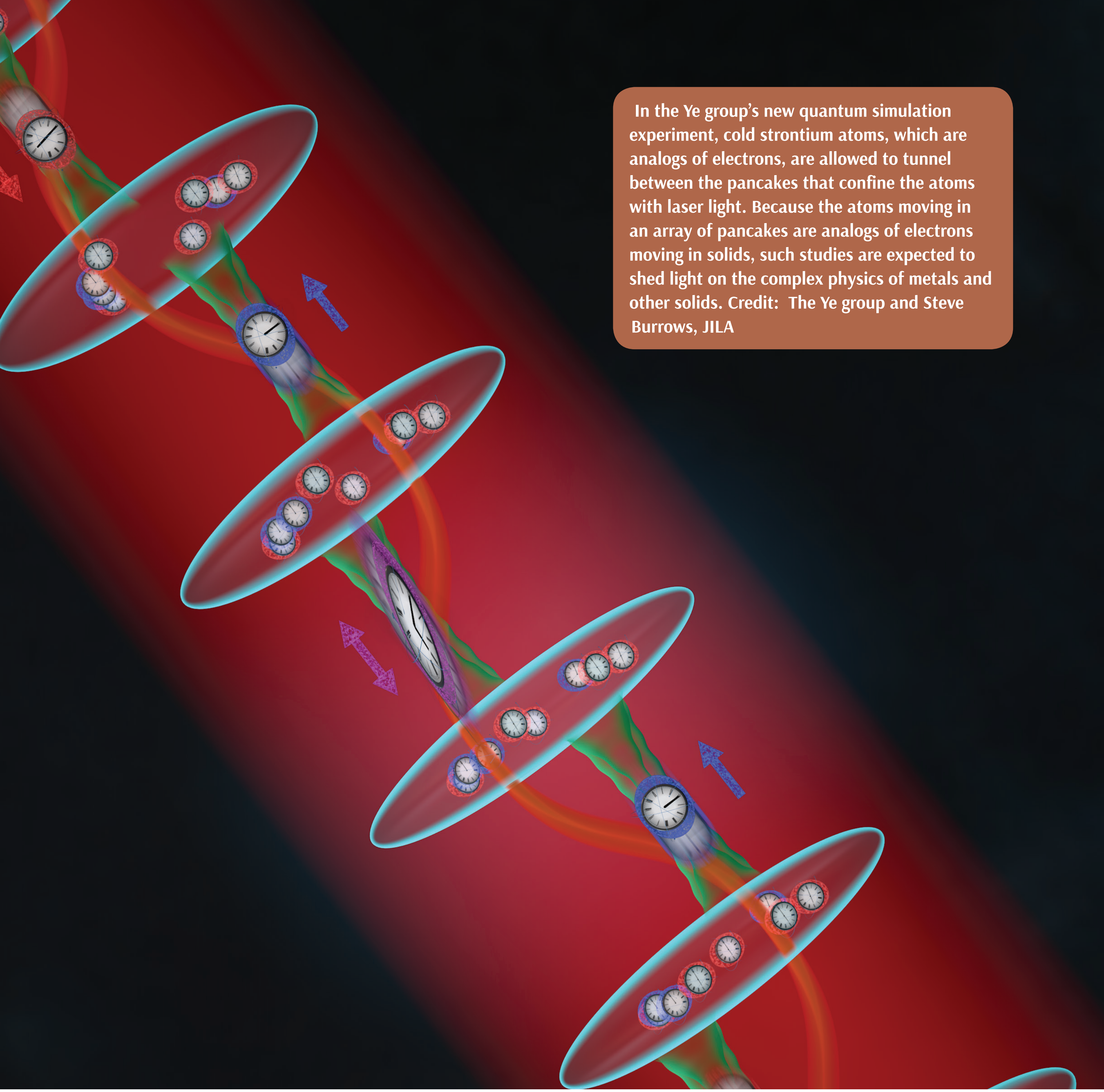
In the clock, strontium atoms play the role of electrons in a solid. The atoms are confined in stacks that look like pancakes with laser light, which uncouples their motion from their internal states. This decoupling is what makes the device such a good clock.

However, in the new experiment the group allows the atoms, which are the analogs of the electrons in solids, to "hop" from pancake to pancake. The hopping motion of the atoms between pancakes is a quantum effect that happens via quantum tunneling. Quantum tunneling allows the atoms to pass through energy barriers rather than climbing over them.

"The atoms move from site to site on the lattice (a crystal of light created by the laser), and that's a lot like the physics you get in a solid like a metal or other material where electrons move around in a periodic crystalline structure," Kolkowitz explained. This means the new clock experiment can simulate some of the same physics you find in solids, including the Rey theory group's prediction of spin-orbit coupling, in which the motion of atoms becomes correlated with their spin.

Thus far, the group has been able to "see" some interesting physics in their experiment, including spin-orbit coupling and another interesting behavior called Bloch oscillations, in which the strontium atoms appear to slosh back and forth under certain conditions.

The researchers were also able to simulate more exotic physics with this system. They saw the atoms moving in what physicists call "chiral currents." Chiral currents go around the edge of a material, such as one of the pancakes, either clockwise or counterclockwise. Under the right circumstances, they are predicted theoretically to be robust enough to create a kind of superconductivity, which the researchers are hoping to observe when atomic interactions are introduced into the experiment.



In the Ye group's new quantum simulation experiment, cold strontium atoms, which are analogs of electrons, are allowed to tunnel between the pancakes that confine the atoms with laser light. Because the atoms moving in an array of pancakes are analogs of electrons moving in solids, such studies are expected to shed light on the complex physics of metals and other solids. Credit: The Ye group and Steve Burrows, JILA

The researchers responsible for the theoretical and experimental work leading up to this exciting, new optical-lattice-clock experiment include Kolkowitz, graduate students Sarah Bromley, Tobias Bothwell, and Andrew Koller, research associate George Marti, former senior research associate Michael Wall, former research associate Xibo Zhang, and Fellows Ana Maria Rey and Jun Ye. ✺

S. Kolkowitz, S. L. Bromley, T. Bothwell, M. L. Wall, G. E. Marti, A. P. Koller, X. Zhang, A. M. Rey and J. Ye, *Nature* **542**, 66–70 (2017).

Force spectroscopy unveils hidden protein-folding states

Specially developed short, bendy cantilevers may be the key to accessing biomolecular dynamics.

Reproduced from Johanna L. Miller, "Force Spectroscopy Unveils Hidden Protein-folding States," *Physics Today* **70**(5), 16 (2017), with the permission of the American Institute of Physics.

For 30 years atomic force microscopy (AFM) has been imaging surfaces with subnanometer resolution. As a thin, flexible cantilever with an automatically sharp tip is scanned back and forth across the surface, the tip's vertical position is monitored by reflecting a laser beam off it. The cantilever's minute deflections reveal the surface topography.

But AFM is not limited to determining where atoms and molecules are—it can also manipulate them. In single-molecule force spectroscopy, for example, an AFM tip attached to one end of a protein, as shown in figure 1, is gently raised to unravel the folded chain of amino acids. From the heights at which the cantilever stalls on its upward trajectory, researchers infer the presence of stable intermediate states of the partially unfolded molecule.[1] Those states offer clues about the energetics of how the molecule folds into its correct structure to begin with.

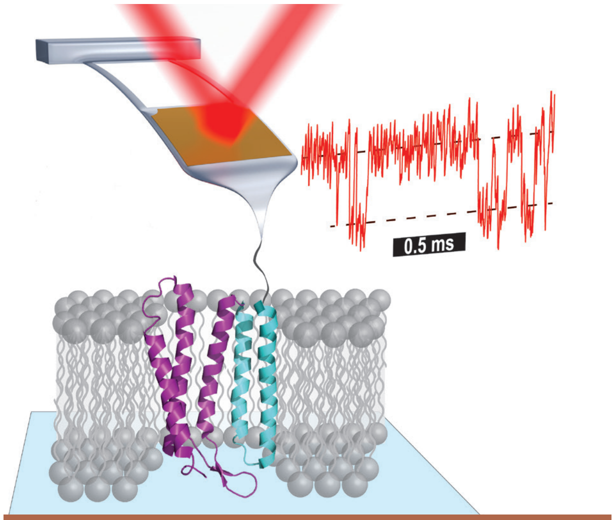


FIGURE 1. IN SINGLE-MOLECULE FORCE SPECTROSCOPY of the membrane protein bacteriorhodopsin, the tip of an atomic force microscopy cantilever is attached to the protein. As the cantilever is raised, it gently tugs on the protein, and its vertical position is tracked by a reflecting laser beam. Bacteriorhodopsin consists of seven vertical helices; for clarity, only five are shown here.

In contrast to the atomic-resolution surface images, AFM measurements of protein-folding dynamics have offered only a coarse view. The problem is water: Proteins need to be studied in an aqueous environment, and hydrodynamic drag slows a standard cantilever's response time to hundreds of microseconds. Any change in the protein's state that occurs on a faster time scale is invisible to such an approach.

For the past decade, Thomas Perkins and colleagues at JILA in Boulder, Colorado, have been working to develop a cantilever optimized for studying protein folding with high time resolution. Now the JILA researchers have put their most advanced cantilevers to work to probe the folding dynamics of bacteriorhodopsin, a protein that harvests photon energy to pump protons across the cell membrane.[2] With 10 times the force precision and 100 times the time resolution of previous AFM measurements of bacteriorhodopsin, they've uncovered an intricate protein-folding landscape that had never been seen before.

All that glitters

The perfect cantilever for force spectroscopy needs several qualities. It should move through water easily enough to respond to a microsecond change in the protein's state. It should be supple enough that a piconewton force produces a measurable deflection. It should be over-damped, so a change in the applied force doesn't set it oscillating. It should be optically reflective, so the laser signal can be detected. And it should be stable over the course of an experiment, so a given force always produces the same deflection.

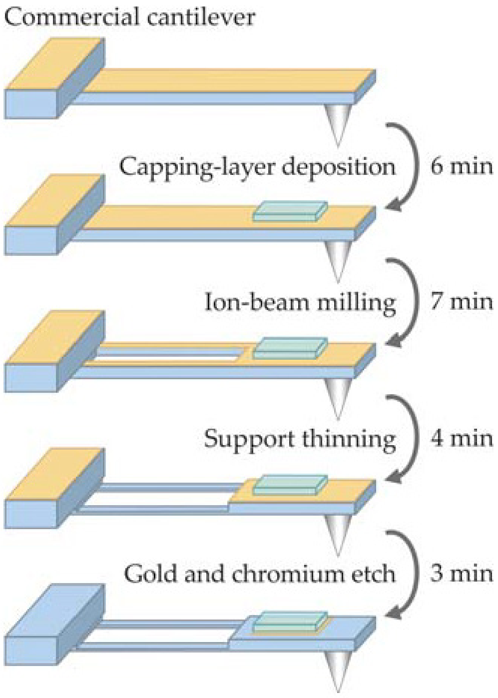


FIGURE 2. A COMMERCIAL CANTILEVER in an aqueous environment creates too much hydrodynamic drag for microsecond-resolution force spectroscopy, and its gold coating causes force measurements to drift over time. To overcome both those problems, Thomas Perkins and colleagues modify the cantilevers with the quick four-step protocol shown here. (Adapted from ref. 4.)

Sometimes those requirements are at odds with one another. The easiest way to reduce hydrodynamic drag is to make the cantilever shorter, but that also increases stiffness and reduces damping. Commercial cantilevers come coated in gold to maximize their reflectivity. But Perkins and company discovered that—for reasons not entirely understood—the gold causes the cantilever's free-standing position to drift over time, which destabilizes force measurements.[3]

Figure 2 shows the protocol the JILA researchers developed to mitigate those tradeoffs.[4] Starting with a commercial cantilever, they apply a transparent capping layer to protect part of the gold coating. Next, they use a focused ion beam to cut away part of the cantilever, thin the supports, and etch away the unprotected gold and underlying chromium. The process is quick and straightforward, says Perkins: "This set of cantilever modifcations was developed by a talented undergraduate, and undergraduates in our lab routinely make these modifications."

Thus modified, a short (40 μm) cantilever can be used in a standard AFM with no problems. But when Perkins and colleagues progressed to modifying ultrashort (9 μm) cantilevers, they found that the remaining area of gold was too small to reflect the laser beam. So they engineered a new detection-laser module for their AFM system to focus the laser to a sufficiently small spot.[5]

Bacteriorhodopsin

Although the JILA researchers performed proof-of-principle tests along the way to check their modified cantilevers' time resolution and force precision, the new work represents their first move toward a system of biophysical interest. Bacteriorhodopsin, a protein in the cell membrane of saltwater-dwelling single-celled organisms, is homologous to G-protein-coupled receptors (GPCRs), an important class of membrane proteins in more complex organisms, including humans. The receptors are responsible for many types of cellular signaling, and as such, they're the targets of some 40% of all pharmaceutical drugs.

But the dynamics of GPCRs and other membrane proteins are not well understood, for several reasons. They tend to be larger than the more commonly studied globular proteins, and their structure and function depend critically on the heterogeneous environment of the cell membrane. Unlike many smaller proteins that find their correct folded structures on their own, membrane proteins fold via an intricate process that often requires the assistance of so-called chaperone molecules.

Like GPCRs, bacteriorhodopsin consists of seven helical structures that extend across the membrane. Previous force spectroscopy studies typically found intermediate states that corresponded to the full unfolding of each of those helices. But molecular dynamics simulations predict that many more intermediates should exist.

With their improved cantilevers, Perkins and colleagues studied the bacteriorhodopsin helices shown in blue in figure 1. They found a series of 14 distinct intermediates, many of them separated by the unwinding of less than a single helix turn. Figure 3 illustrates the complexity of their observations. The force–time data in figure 3a show the molecule hopping among adjacent intermediates several times a millisecond. Figure 3b sketches the first five intermediates, corresponding to the unfolding of half of the first helix. The thicknesses of the purple and orange connecting lines represent the prevalence of transitions between pairs of intermediates. Notably, transitions were not limited to adjacent intermediates, and both unfolding and refolding transitions were observed.

The surfeit of data is just the beginning; just what it all means remains to be seen. Comments Michael Woodside of the University of Alberta in Edmonton, "As we've seen repeatedly in other contexts, an order-of-magnitude increase in resolution often leads to big changes in understanding of the underlying physics. I expect something similar to happen here."

Off the shelf

Perkins and colleagues' modified AFM apparatus isn't the only way to obtain a microsecond view of biomolecular folding. Last year, Woodside and colleagues achieved similar resolution by tethering each end of a molecule to a bead held in an optical trap. (See "Physics Today", June 2016, page 14.) That approach is useful for some applications, but it has the disadvantage of requiring a custom-built setup. Using a commercial AFM instrument, even with a few modifications, is much easier.

And Perkins is hoping for a day when researchers won't have to make those modifications themselves. "None of our cantilever improvements are covered by a patent or pending patent," he says, "and there's no reason why cantilever companies and AFM manufacturers can't implement 90% of them

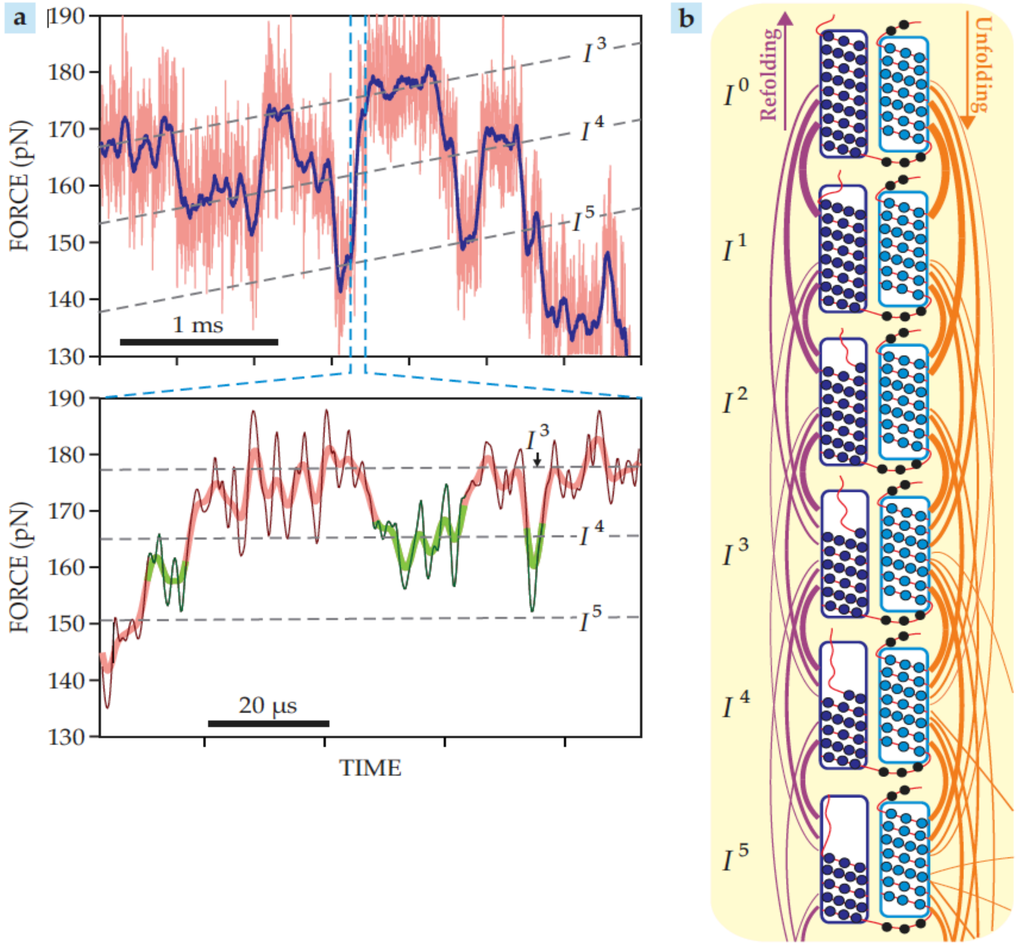


FIGURE 3. UNFOLDING TWO HELICES of bacteriorhodopsin revealed 14 stable intermediate states (I^n for n = 1–14, with I^0 representing the fully folded helices), most of which had never been detected before. (a) Force–time plots show the molecule hopping among the third, fourth, and fifth intermediates, indicated by the dashed lines. As highlighted by the green segments in the bottom panel, sometimes intermediates are occupied for just a few microseconds. (b) The first five intermediates, schematically shown here, span the unfolding of half of the first (dark blue) helix. The orange and purple curves indicate the likelihood of various unfolding and refolding transitions. (Adapted from ref. 2.)

using wafer-scale manufacturing." In the short term, he's collaborating with other groups to demonstrate the cantilevers' scientific applicability; in the longer term, he hopes those studies will spur demand for manufacturers to commercialize the modified cantilevers.

—Johanna Miller

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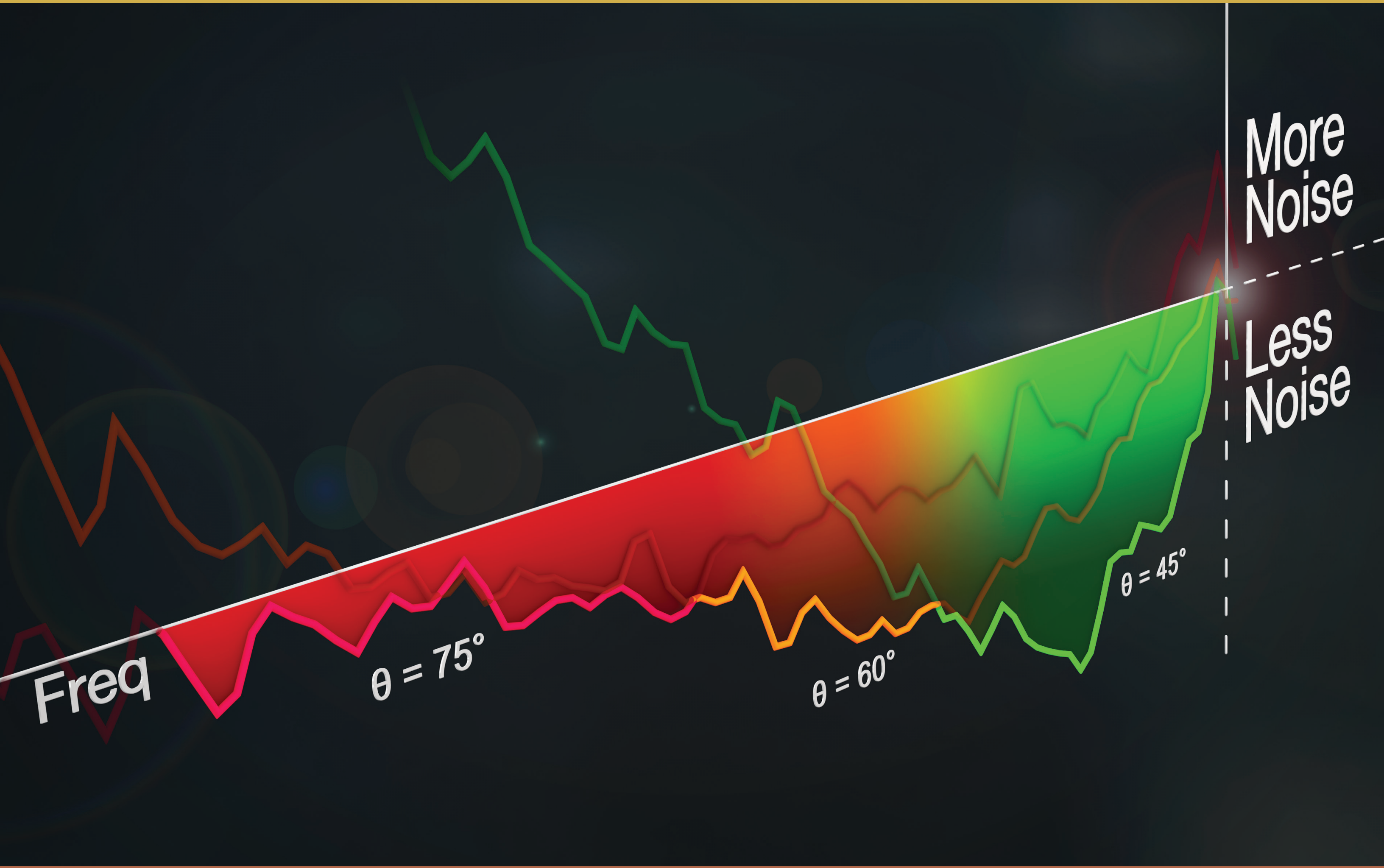
5. D. T. Edwards et al., *Nano Lett.* **15**, 7091 (2015).



Using the chameleon interferometer, the Regal group used quantum correlations to reduce quantum noise in measurements of a membrane vibrating at certain frequencies. Credit: The Regal group and Steve Burrows, JILA

The Chameleon Interferometer

It's all about making measurements better

The Regal group recently met the challenge of measurements in an extreme situation with a device called an interferometer. The researchers succeeded by using creative alterations to the device itself and quantum correlations. Quantum correlations are unique, and often counterintuitive, quantum mechanical interactions that occur among quantum objects such as photons and atoms. The group exploited these interactions in the way they set up their interferometer, and improved its ability to measure tiny motions using photons (particles of light).

The group started with an ordinary interferometer, a device that has long been used for making precision measurements. However, this particular interferometer included a tiny vibrating membrane. In typical interferometers, sending more photons into the device improves the measurement precision. But, the Regal group accessed a strange regime in which sending more photons into the interferometer actually reduced the precision of the measurements.

But instead of giving up on improving their measurements, the researchers were able to make a record-setting measurement of a vibrating mechanical membrane in the interferometer. The researchers set up the interferometer in a new way that allowed its quantum behaviors to work towards bettering the overall measurement precision. In the end, they made measurements better than what the standard quantum limit, or SQL, would dictate for their experiment. The SQL is like a "brick wall" of noise limiting how precisely even the most careful quantum measurements can be made. But, as the Regal group has just shown, the SQL only applies to measurements in an ordinary interferometer.

The group's creative device that bested its predicted SQL has been dubbed the chameleon interferometer. The chameleon interferometer is the group's solution to how to reduce measurement noise due to both shot noise produced in the detector and quantum backaction. What produces backaction is the light the researchers use to measure the vibrating membrane. Photons in the light bounce off the membrane, causing it to shake. This shaking is the backaction; hence more photons make things worse.

When the group used its interferometer to measure the vibrating membrane, the detector collected the photons from the interferometer. However, there was some quantum noise associated with that process—called shot noise. So two things were happening that affected the measurement: the shot noise associated with the detector and the backaction that occurred when the photons hit the membrane.

In the midst of all this quantum noise—the shot noise and the quantum backaction—the group wanted to precisely measure the position of the membrane. So, the researchers decided to take advantage of quantum correlations to reduce the noise in the measurement of the membrane motion. The researchers tuned the interferometer to produce less quantum noise in the measurement they were interested in, but more noise and uncertainty somewhere else.

The group made multiple changes to the interferometer before it found the best configuration for making the measurement. With this configuration, they were able to measure the position of the membrane better in their chameleon interferometer!

"The interferometer we now have is tunable with a simple knob," Regal said. "We introduced quantum correlations to detect the membrane better. And, to tune up the measurement for a certain vibration, we just turn our knob to take best advantage of the correlations."

In other words, the group turned its perfectly normal interferometer into a chameleon interferometer whose configuration can be changed to best suit the measurement at hand. And, in so doing, it succeeded in a stunning demonstration. The researchers responsible for this new insight into working with quantum correlations in measurement science include former research associate Nir Kampel, graduate student Robert Peterson, research associate Ran Fischer, JILA Ph.D. Pen-Li Yu, Fellows Konrad Lehnert and Cindy Regal, and NIST colleagues Katarina Cicak and Ray Simmonds. ✺

N. S. Kampel, R. W. Peterson, R. Fischer, P.-L. Yu, K. Cicak, R. W. Simmonds, K. W. Lehnert, and C. A. Regal, *Physical Review X* **7**, 021008 (2017).

Star Model

Astrophysicist Jeff Linsky and his colleagues recently created a sophisticated mathematical model of the outer atmosphere of the small M-dwarf star called GJ832. The new model fits well with spectral observations of the star made with the Hubble Space Telescope (HST).

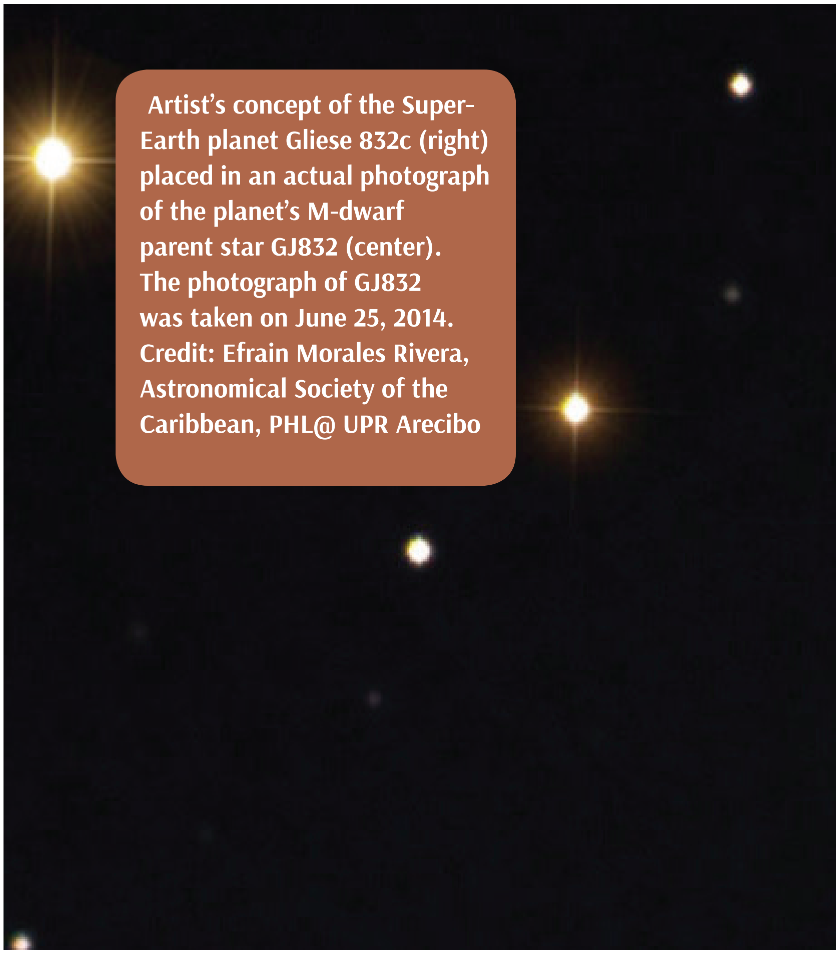
This accomplishment bodes well for two reasons: First, it provides a tool for better understanding M-dwarf stars–the most common type of star in our galaxy. Second, it may aid in determining whether oxygen in the atmospheres of planets orbiting M-dwarf stars is produced by photochemistry or by living organisms such as green plants on Earth.

Astronomers have already discovered several thousand planets orbiting other stars, including two around GJ832, which is 16.1 light years away from Earth and one around Proxima Centauri, just 4.25 light years away. The planet orbiting Proxima Centauri, Proxima b, is just a little larger than Earth, and it orbits inside the "habitable" zone where liquid water could exist.

"Since the nearest star to the Sun has a rocky planet inside the habitable zone, then there's going to be an enormous number of rocky planets in the habitable zones around other stars," Linsky said.

Most stars in the galaxy are smaller, cooler M-dwarfs stars (including GJ832 and Proxima Centauri). Thus, it's likely that the first habitable planets discovered in the next few years orbit M-dwarfs. For this reason, Linsky and his colleagues wanted to understand the spectra emitted by a typical M-dwarf star because a star's light affects the atmospheres of the planets orbiting it [See SIDEBAR]. The researchers chose GJ832 because it is relatively close to Earth, and the HST had already acquired excellent observations of its spectral characteristics.

What Linsky and his colleagues did was come up with a complete theoretical description of GJ832's upper atmosphere, or chromosphere. The chromosphere is the origin of the radiation from the star that has been observed by the HST. The new model is so good that it can now be used to accurately predict the spectrum of an M-dwarf that cannot be directly observed.



Artist's concept of the Super-Earth planet Gliese 832c (right) placed in an actual photograph of the planet's M-dwarf parent star GJ832 (center). The photograph of GJ832 was taken on June 25, 2014. Credit: Efrain Morales Rivera, Astronomical Society of the Caribbean, PHL@ UPR Arecibo

The proof was in the pudding. The team was able to use their new model to accurately predict the observed UV spectrum of GJ832! ✺

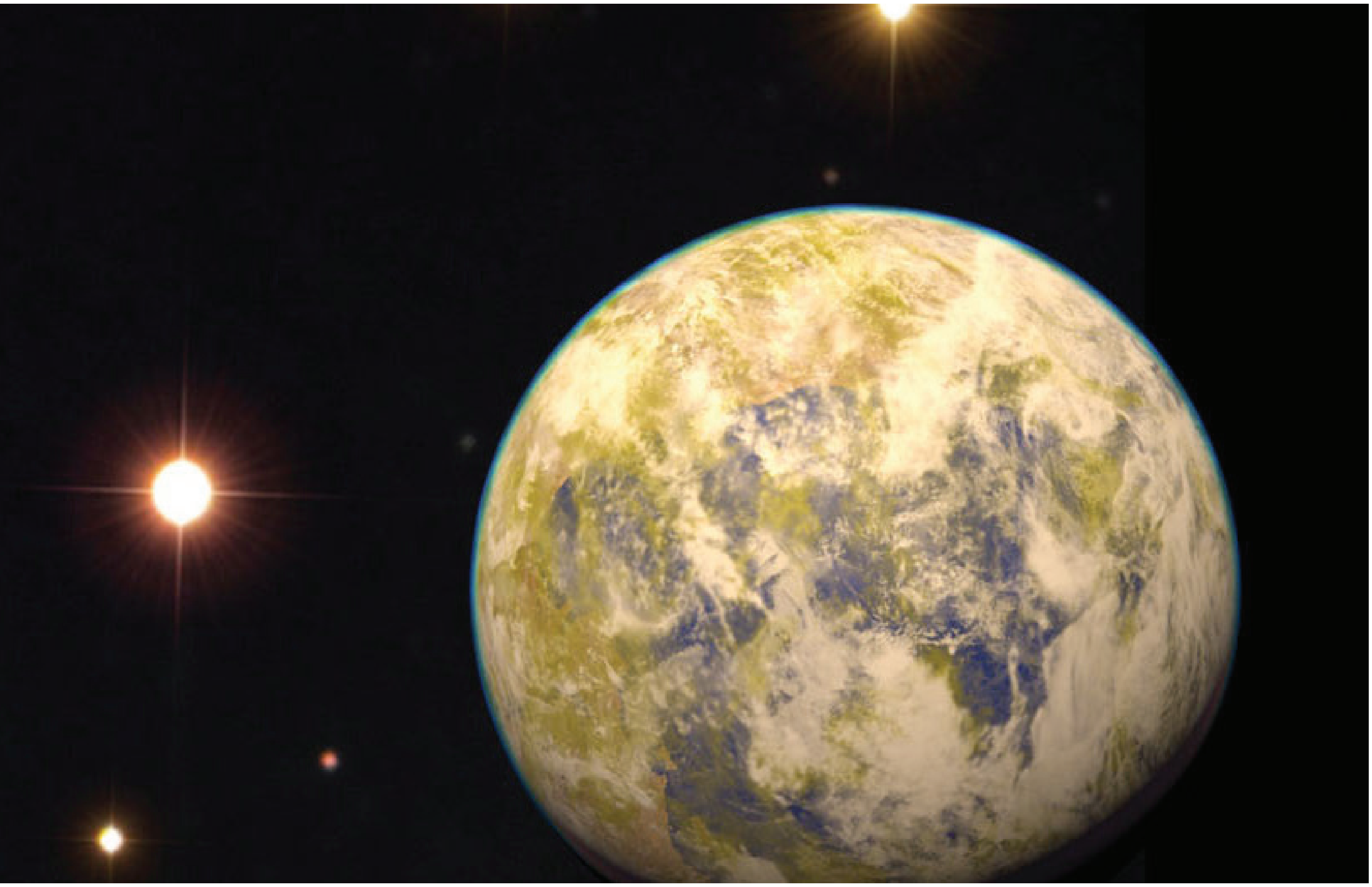
J. M. Fontenla, Jeffrey L. Linsky, Jesse Witbrod, Kevin France, A. Buccino, Pablo Mauas, Mariela Vieytes, and Lucianne M. Walkowicz, *The Astrophysical Journal* **830**, 154 (2016).

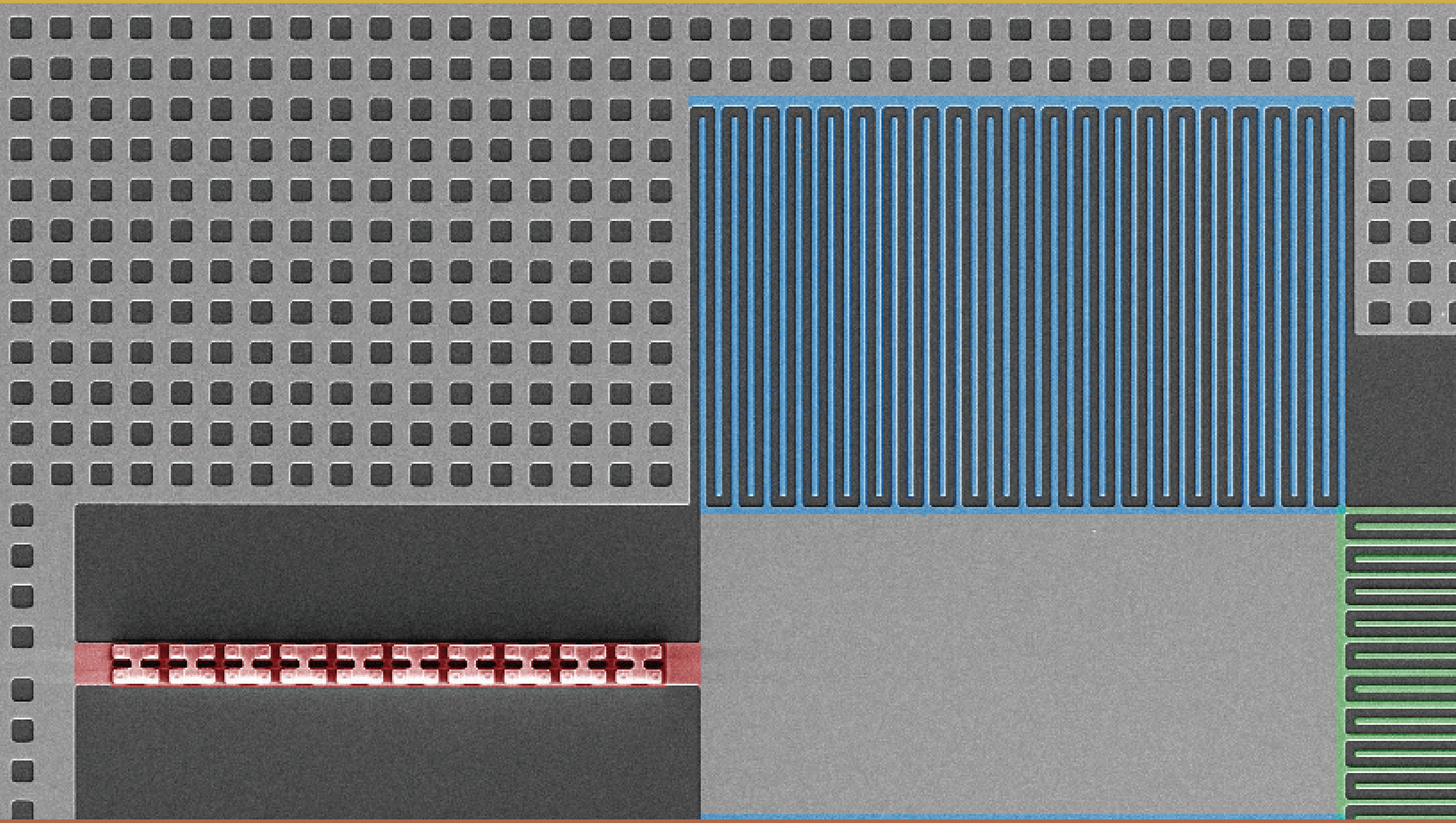
SIDEBAR: Stellar Radiation and the Evolution of Planets

Stellar radiation can affect planets in three ways: First, ultraviolet (UV) light from the star can photodissociate such molecules as water, carbon dioxide, and methane in the atmospheres of planets like GJ832c. If a star emits lots of high-energy UV light and very little lower-energy UV light, then this radiation will produce oxygen in the atmosphere of exoplanets via chemical reactions alone.

Second, if there is lots of lower-energy UV light and very little high-energy UV light, then oxygen in a planet's atmosphere may come from living organisms like plants on Earth (via photosynthesis) or from processes not yet understood.

Third, if there's too much extreme UV or X-ray radiation coming from a star also producing a stellar wind, the result may be the complete loss of a planet's atmosphere. Astrophysicist Jeff Linsky believes this may be the explanation for what happened to the atmosphere of Mars. Fortunately for our readers, Earth's strong global magnetic field has long protected our planet from extreme radiation coupled to the solar wind. Mars, unfortunately, does not currently have a protective global magnetic field, although it likely had one in the distant past.





Scanning-electron microscope image of the circuit used in searches for axions, a hypothesized form of dark matter. The superconducting Josephson junctions (shown in red) were developed by the Lehnert group in JILA. They are what make the dark-matter detector sensitive enough to identify microwave photons produced by axions affected by the experiment's strong magnetic field. Credit: M. Malnou/NIST/JILA

The Hunt is On for the Axion

JILA scientists & their collaborators search for axions in the Milky Way Halo

The first results are in from a new search for the axion, a hypothetical particle that may constitute dark matter. Researchers in the Haloscope At Yale Sensitive to Axion Cold Dark Matter (HAYSTAC) recently looked for evidence of the axion, but so far they have found none in the small 100 mHz frequency range between 5.7 and 5.8 GHz.

The experiment relied on the Lehnert group's microwave circuits, which performed as well as the laws of quantum mechanics allow. The group's circuits are among the most sensitive devices ever made.

"Did we find an axion?" Lehnert said. " No, but we found where it isn't." However, there are many other frequencies where axions could still be detected.

The axion is a hypothetical particle that could make up "dark matter." Dark matter constitutes more than 80% of the mass in the Universe, including the halo surrounding our Milky Way Galaxy. No one knows for sure what dark matter is made of, but if dark matter is made up of axions, the Lehnert group and its collaborators at Yale University, the University of California, Berkeley, and Lawrence Livermore National Laboratory have a method for detecting them in the laboratory. To do so, however, requires that the researchers look in the exact microwave frequency range determined by the mass of the axion particles, which could exist in a wide range of ultrasmall masses.

If axions exist, they are detectable because they can convert into microwave photons in the presence of intense magnetic fields. And, if axions happen to be inside a microwave cavity that resonates with the mass of the dark-matter axions and the cavity is inside an incredibly cold refrigerator, the axion-to-photon conversion may happen often enough for researchers to detect the microwave photons in the lab. This is what the HAYSTAC collaboration was looking for in their first results.

Lehnert's group specializes in making devices that control and measure electricity as well as the laws of quantum mechanics allow. It invented tiny electric circuits that include superconducting Josephson junctions, which made the detector in the HAYSTAC experiment sufficiently sensitive to detect any axions that appeared in a single 100 mHz section of the device's full range of 4–8 GHz.

"For reasons unrelated to searching for axions, my NIST colleagues and I had constructed devices that measure microwave frequency signals in the range of 4–8 GHz," Lehnert said. "We were interested in how close a measurement could come to the limit imposed by quantum mechanics. Coincidentally, these devices had just the right properties to be used in the HAYSTAC that was being constructed at Yale.

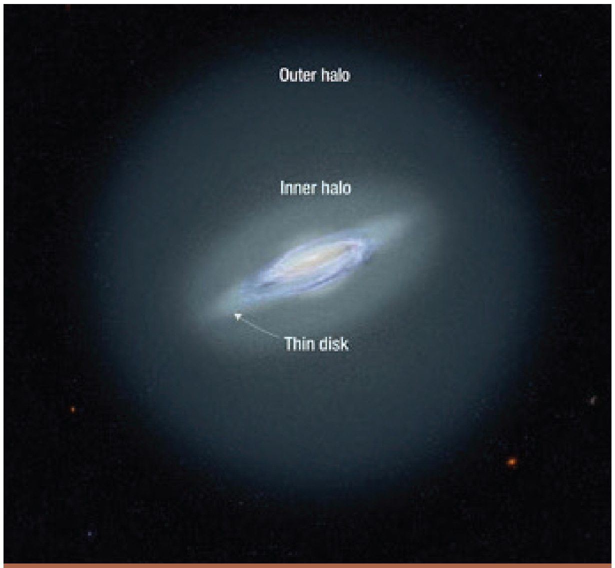


Illustration of the structure of the Milky Way halo that consists mostly of dark matter. Axions are a hypothetical constituent of this dark matter. Credit: NASA, ESA, and A. Field (STSci).

"Our role was to build the devices that would perform the delicate measurement of electrical currents at the quantum limit." Lehnert is optimistic about future searches since there are still lots of frequencies to search.

The researchers responsible for this exciting first result in the search for axions include graduate student Dan Palken, research associate Maxime Malnou, JILA Ph.D. Will Kindel, former graduate student Mehmet Anil, Fellow Konrad Lehnert and colleagues from Yale University, the University of California, Berkeley, and Lawrence Livermore National Laboratory. ✺

B. M. Brubaker, L. Zhong, Y. V. Gurevich, S. B. Cahn, S. K. Lamoreaux, M. Simanovskaia, J. R. Root, S. M. Lewis, S. Al Kenany, K. M. Backes, I. Urdinaran, N. M. Rapidis, T. M. Shokair, K. A. van Bibber, D. A. Palken, M. Malnou, W. F. Kindel, M. A. Anil, K. W. Lehnert, and G. Carosi, *Physical Review Letters* **118**, 061302 (2017).

Spotlight on Ann-Marie Madigan

Associate Fellow and University of Colorado Assistant Professor Ann-Marie Madigan began the journey that led her to a career in theoretical astrophysics when she walked into her first physics class in an all-girls convent school at age 16. There she discovered a deceptively simple question written on the blackboard: What is Light? She thought the question was absolutely fascinating. From that day forward, she wanted to go to college and learn about physics.

Madigan went to college at the National University of Ireland, Galway. In 2004, she graduated with honors with a major in Physics & Astronomy. She wasn't sure yet what she wanted to do with her life, but she knew she wanted to learn more about physics. So she went backpacking in India for a year, which was a wonderful experience.

While she was in India, Madigan applied to several programs offering research Master's degrees. She wanted to get some research experience before applying to a Ph.D. program. Enticed by an artistic website on cosmology, she applied and was accepted to Leiden University in the Netherlands.

There she met Professor Yuri Levin and postdoc Clovis Hopman. The two researchers jointly advised both her Master's and Doctoral work. Levin won her admiration via his class in general relativity in which he derived everything from first principles. Madigan discovered she could do the math and actually derive white holes and space-time diagrams. For his part, Hopman introduced her to stellar-sized black holes, neutron stars, white dwarfs, and supermassive black holes. Madigan arranged to work with both of them.

The three became a research team. For her Ph.D. research, Madigan won a Netherlands Organisation for Scientific Research (NWO) Top Talent award that provided funding for her to investigate the stars and gas swirling around a black hole. Because of the award, she was able to design her own Ph.D. research program, which is quite rare. Her thesis reported the results of her theoretical astrophysics work on the "Secular Stellar Dynamics Near Massive Black Holes."

> For her Ph.D. research, Madigan won a NWO Top Talent award that provided funding for her to investigate the stars and gas swirling around a black hole.

After earning her Ph.D. from Leiden University, Madigan won a NASA Einstein Postdoctoral Fellowship that she used to continue her theoretical astrophysics work at the University of California at Berkeley. Her postdoc proved challenging since there were no faculty in theoretical astrophysics working on topics she wanted to pursue. So once again, Madigan designed her own research program. For the last two years of her four-year postdoc at Berkeley, Madigan worked with graduate student Mike McCourt and

postdoc Ryan O'Leary to delve more deeply into gas dynamics around black holes.

Madigan also expanded her research to include planetary dynamics because the disks of stars around black holes share some similar characteristics with disks of planets around stars.

Madigan discovered that the bizarre dynamics exhibited by stars in a thin disk in eccentric orbits look a lot like what she thinks may happen to the minor planets in the outer solar system. Her work on the solar system suggests that this gravitational instability occurs because the minor planets gravitationally perturb each other.

Soon after she published a new theory explaining this behavior, another group published a paper hypothesizing the existence of Planet Nine, a new large planet in the outer solar system. Suddenly Madigan's theory and the Planet Nine theory were competing theories to explain the behaviors of dwarf planets in the outer solar system.

Madigan spends about half her time investigating the *Not*-Planet-Nine theory. She has a graduate student working on putting this theory in the context of the solar system that also has Jupiter, Saturn, and Neptune scattering everything. The goal is to predict the location and mass of the solar system's minor planets; this population could form a new structure in the outer solar system, ten times more massive than the Kuiper Belt.

The second half of Madigan's research focuses on disks of stars around black holes in highly elliptical orbits that are clustered together on one side of the disk. This is exactly how a huge number of stars are distributed around the supermassive black hole at the center of our neighboring galaxy Andromeda. Madigan is investigating the dynamics of stars born into this system.

She's interested in understanding how often the stars get sucked into the black hole. This process, known as a tidal disruption, happens when the gravity exerted by the black hole on one side of the star overcomes the forces that bind the star together, literally ripping the star apart. Such a tidal disruption produces a luminous event around the black hole that we can see with telescopes on Earth.

In her spare time, Madigan enjoys studying geology and hiking through national parks.

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

University of Colorado **Boulder**

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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 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 Sciences; 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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