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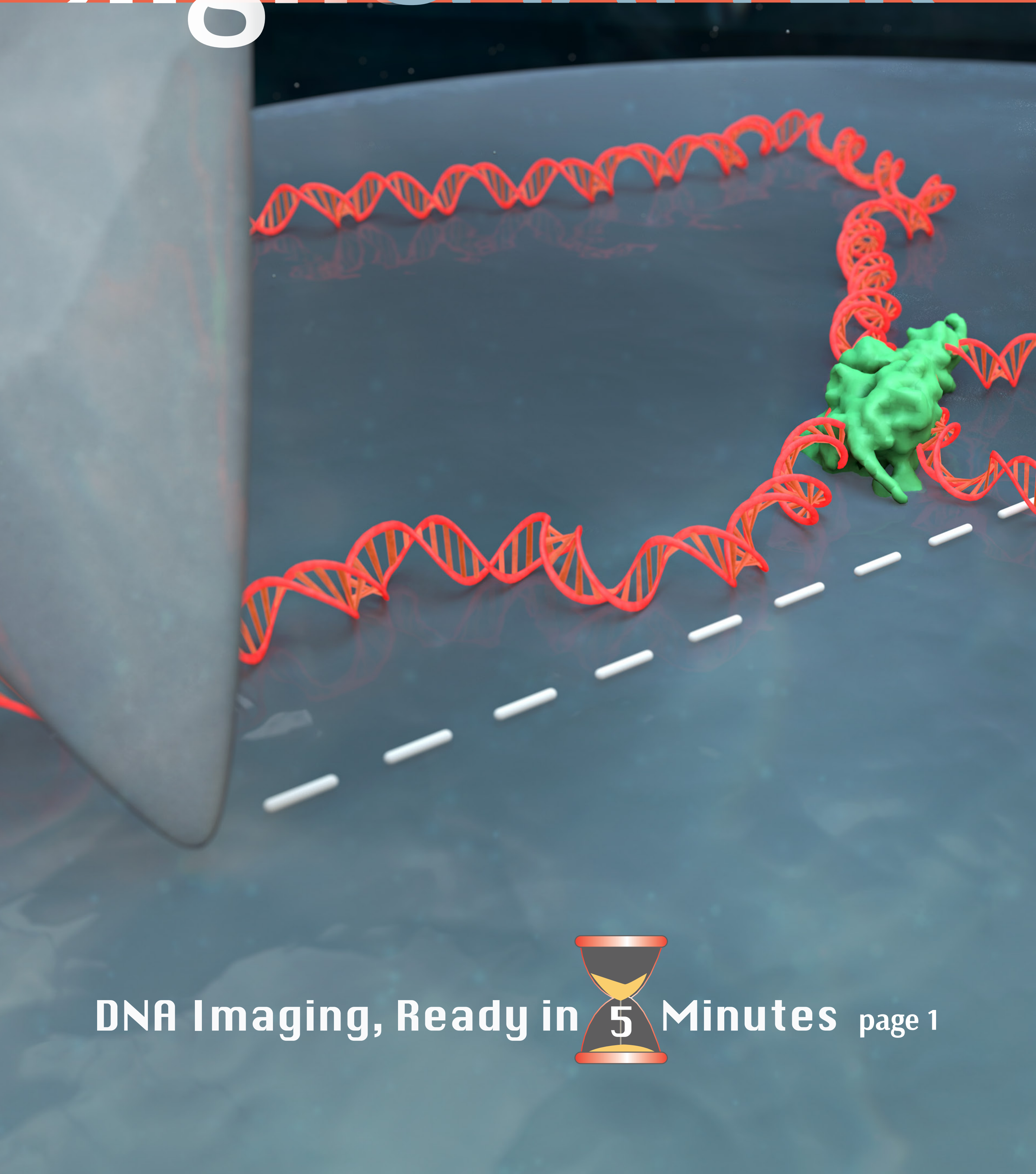
JILA light&MATTER



DNA Imaging, Ready in 5 Minutes page 1

JILAns celebrate the holiday season with the annual JILAday evening in the Byron R. White room at Folsom field.

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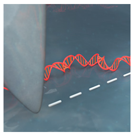
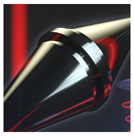
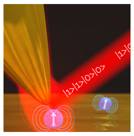
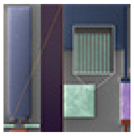
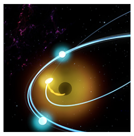










Features

DNA Imaging, Ready in 5 Minutes

New, fast technique produces clear images of DNA

It's tricky to get a good look at DNA when it won't stick to your slide, or lay down in a straight strand.

CU biochemist Tom Cech came to Tom Perkins' atomic force microscopy lab with this very problem. His group was trying to understand how certain proteins interact with DNA. They knew their proteins interacted with DNA but they couldn't get a good image of that interaction in liquid, DNA's native environment.

"You have this nanoscale string in a ball shape that's undergoing thermal fluctuations, and then take this three-dimensional configuration, and squish it down really fast onto a surface," Perkins explained. That squished DNA is often an uninterpretable blob.

"I kind of think of it like a bowl of spaghetti noodles. If you drop them on the floor, they'd be kind of all globbed up and in weird shapes," explained Patrick Heenan, a graduate student in Perkins' group.

The goal was to develop a process that would separate those globs into individual noodles. Heenan started working on this problem about two years ago, and he developed a technique to get your slide perfectly prepared to image a DNA sample. The best part? It's fast—ready in just five minutes.

Tiny globs of DNA

DNA is about two nanometers wide – 100,000 times thinner than a sheet of paper. To get a good look at it, you need to put it on a slide that is truly flat. Mica, a light, soft silicate mineral, is a great candidate for a slide. All it takes to get a flat, thin sheet of mica is a piece of Scotch tape and some deft hands, Heenan explained.

"The beauty is it's super, super flat, so it is the perfect substrate," Heenan said. "You can see all the atoms, and in some cases, you can see voids in the lattice."

However, mica and DNA are both negatively charged; they repel each other. Scientists had tried changing the surface of the mica to make the DNA stick—soaking it for hours or days in various coatings and rinsing it with distilled water.

But the DNA still ends up in globs. When the apex of the atomic force microscope (AFM) tip runs over the DNA, the picture comes out blurry. Scientists can't see how proteins or other molecules are interacting with the DNA. Many had given up on imaging DNA in liquid on bare mica, figuring it didn't work or using coatings that made the images blurrier but still yielded globs. So Heenan started digging through the literature to see what others had tried.

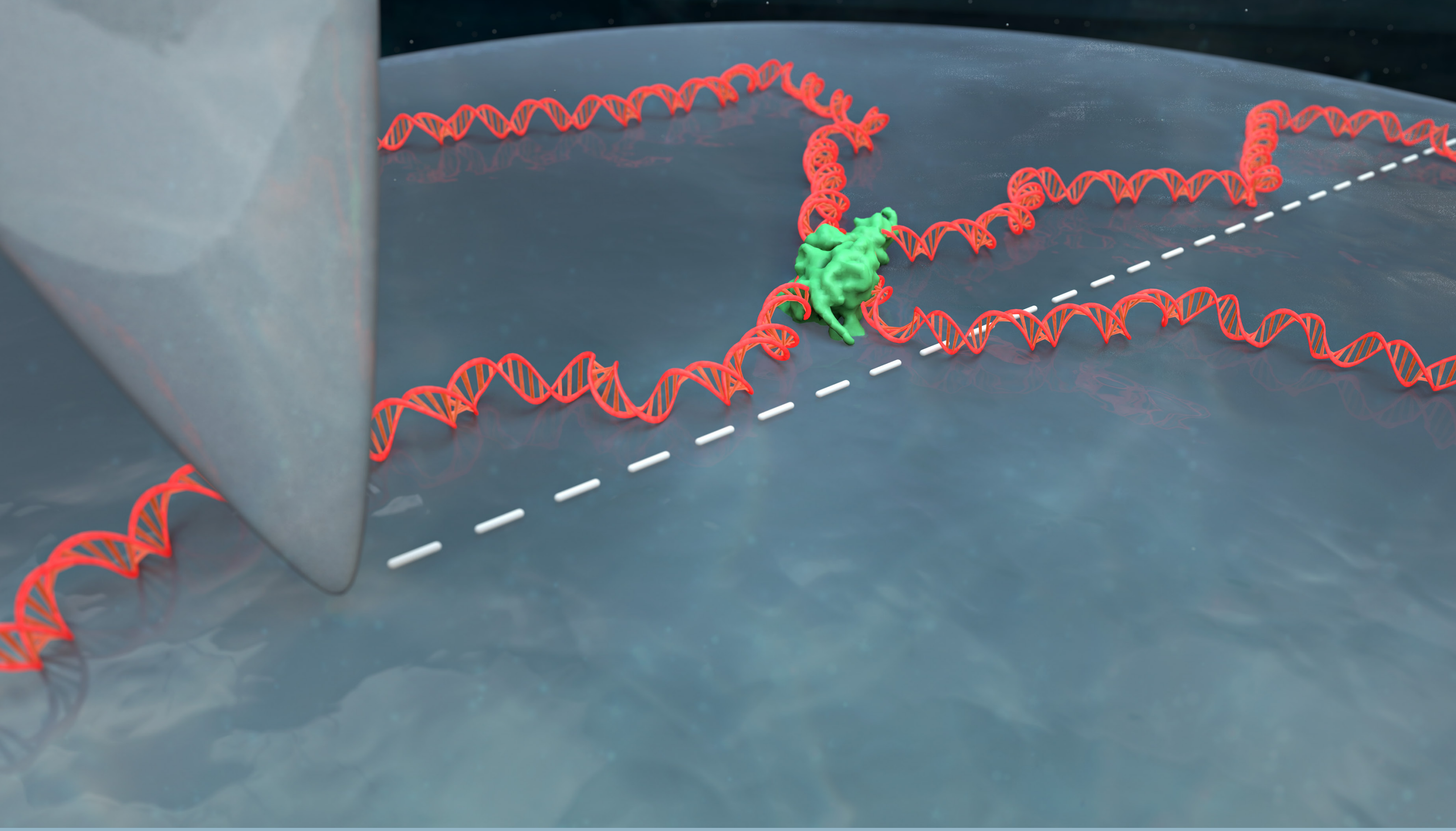
"I read lots of papers, and I prepped hundreds of samples," Heenan said. "It was a little bit like whacking through the weeds."

Ready in five

It turned out soaking the mica for too long was part of the problem. Plus, the DNA wasn't able to equilibrate on the surface, resulting in the squished ball shapes rather than nice, separate strands.

"If you let it sit for a long time, you're actually losing some of the surface charge and impurities in the water are being sucked down into the surface," Perkins explained.

Here's how the improved process works. The mica



A new technique from the Perkins group allows crisp, clear AFM images of DNA. The best part? It's ready in five minutes. Image Credit: Steven Burrows and the Perkins Group/JILA

is pre-soaked in a concentrated nickel-salt solution, then rinsed and dried. Then the DNA is bound to the mica with a solution of magnesium chloride and potassium chloride. Those conditions closely resemble the salts found naturally in cells, allowing the proteins and DNA to behave the way it normally would. Finally, the mica is rinsed with a nickel-chloride solution, which helps the DNA structure stick to the mica more tightly.

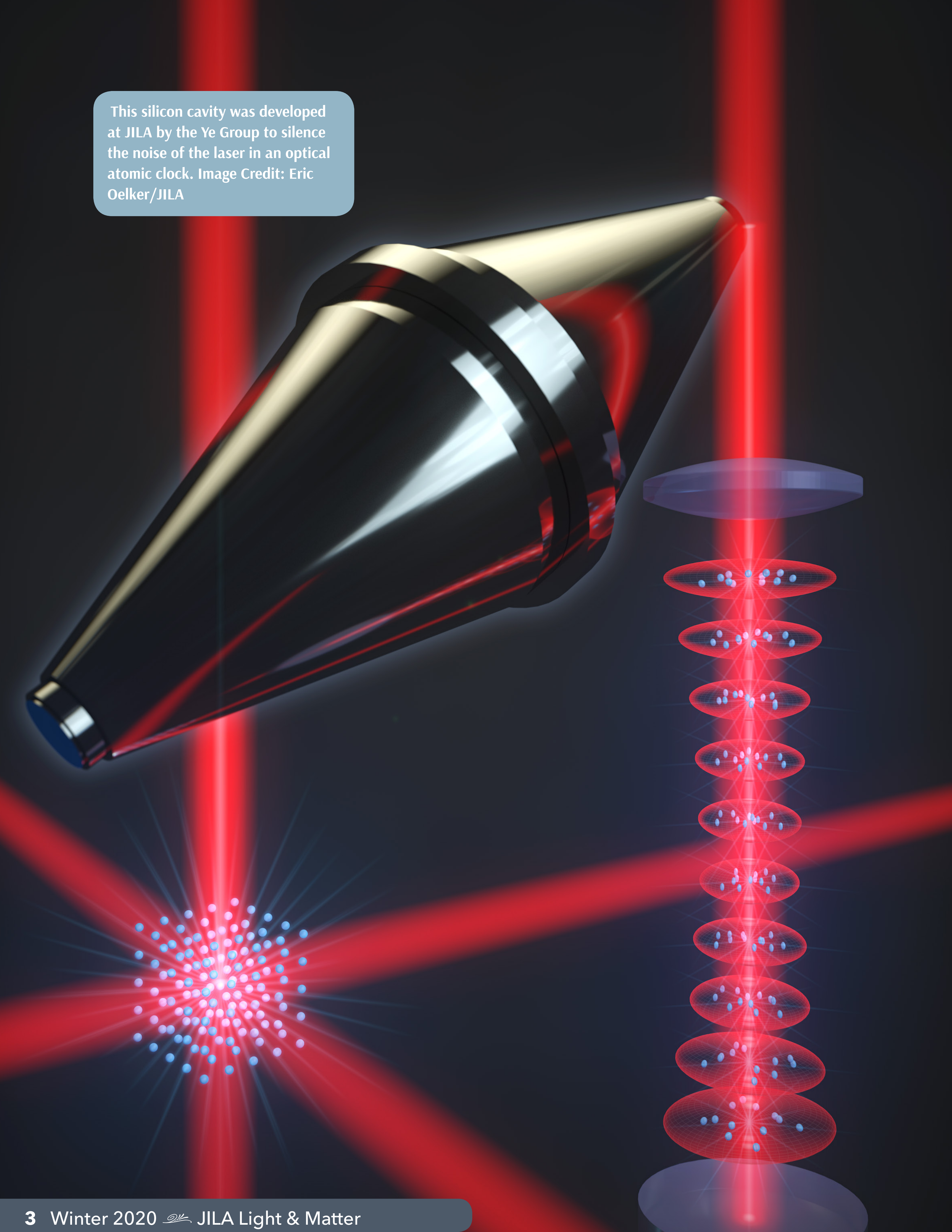
"It's kind of like the whole surface is uniformly sticky, so it can stick wherever it wants, and therefore it's easier for it to move around," Heenan explained. "Everything is equally sticky."

And it's all ready for imaging in five minutes. Not only is it ready, but it delivers a clear picture—so clear that the double helix of the DNA is visible.

This development will help scientists study how DNA, protein and other molecules interact, as well as how DNA repairs itself.

"Patrick took on the challenge to image in liquid at biochemically-relevant conditions rather than in air, which, prior to Patrick's work, we and others would have assumed was impossible," Perkins said. "What Patrick has developed is something that once you learn the eight steps, almost anybody can do it. It's really simple. It uses common salts, it takes five minutes, and you get higher signal-to-noise ratio, so basically, all sorts of good things."

P.R. Heenan and Perkins, T.T., *ACS Nano* **13**, 4220–4229 (2019).



This silicon cavity was developed at JILA by the Ye Group to silence the noise of the laser in an optical atomic clock. Image Credit: Eric Oelker/JILA

Keep It Steady

Using a silicon silencer, the Ye Group has reached record stability for optical atomic clocks

Imagine trying to read a clock with hands that wobble. The worse the wobble, the more difficult it is to accurately read the time.

Optical atomic clocks have the same problem. An optical atomic clock uses a laser to measure the frequency of a collection of atoms in a lattice, the way a grandfather clock measures the frequency of a swinging pendulum to mark the passage of time.

Optical atomic clocks measure time in attoseconds, which are billionths of a billionth of a second. On scales that small, everything needs to be exact. But the laser's frequency can fluctuate, like that wavering clock hand.

"That's what ends up limiting the stability of the clock. So, say I'm trying to do this measurement, but this laser frequency is moving around a whole bunch…. If this light is perfectly on resonance then you'll get a certain signal," said Eric Oelker, a JILA postdoctoral fellow in Jun Ye's group. "But then if it's a little bit off from resonance you get a slightly different looking signal."

In a recently published paper in *Nature Photonics*, Oelker found a way to significantly silence the noise from the laser to demonstrate the best stability for a clock to date.

Shh…the silicon silencer

Physicists measure the frequency of a laser in an optical atomic clock to mark the passage of time. To make sure the laser is "ticking" at the right rate, this oscillation frequency can be checked against the frequency of the strontium atom and tuned to ensure that the clock continues to tick at the correct rate with a minimal wobble. The laser that interrogates the strontium atom is our local oscillator (LO); it's like the swinging pendulum of a grandfather clock.

On its own, a laser is too noisy to function as a clock LO. Its frequency is far too wiggly or unstable, which makes it difficult to measure the narrow strontium clock transition. To silence that noise, Oelker and his team stabilized the laser using a 21-centimeter (a little more than 8.25 inches) silicon cavity. The cavity is shaped like a football with two narrow ends and a wide middle. The laser light enters the cavity, where it bounces between reflective surfaces many times and comes back out again. This returning light contains a signal that can be used to stabilize the laser. However, if the length of the cavity changes, even slightly, the laser still comes out pretty noisy.

That's why this new cavity is special. That silicon material makes it incredibly quiet, especially at 124 Kelvin, Oelker explained.

"The really nice feature of silicon is that it has intrinsically lower thermal noise, and also it can be used at cryogenic temperatures," Oelker said. "At a 124 Kelvin, it's this kind of magic point where the (silicon cavity) neither expands nor contracts when the temperature changes."

To check that it works, the quieter laser is sent to two different JILA strontium optical lattice clocks–one is a one-dimensional lattice, where atoms are aligned in a single row like a stack of pancakes, and the second a three-dimensional optical lattice clock, where atoms are arranged to be confined one in each lattice site.

"We use the cavity to interrogate both and then we're looking at the signal for both of these clocks and comparing them," Oelker said. "Essentially, you're taking the two watches and you're putting them next to each other and you're comparing the time that they're measuring."

The point of precision

Adding this silicon cavity improves the stability by a factor of three, down to 6.6x10^{-19} over an hour. That might seem small, but it means it takes a factor of ten less time to make a measurement.

"For us, that's huge, right? That's the difference between me sitting there and running my clock for an hour versus running my clock for ten hours," Oelker said.

Atomic clocks help the world set standards for timekeeping, making sure everyone is measuring a second the same way. But clocks can do more than that. Stable, accurate, optical atomic clocks are capable of detecting small shifts in the world around it. For geologists, that could mean sensing shifts in density and mass of magma beneath our feet. For physicists, that could mean detecting interactions between the atoms, passing gravitational waves or even dark matter.

"It turns out atomic clocks are not only good for telling time…. We can probe a lot of physics using this device, but once again, if I'm trying to measure some very small shift in the frequency but this hand of the clock is doing this," Oelker said, waving his hand back and forth. "I'm never going to be able to see it."

E. Oelker, Hutson, R.B., Kennedy, C. J., Sonderhouse, L., Bothwell, T., Goban, A., Kedar, D., Sanner, C., Robinson, J.M., Marti, G. E., Matei, D.-G., Legero, T., Giunta, M., Holzwarth, R., Riehle, F., Sterr, U., and Ye, J., *Nature Photonics* **13**, 714–719 (2019).

Remembering JILA Quantum Physics Division Chief Tom O'Brian

NIST and JILA mourn the passing of JILA Quantum Physics Division Chief Thomas O'Brian. O'Brian passed away unexpectedly in his home on Thursday, November 21 at the age of 64.

"Tom was a wonderful boss, and a wonderful human being. I admired him for his sense of responsibility for those around him, his caring," said JILA Fellow Eric Cornell. "His untimely death was a huge loss for the JILA community. I miss him a lot."

An exemplary scientist and manager, O'Brian joined NIST in 1991 as a National Research Council postdoctoral fellow in the former NIST Physics Laboratory. His research specialized in laser light interactions with atoms, and later the use of synchrotron radiation as a precision measurement tool.

After working his way up through the ranks at NIST in Gaithersburg, Maryland and Boulder, Colorado, O'Brian became the director of the NIST Program Office in 2002. He was named director of the NIST Boulder Laboratory in 2006. O'Brian assumed his duties as the chief of the Time and Frequency Division at NIST's Physical Measurement Laboratory in 2008, and of the Quantum Physics Division at JILA in 2009, where he served until his death. O'Brian also founded and advocated for the NIST-on-a-chip program, which would make NIST's precision measurement tools portable and inexpensive for the public.

As a leader, O'Brian was a tireless advocate for science and its role in the community, working to engage the public and the scientific communities in this important work. He championed the work of scientists and researchers throughout NIST, JILA, and the University of Colorado Boulder, including JILA's three Nobel laureates. In 2012, he was overjoyed to introduce NIST's most recent Nobel laureate David Wineland at a NIST press conference.

O'Brian was at his best when mentoring young scientists, and had a passion for ensuring that individuals were considered, heard, and respected throughout the organizations he served.

"All of JILA will miss Tom," said JILA Chair Thomas Perkins. "He was a tireless advocate for JILA, its students, staff and fellows. Tom provided invaluable guidance and advice to many of us, both as a boss and a mentor. Finally, Tom loved to celebrate the success of our students, their awards, and how they became JILA's ambassadors to the broader international scientific enterprise."

"Tom's exceptional intelligence, laser sharp insights, and dedication to NIST were clear to not only those who knew and admired him, but to the much broader scientific community as well. He will be sorely missed and remembered as a model for us all," said James Kushmerick, director of the Physical Measurement Laboratory at NIST.

JILA Quantum Physics Division Chief Thomas O'Brian passed away on Thursday, November 21. Image Credit: JILA

Tom took great pride in mentoring young scientists early in their careers. To honor his memory, JILA has formed the Thomas O'Brian Memorial Fund for Graduate Student Support, which will help young scientists at JILA. If you would like to make a gift in Tom's memory, you can do so online at giving.cu.edu/fund/tobrian. Contact Chris Natynski at: chris.natynski@colorado.edu or 303-735-8451.

Bringing Quanta Out of the Cold

New technique from JILA researchers could free quantum technology from cold temperatures

When it comes to working with atoms, or other quantum systems, some physicists prefer to keep them cold. That generally works well, but Earth is a warm place.

We live in a heat bath, joked Molly May, a JILA graduate student in the Raschke group.

Despite their small size, atoms have the ability to contain and carry information which makes them a promising platform for quantum sensing, metrology, and information processing. However, artificial atoms in the form of quantum dots can also encode information, and the information in those quantum dots can be controlled with light, May explained, making them attractive for these new applications.

> “As we come closer and closer to the quantum dot, we see that the coupling kind of kicks in.”

But that gets tricky. Quantum dots and atoms tend to lose the information rapidly to their surroundings, so one has to work quickly and precisely. That typically means working in extremely cold temperatures. Extremely cold temperatures isolate the atoms, preventing them from interacting with their environment—which makes them easier to work with and control.

And if controlling and working with atoms is restricted to cold temperatures, that makes it harder to take advantage of atoms' potential applications outside the lab, added JILA Fellow Markus Raschke. Now an advance from the Raschke group at JILA, and their collaborators at the University of Maryland, has brought quantum dots out of the cold, allowing them to work at room temperatures with precision and control.

Writing on a nanoscale

The Raschke group works with quantum dots that are about eight nanometers across, more than 1,000 times smaller than a human hair, which is big compared to atoms.

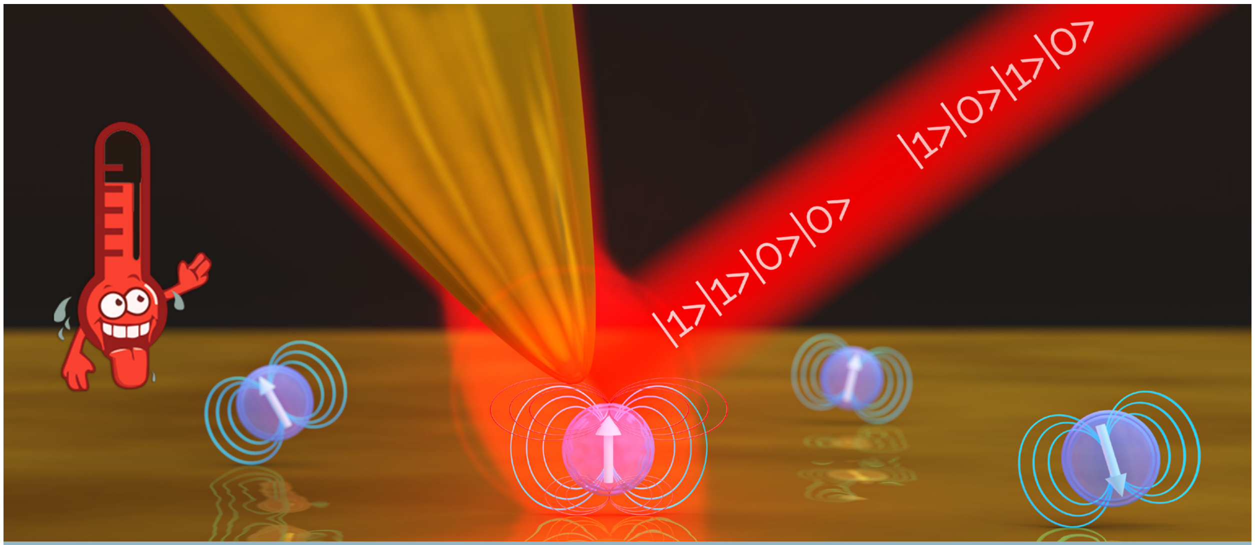
Writing information on a quantum dot involves changing its energy level from its ground state to an excited state. And photons—tiny packets of energy that make up light—can do that when they have a strong interaction (or are coupled) with the dot or atom.

But compared to the quantum dots or atoms, light—especially visible light—has a very long wavelength, almost a hundred times larger than the quantum dot. As a result, it has a very weak interaction with the quantum dot. Light needs to shine on the quantum dot for a long time to excite its energy level, i.e., write information on it.

However, over that time, the movement and coupling of the atom knocks its excitation out of phase, hitting other atoms and molecules, or simply internal processes. That phase decoherence causes the atom to lose its information to the surrounding environment.

There are two ways to work around this. One option is to work in high vacuum and at ultra-cold temperatures, usually around a few micro-Kelvin, to reduce the chances of this phase decoherent interaction. That requires complex cooling or refrigeration techniques in a lab, which isn't always ideal.

The other option is to squeeze your light into a space smaller than its wavelength, ideally



Using atomic force microscopy the Raschke group was able to write information on a quantum dot at room temperature. Image Credit: Steven Burrows and the Raschke Group/JILA

comparable to the size of the quantum dot. Using nanoscale antennas, e.g., made by metallic nanostructures, you can create an optical nano-cavity, squeezing the light into a smaller space. But those cavities are static. You either hit the dot or you don't, May explained.

"Even when you get lucky and find a quantum dot, you cannot tune the cavity or control the interaction," she added.

Some like it hot

To work at room temperature and control the quantum state, May looked to optical atomic force microscopy (AFM), a technique already used at JILA that uses a 10-nanometer needle-like gold tip as a tool to compress the light into the tiny space needed to get strong interaction with the quantum dot.

When she shines light on the gold tip, it focuses the light into a narrow region at the tip apex, creating an optical nanocavity with the quantum dot sample positioned into the near-field of the tip apex–one small enough to interact with that tiny dot.

"It works like the antenna in your phone, just for light. The tip nano-cavity collects the light that we shine on it and focuses it to a tiny spot," May said.

The AFM now provides the advantage that the tip can move around. So May can position the tip near the quantum dot with atomic precision. Strong coupling sets in at very short distances between the tip and the quantum dot. When that happens, the tip and the dot exchange information really well, May explained, tossing photons back and forth like ping-pong ball.

"As we come closer and closer to the quantum dot, we see that the coupling kind of kicks in." May said. "I was actually impressed by how well it works. And, that really hasn't been done before. We can really optimize the interaction."

Seeing the results, Raschke was surprised. "At first we almost did not believe the results and thought something had gone wrong," he said. "It was truly exhilarating when we saw the signal for the first time and were convinced it is real."

That strong-coupling effect using the AFM tip lets May and her fellow researchers tune, control, and image the interaction with the quantum dot in real time and space. Pull the tip back, by a distance of even just one atom diameter, and the signal gets weaker. Push it closer, and the signal gets stronger.

Free from the fridge

Being able to write and read the energy level of a single quantum dot or atom using light is an enabling step for several emerging quantum technologies, like metrology and sensing tools. And breaking out of the ultra-cold regimes could help bring these tools out of the lab for wider applications.

"Often, quantum physics and tailored light-matter interactions happen in dilution refrigerators which create ultracold, ultrahigh vacuum, very pristine conditions," May said. "And it's attractive to think about moving away from that, because if we want to use these technologies more broadly, it's so much cheaper to be able to just do it in your lab or your office or your living room."

It won't get rid of the need for research and technologies at low temperature because of other important virtues, Raschke clarified. But this finding complements and expands quantum science and technology into new regimes at room temperature. But it also serves as a new tool to provide fundamental new insight into how quantum information is lost in interacting environments, which can help optimize quantum systems more broadly.

"This is exploratory research for broadening quantum technologies, creating a wider range of platforms and broader accessibility. We are bringing quantum technologies into more real-world applications, which is really exciting," he said.

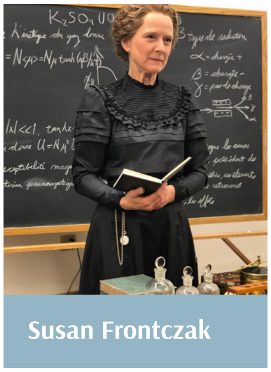
K.-D. Park, May, M. A., Leng, H., Wang, J., Kropp, J. A., Gougousi, T., Pelton, M., and Raschke, M.B., *Science Advances* **5**, eaav5931 (2019).

"Women of JILA Present" speaker series features ideas on diversity and inclusion

Marcia Lesky

Great science requires great people, but women and minorities often face roadblocks in the field. JILA is committed to maintaining an inclusive and welcoming environment for everyone. In addition to an institute-wide focus, there are two groups within JILA specifically dedicated to addressing issues around diversity and inclusivity: JEDI (JILA Excellence in Diversity and Inclusivity) and Women of JILA.

The "Women of JILA Present" speaker series provides opportunities for all JILAns to gain tools, strategies and knowledge to enhance their current and future professional careers and achievements. Women of JILA also aims to candidly explore issues related to gender in a proactive manner, with practical advice and insight to deal with real-world problems. All JILAns are welcome, including JILA fellows, staff, students, postdocs and visitors.



Susan Frontczak

In its inaugural year, the series hosted "A Visit from Madam Curie," a performance by Susan Frontczak portraying the life of Marie Curie, and during spring 2019, Laura Oliphant, general partner at Venture Fund, gave a talk titled "Innovation in the Semiconductor Industry: Implications for Education and Diversity".

The fall 2019 series speakers included The Optical Society's Marcia Lesky and CU's Terri Fiez.

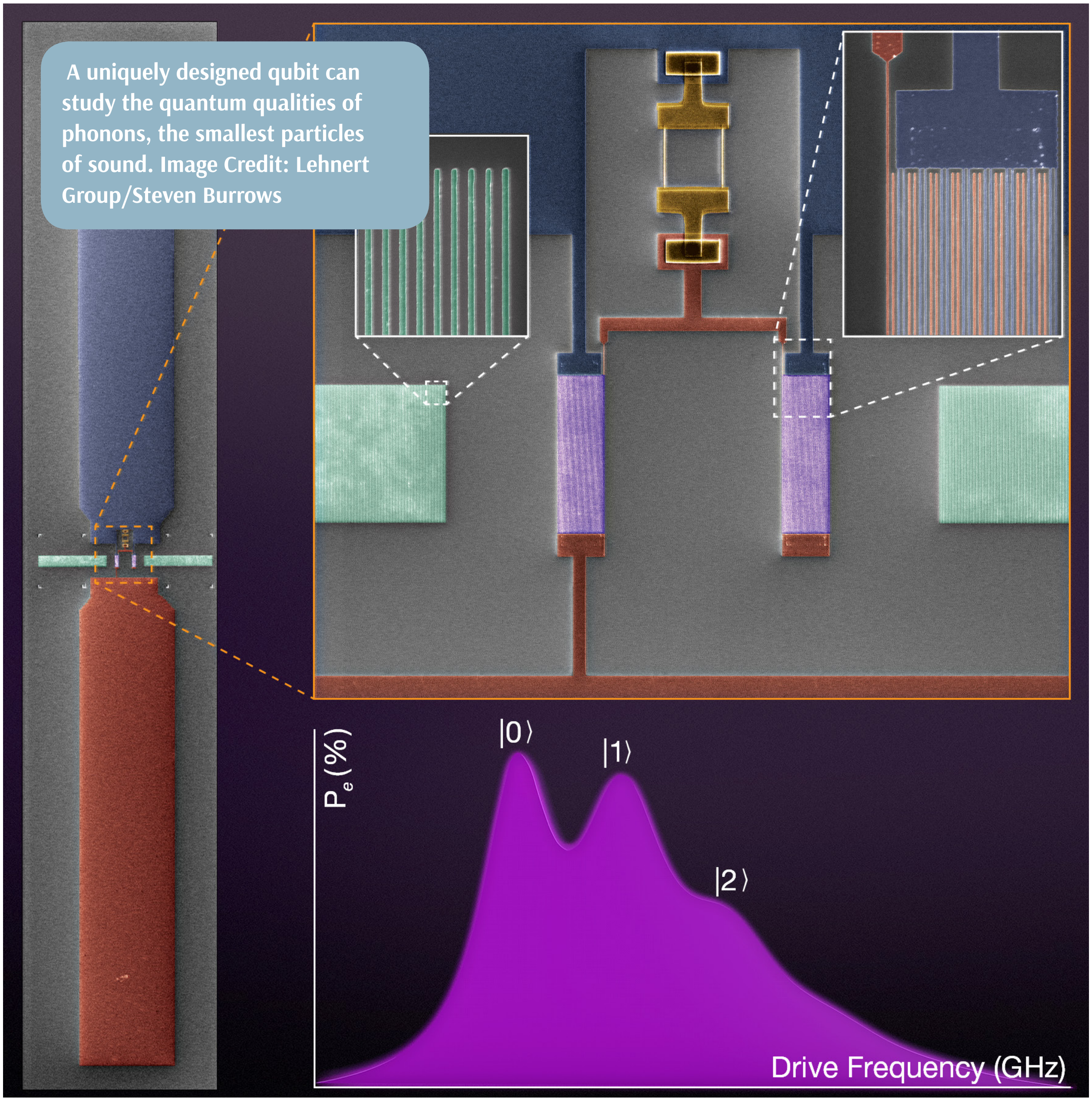
Marcia Lesky serves as the senior director of diversity, inclusion and volunteer cultivation for The Optical Society (OSA). She develops strategies and implements programs to advance diversity across the organization and promote greater inclusivity throughout the optics and photonics community. Her talk at JILA focused on how OSA has increased diversity in the organization by alleviating some of the obstacles faced in career advancement. (For example, OSA created a fund to cover some caregiver costs for members going to conferences.) They also focused on recruitment and making space specifically for women at conferences and other events.

Terri Fiez, CU vice chancellor for research and innovation and dean of the institutes, spoke to JILAns on the importance of leadership. With a background in electrical engineering, she is passionate about creating partnerships with industry, the startup community and federal labs. Fiez focused on the role of leadership in creating diverse and productive environments for innovation. She also covered developing leadership programs for faculty, including how scientists can talk about their research to those outside their field.

Terri Fiez

"Women of JILA Present" will continue its second year in 2020 with additional speakers, including Regan Byrd, a consultant who works with businesses and communities. Byrd will speak on changing oppressive systems from within on January 23, followed by a discussion on advice for graduate students with a panel of women JILA fellows on February 11. Additional speakers for spring 2020 include Anne Libby, professor and vice chair for academic affairs in the CU Anschutz Department of Emergency Medicine, and co-founder of the Colorado Mentoring Training Program (CO-Mentor); and Kate Kirby, American Physical Society CEO.

Thank you to all of our inaugural year speakers for taking the time to share your insights with JILA!


A uniquely designed qubit can study the quantum qualities of phonons, the smallest particles of sound. Image Credit: Lehnert Group/Steven Burrows

COUNTING THE QUIETEST SOUNDS IN THE UNIVERSE

A new means of studying phonons could turn up the volume on quantum computers

In the Lehnert Lab at JILA, a qubit sits in a small copper box. The qubit itself would fit on your pinky nail. Using that qubit, graduate student Lucas Sletten can measure the quietest sound in the universe: individual phonons, the smallest particles that carry sound.

This qubit is designed to help us answer two simple but profound questions: Can we control sound in a quantum way? And if so, what can we do with sound that we can't do with light?

"People have been curious about using sound as a quantum technology for a while. It's just difficult," Sletten said. "[The qubit] lets you take your classical, grubby hands and do quantum things. It lets us see the quantum of nature of something which is normally linear and very classical looking."

Hearing the quietest sound

"One phonon is the quietest sound," Sletten said. The device lets scientists break a sound into its individual phonon bits, the quantized packets that make up a sound. The phonons Sletten focused on are 4.25 gigahertz, a frequency a billion times higher than what humans can hear.

So how do you hear the quietest sound in the universe? With a very sensitive microphone and speaker.

Their qubit was made on a piezoelectric material, which means any motion on the surface generates a voltage. As phonons travel across the surface of the chip, they create small voltages that are picked up by the qubit's transducer, which Sletten explained is both a microphone and a speaker.

To enhance the sensitivity of the device, Sletten uses two mirrors to create an echo chamber (an acoustic cavity) around the transducer. The trapped phonons bounce back and forth, passing under the transducer many times.

Each phonon in the cavity shifts the qubit's frequency by a fixed amount. By playing a quiet sound and precisely measuring the qubit's frequency, Sletten observed that the qubit's frequency shifts in discrete steps. These steps arise directly from sound's particle-like, quantized nature.

A sound advantage over light

A similar version of this experiment had already been done with light a decade ago, making this an "acoustic cover of an electronic hit," Sletten joked. However, as sound is nearly a million times slower than light, the acoustic version can access new physics.

"This is not the race car of the superconducting qubit world," Sletten said. "When you switch to sound, you lose a fair amount of things, but you also gain some cool stuff."

Sound waves used in this experiment are a million times smaller than light because sound is a million times slower. Phonons are also usually much longer-lived than photons.

"The slowness of sound let us build a cavity for sound in an on-chip device which would be really, really long if you made it for light," Sletten said.

Why build an effectively long cavity? It has to do with the amount of quantum information that a device can store. The echo chamber has certain frequencies that resonate, similar to the pitches you can play on a wind instrument. The longer the instrument, the smaller the difference between adjacent notes. (As a tuba player, Sletten is keenly aware of how tightly spaced these notes become when the instrument becomes very long.) Each acoustic resonance can independently store information. Thus, more resonances means higher capacity.

And that's good news for quantum computers, which need a way to expand the computing power by adding more qubits. Sound could give quantum computers an alternative way to go from one qubit to many.

"If you can control the quantum state of the sound in these modes, then you can use these as your qubits," Sletten explained. "And you can make more of them just by taking the mirrors and moving them apart. So, this gives you a different path [to go from one] to many."

L.R. Sletten, Moores, B., Viennot, J.J., and Lehnert, K.W., *Physical Review X* **9**, 021056 (2019).

Black Holes Continue to Tear Stars Apart

As the original maps, calendar, and fortune tellers, stars have forever complemented our nightly imaginations with their consistent patterns. But like everything, they too come and go. Sometimes they fade with a peaceful final twinkle, but other times, they're destroyed in violent calamity.

When a star ventures too close to a black hole, gravitational forces can stretch the once brilliant ball of light like taffy in what is called a tidal disruption event, or TDE. The stretch eventually rips the star apart, pulling some into the abyss and leaving merely debris to circle the drain.

At JILA, astrophysicists have been simulating TDEs in an effort to understand not only why these events occur, but how often. Recently, they made a simple-yet-promising model more realistic by including the effects of general relativity. And while the researchers expected general relativity to destroy all promise, they were happily surprised to find their model still stands.

TDEs were predicted decades ago as the inevitable outcome of a star that ventures too close to a black hole. But since the first, and subsequently many, detections, we've noticed their occurrence is much more frequent than first predicted. This discrepancy challenges our understanding of not only TDEs, but possibly even our universe.

Yet one simple solution, proposed by JILA Fellow Ann-Marie Madigan, is that TDEs occur more often than first predicted because eccentric nuclear disks are more common than first predicted.

Eccentric nuclear disk is a term that describes an entire group of stars closely orbiting a black hole in flat, elongated paths, like stellar race cars with a daredevil mindset. While once thought to be exotic (the prevailing picture today is that most black holes host a ball of randomly orbiting stars), there is evidence suggesting they might be common. In 1995, researchers discovered that our nearest neighbor, the Andromeda Galaxy, hosts an eccentric nuclear disk at its center.

Vital to Madigan's solution, however, is the idea that TDEs can occur in eccentric nuclear disks. And so, last year Madigan and her team modeled a basic eccentric nuclear disk. They found that TDEs do occur, and quite frequently.

But Heather Wernke, part of Madigan's team and JILA graduate student in astrophysics, points out that this original simulation wasn't realistic.

"You want to make sure understand the basic idea before you start adding in complications," said Wernke. "Once you understand the basic physics, then you add things in to make it more realistic."

And according to Wernke, one of the most striking deficiencies of the original model was a lack of general relativity.

"A black hole is general relativistic, so these stars will feel the effect of that general relativity anytime they get close."

General relativity amends our original picture of gravity—the force which pulled Newton's apple downward—as arising from the curvature of spacetime. Because black holes are so massive, their dominating force is gravity. Our researchers therefore expected general relativistic effects to significantly modify their TDE-predicting simulations.

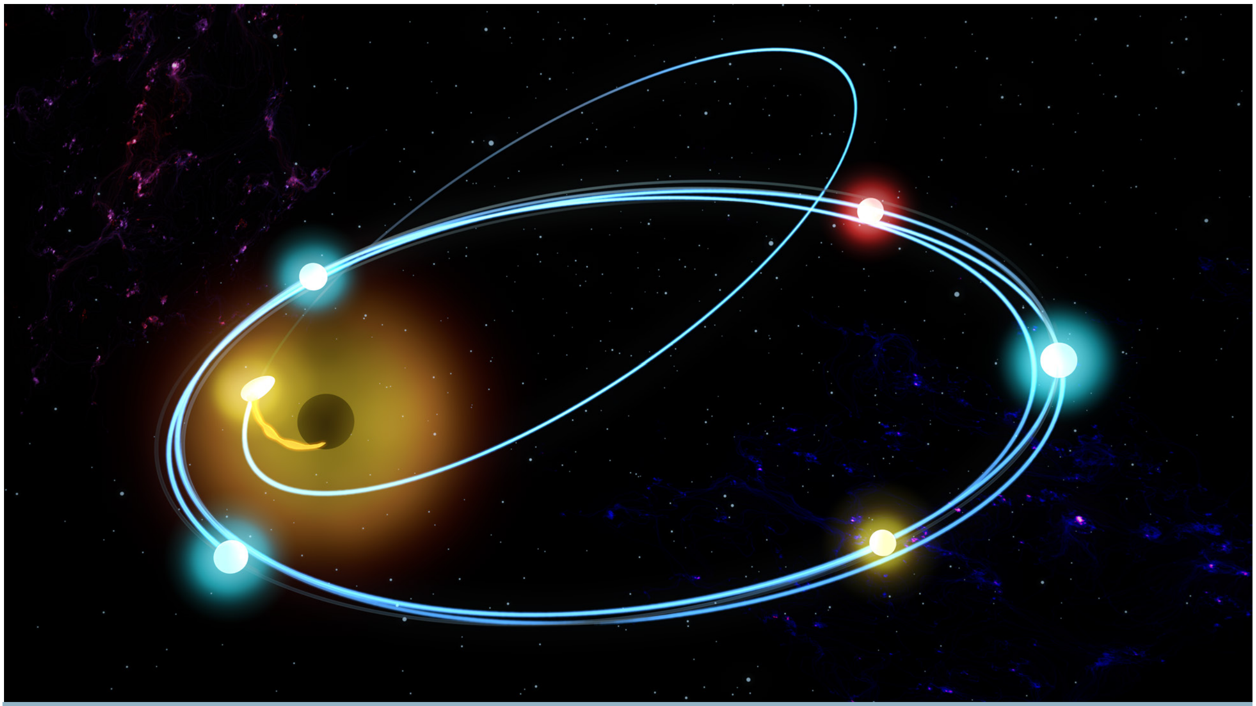


Image Credit: Steven Burrows and the Madigan Group/JILA

And by modify, the researchers meant destroy. Wernke said that general relativistic effects usually round-out an orbit, or make it less eccentric. This rounding would suppress the orbital torques, which are the primary cause of TDEs.

"We thought that general relativistic precession would totally kill the TDE rate," she said, "but it turns out it didn't."

In fact, after simulating the eccentric nuclear disks both with and without general relativity, Wernke found the orbits looked statistically the same. "It was very surprising."

Wernke believes the TDEs still occur because the orbital torques work on timescales much too fast for general relativity to suppress.

And not only are Wernke's simulated TDEs occurring too fast to be suppressed, they are occurring so often that their debris might entangle. "You could have two TDEs occur close enough in time that their debris steams cross. We don't know exactly what that would look like, but it could be observationally really cool."

Having passed the first test of realism, eccentric nuclear disks are still a strong candidate for the explanation of frequent TDEs. But, Wernke said, the next step is to make the eccentric nuclear disk simulations even more realistic, this time by varying the mass of the stars. "In the simulations that I've done, it's all equal-mass stars…but other people in our group are adding in different mass populations."

And as for Wernke, she is now focused on visualizing an eccentric nuclear disk. "What would it look like if we saw this in the sky? Knowing this will help us determine how common they are in the local universe."

H. Wernke and Madigan, A.-M., *The Astrophysical Journal* **880**, 42 (2019).

IN THE NEWS

Jason Dexter, JILA's newest fellow, wins Breakthrough Prize

The Breakthrough Prize is considered the highest-paying prize in science, with a total of $21.6 million for achievements in fundamental physics, mathematics and life sciences. On Thursday, September 5, 2019, JILA's newest fellow Jason Dexter was one of 347 scientists to be honored with the Breakthrough Prize in Fundamental Physics for their work on the Event Horizon Telescope.

But don't worry; he won't be quitting his job at JILA any time soon. The $3 million prize for the team works out to about $8,600 per participant–so it might be enough to pay rent in Boulder, he joked.

Dexter worked on predictions on what the Event Horizon Telescope would see while he was doing his Ph.D. in Seattle. And his group's prediction for M87, the black hole in the now famous image, was pretty close. Seeing the results come back from the experiment was incredible.

Prior to arriving in Boulder, Dexter was at the Max Planck Institute for Extraterrestrial Physics, where he was also involved in the GRAVITY project. But many of the American Physical Society experts on black holes are here at JILA, so Dexter chose to come here.

"It allows for a lot of lively discussions on black hole physics," he added.

At JILA, Dexter is now building his research group, and continues to study images and videos of gas falling into black holes, and what that can tell us about how black holes work. As an astrophysicist, his work focuses on theory and interpretation around these observations–and seeing that image from the Event Horizon Telescope is just the start of new discoveries in physics, he added.

"Now that evidence comes down to the scale of the event horizon itself," he said. "The best is yet to come."

"It was amazing," Dexter said. "For me, personally, it's the coolest thing that I've seen in science."

Graduate student Chris Kiehl wins poster prize at conference in Germany

Regal Group graduate student Christopher Kiehl won a poster prize for their work at the WE-Heraeus workshop on quantum sensing and metrology in Ban Honnef, Germany this August. The conference focused on advances in quantum sensing technology, such as atomic sensors, ion traps and superconducting quantum interference devices (SQUIDS).

Kiehl and his collaborators in Svenja Knappe's mechanical engineering group at University of Colorado Boulder are working on a sensitive, self-calibrated vector magnetometer with a hot atomic vapor cell. Kiehl describes it this way:

"The idea is that in the magnetometry field there are very sensitive technologies to measure the scalar (length) of a magnetic field. To not only measure the length but also the direction of a magnetic field is a much harder problem where systematic errors can accrue that are difficult to calibrate. In other words, accurate vector magnetometry is challenging. In our vector magnetometry technique we can determine and calibrate systematic effects that would normally lead to an inaccurate measurement. In addition, the technique is self-calibrating such that we can tell if we have accounted for all of the systematics affecting our sensor to within the sensitivity of our measurements."

The prize was one of three awarded at the conference. Each of the researchers received 100 Euros as part of the prize. This research is funded in part by the National Science Foundation Physics Frontier Center grant.

JILA ADJOINT JEFFREY LINSKY PUBLISHES NEW BOOK

As astronomers and physicists explore the universe beyond our solar system, exoplanets are tantalizing mysteries. Are there other planets like Earth? Could these planets host life? Do they have oceans?

Since 1995 NASA has confirmed the existence of more than 4,000 planets outside our solar system. But if you want to learn about an exoplanet, JILA Fellow Adjoint Jeffrey Linsky says there's an important factor that is often overlooked.

"You can't understand an exoplanet without studying its host star," he said.

That succinctly sums up Linsky's most recent book *Host Stars and their Effects on Exoplanet Atmospheres*. After 60 years of studying stellar atmospheres, Linsky decided it's time to do a "data dump" and impart that knowledge to future scientists.

Our own sun is host to broad diversity of planets. Exoplanet studies have discovered planets we couldn't imagine: hot Jupiters, super Earths, and mini-Neptunes to name a few. These new planets all vary in size and composition (whether it's rocky or a gas planet) but those are not the only factors that create a planet's environment.

"What we've learned over the last 20 years is this is complicated. There are many variables, from the star, the planet's magnetic field, and the spectral energy distribution of starlight from X-rays to the infrared," Linsky said. "My book is 'here's what stars do.'"

A host star can explain, even predict, the environments of the planets orbiting them. It's not just about how hot the star is. Its stellar winds, coronae and chromospheres can drastically change how their surrounding planets form and evolve. Space telescopes like the Chandra X-Ray Observatory and Hubble use X-rays and ultra violet wavelengths of light to study a star's atmosphere. That information can shed a lot of light on new exoplanets orbiting these stars.

"One of the joys of the field is that there's all these young people doing very important work," Linsky said. However, many of those bright young minds don't know as much about how a star affects its surrounding planets. The book is intended for anyone with a science background, but it's particularly helpful for graduates who are interested in pursuing exoplanet studies.

MINOR PLANET NAMED FOR JILA FELLOW ADJOINT PETER CONTI

JILA Fellow Adjoint Peter Conti now has his name among the stars—or rather, among the celestial objects in our solar system. The International Astronomical Union has named an asteroid after Conti.

Astrophysicist Conti is known for his studies of hot luminous stars and the evolutionary connection between them. His work has studied O-type, Wolf-Rayet and Luminous Blue Variables.

As asteroids go, Minor Planet 25961 Conti is fairly average in size. The asteroid is 4.5 kilometers, about 2.79 miles, in diameter. Conti sits about 2.6 astronomical units from the sun, between Mars and Jupiter. The asteroid takes a little more than four years to make one trip around the sun, traveling in a pretty circular orbit.

AUSTRALIAN FELLOWSHIP NAMED FOR THE LATE JILA FELLOW DEBORAH JIN

JILA Fellow Deborah Jin's research was literally the coolest. She created the first fermionic condensate and the first quantum degenerate molecular gases, expanding our knowledge of how atomic and molecular behavior changes at ultracold temperatures. Jin was not only a prominent physicist, she was a role model and mentor for young scientists, particularly women.

"She was a physics giant. Her research on fermionic gases helped us advance our field in an impressive way," said JILA Fellow Ana Maria Rey, who worked with Jin. "Besides being one of the most prominent physicists in our field, she was a caring mother, a fantastic wife and a supportive colleague and friend."

Although Jin passed away in 2016, her research continues to influence physicists around the world. The Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS) is now offering Deborah Jin Fellowships to two early career female scientists.

“This prestigious fellowship is a great testimony to Debbie’s continuing international impact in research and training,” JILA Quantum Physics Division Chief and Fellow Tom O’Brian said.

EQUS is Australia’s national quantum research and development initiative, similar to the United States' National Quantum Initiative or Europe’s Quantum Flagship Initiative. The Deborah Jin Fellowships are three-year appointments at either the University of Queensland, University of Sydney, Macquarie University or University of Western Australia.

JILA POSTDOCTORAL RESEARCHER MARISSA WEICHMAN WINS POSTER PRIZE

NIST National Research Council postdoctoral fellow Dr. Marissa Weichman recently won the poster prize at the Dynamics of Molecular Collisions conference in Big Sky, Montana.

Weichman works with buckyballs, "molecular soccer balls" made up of 60 carbon atoms. They're huge, for a molecule, but they still play by quantum mechanics' rules. Using frequency comb spectroscopy Weichman and her team can observe buckyballs' rotational and vibrational quantum states to learn when they keep to the rules and when they break them.

"This is the first time anyone has done these kind of quantum-state-resolved measurements for a molecule that is either this large or this symmetric," Weichman explained.

Weichman won $200 as prize money for the competition. Congratulations to Weichman and the Ye group!

APOLLO 11'S LAST WORKING EXPERIMENT ON THE MOON

“Houston, Tranquility Base here. The Eagle has landed,” Neil Armstrong said as the Lunar Module landed on the moon, July 20, 1969.

While the world cheered, Dr. James Faller was running around Lick Observatory in the mountains near San Jose, California, anxiously waiting to run his own experiment. Getting to the moon was already a monumental achievement for science. But for Faller and other scientists back on Earth, the mission was only just beginning as they waited for Buzz Aldrin and Neil Armstrong to deploy their experiments on the lunar surface.

In the 50 years since the moon landing, most of those experiments have stopped working. Except one: Faller’s Laser Ranging Retroreflector, or LRR. Faller had joined JILA, then the Joint Institute for Laboratory Astrophysics, as a fellow.

The LRR is really fairly simple, Faller explained. It’s an array of corner cubes. These fused silicone cubes have one flat surface; the opposite side consists of three flat surfaces intersecting at perpendicular angels, which gives it a unique property.

“I always say it’s the Mona Lisa of optics,” Faller said. No matter where you stand in the Louvre, the eyes of the Mona Lisa seem to follow you. Similarly, the corner cube sends light directly back to their source.

Faller thought up the lunar ranging experiment when he was a graduate student at Princeton. Put an array of corner cubes on the moon. Fire a beam of light at it, and time how long it take the signal to return to Earth. Knowing the speed of light, you could then calculate the exact distance from Earth to the moon.

“Does this idea make any sense?” wrote young Faller on his thesis paper. His thesis advisor, Dr. Robert Dicke, wrote back, “Maybe we can talk about it sometime.”

With the Apollo mission in development, Faller finally had an opportunity to get his experiment to the moon.

"It was simple physics, simple electronics, almost simple optics, but performed over an enormous distance," Faller said.

The experiment almost didn't happen. Faller's experiment didn't get moved up the priority list until a year or so before the launch. Mission leads began to worry about the amount of time astronauts needed to spend on the surface setting up different possible experiments. The LRR fit the bill. A hundred or so small corner cubes fit in an array the size of a briefcase. All the astronauts had to do was make sure it was level and pointed toward Earth.

As televisions broadcast the landing, Faller waited for the astronauts to report their exact position so he could start lunar ranging. But as the first men on the moon, Armstrong and Aldrin weren't exactly sure where they were either, at least not within 10 miles. So Faller and his students began hunting and pecking with their laser trying to hit their target on the moon.

"Looking for this thing, which about this big [about the size of a briefcase] within a 10-mile square on the moon, which is pretty far away, was not a trivial exercise," Faller said. His former advisor, Dicke, came to the observatory to watch Faller's ranging experiment play out, and was there when the signal finally bounced back to Earth.

The accuracy of lunar ranging has significantly improved since the first measurements in 1969. Scientists are now able to measure the distance to the moon down to the millimeter–on average 247,692 miles. More importantly, scientists could now accurately measure how that distance changes over time. We learned that the moon is pulling away from Earth at a rate of about 1.5 inches (about 38 millimeters) per year. Judging how its precise distance changes over time also tells us that the moon likely has a liquid core.

Those changes also tell us how gravity affects objects in orbit, and how gravity affects time. These observations confirmed part of Einstein's theory of general relativity: massive objects distort space-time, which is felt as gravity.

That information is not just for theoretical astrophysics. It has practical applications to modern space exploration. GPS satellites orbiting Earth have to adjust for the slight change in time based on their distance from the center of Earth's gravity. Without that knowledge, they would give you the wrong position, causing a position error that would increase by about 10 kilometers every day.

While other retroreflectors have since been placed on the moon, the LRR from Apollo 11 is still in use today. Every so often, Faller looks up at the moon from his home in Boulder and thinks about his experiment up there. Getting it there took more than just science, he reflected.

"Bob Dicke used to say that he felt he gave us some luck. Science also contains the need for luck, Faller said. "The Apollo program at that point needed some luck. And both our work and the Apollo program were lucky."

JILA'S ANA MARIA REY WINS BLAVATNIK AWARD

The Blavatnik Family Foundation and the New York Academy of Sciences named theoretical physicist and JILA Fellow Ana Maria Rey one of three Laureates for the Blavatnik National Awards for Young Scientists. Each year these awards honor three scientists in life sciences, physical sciences and engineering, and chemistry. The other caveat: all laureates are 42 years old or younger.

"We like to think of them as our young Nobels," Brooke Grindlinger, chief scientific officer of scientific programs and Blavatnik Awards at the academy told the Boulder Daily Camera.

Nominated by 169 research institutions from across 44 states, the Blavatnik National Awards received 343 nominees–the largest pool of nominees ever received by the program. For the first time in the awards' 13-year history, all of the laureates are women; as a U.S. citizen who is a native Colombian, Rey is the first Hispanic woman to win this award.

"It is such a huge honor for me to receive this recognition. I could not believe it was given to me," Rey said. "I am really grateful."

"These three women are leading scientists and inventive trailblazers with stellar accomplishments in their respective fields," said Len Blavatnik, founder and chairman of Access Industries, head of the Blavatnik Family Foundation and member of the President's Council of the New York Academy of Sciences. "Their groundbreaking research leads the way for future discoveries that will improve the world and benefit humankind. It's exciting to see these three brilliant scientists chosen as the 2019 Blavatnik National Laureates."

Rey said she would be honored to be seen as a role model for other young women pursuing physics.

"In my point of view, having role models to inspire women is key. It is very important for women to realize that to have a scientific career it is not incompatible with having a family. Facilitating ways that help women to be a successful scientists and mothers at the same time is crucial," she said. Rey added that she was fortunate to have some great women role models in her early career, including the late Deborah Jin, a fellow JILA physicist.

"She was a physics giant. Her research on fermionic gases helped us advance our field in an impressive way. Besides being one of the most prominent physicists in our field, she was a caring mother, a fantastic wife and a supportive colleague and friend," Rey said.

Rey is a top young theorist in quantum information science and technology (QIST) and atomic, molecular and optical (AMO) physics. Her pioneering work has earned her a MacArthur Fellow Award in 2013 and an American Physical Society Fellow Award in 2015, among many other scientific awards and honors. Rey's theories on atomic collisions led to the development of the world's most accurate atomic clock. That clock is in use at JILA and has been critical in experiments across research groups at the organization.

In addition to being a JILA Fellow, Rey is a Professor Adjoint of Physics at the University of Colorado, and a Fellow of the National Institute of Standards and Technology (NIST), that partners with the University of Colorado to form JILA. Rey is also a leading member of the University of Colorado CUbit Quantum Initiative.

"JILA is thrilled to congratulate Ana Maria for her selection as the Blavatnik National Laureate Award in Physical Sciences & Engineering. We also thank the Blavatnik Family Foundation for celebrating the successes of young scientists and engineers in the US and worldwide," said JILA Fellow and Chair Thomas Perkins.

All Blavatnik National laureates and finalists are invited to the Blavatnik National Awards ceremony at the American Museum of Natural History in New York in September. The award comes with an unrestricted $250,000 prize for each winner. Rey says she doesn't have an immediate plans for the winnings, but she couldn't have achieved this honor without her colleagues at JILA, NIST and the University of Colorado Boulder.

"All my research has been inspired by a close collaboration with experimental groups. In particular, the work done at Jun Ye's, James Thompson's and John Bollinger's labs have been the driving force for my research," Rey said. "Also all the successful developments in my group have been possible thanks to the fantastic group of postdocs and graduate students who have worked very hard to accomplish our research goals. I owe all of them so much. I am really grateful and hope that they consider this award as a recognition to their work."

JILA FELLOW PHIL ARMITAGE MOVES ON

JILAns bid "bon voyage" to Fellow Phil Armitage on Friday June 21, 2019.

While at JILA, Armitage researched theoretical and computational astrophysics, focusing on planet formation and the physics of black holes. His recent work includes the development of a new model for high-energy accretion based on strongly magnetized disks and analytic and simulation studies of planetesimal formation.

Armitage moved on to Stony Brook University.

JILA's Tanya Roussy wins 2019 GPMFC prize

JILA graduate Tanya Roussy was awarded the poster prize at the 2019 American Physical Society's Division of Atomic, Molecular and Optical Physics meeting, held in Milwaukee on May 27–31, 2019.

Roussy's poster won the prize from the Group on Precision Measurements and Fundamental Constants. It covered her work in the Cornell group using electron electric dipole moment (EDM) to search for dark matter.

"Our experiment's primary goal is to measure if the electron is perfectly round or maybe just a tiny bit oblong (this is the 'EDM' part)," Roussy explained in an email. "But it turns out we can use the same data to look for a signal which would reveal the presence of a certain kind of dark matter, called 'axion-like particles'. Currently, we know that dark matter exists, but nobody knows what it is and nobody has measured it directly. This poster described one attempt to measure dark matter."

Thinh Bui wins Longuet-Higgins Early Career Researcher Prize

Thinh Bui, a postdoctoral researcher in Jun Ye's group, won the 2018 Longuet-Higgins Early Career Researcher Prize from the journal *Molecular Physics*. The journal awards this prize to researchers who have published their paper within five years of earning their doctorate. The Longuet-Higgins Early Career Researcher Prize is $1,000. It's an honor to win, Bui said.

Bui's winning paper, "Spectral analyses of trans- and cis-DOCO transients via comb spectroscopy," was published in the journal in 2018. This study watched how hydroxide and carbon monoxide reacted to create hydrogen and carbon dioxide. This reaction happens in combustion, like inside an engine or lighting a match, in Earth's atmosphere and the atmospheres of other planets.

"When you burn anything, you create these molecules and that dictates what we see (like a flame)," Bui said. The products of that reaction, like carbon dioxide, are at the center of real-life problems like climate change, he explained. That's why scientists since the 1960s have focused basic research on understanding these reactions.

Scientists had suspected that a free radical called HOCO formed in the middle of the reaction between hydroxide and carbon monoxide, but it lived so briefly, that no one had been able to observe it before. Using JILA's finely tuned frequency comb, Bui and his team were able to detect it.

"It lives in a flash," Bui said, lasting only a microsecond. And they found something else. A trans configuration of HOCO didn't produce carbon dioxide. Now research in this field is progressing to understand how we can manipulate these molecules.

Bui added that winning the Longuet-Higgins Prize is also a testament to the working environment at JILA.

"The best part about working in Jun Ye's group is you have a lot of flexibility to explore your intellectual curiosity," he added. "He let me explore these problems that I thought were interesting."

Bui is going on to NIST in Maryland to work on magnetic sensing research.

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

University of Colorado **Boulder**

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 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; Biochemistry; and Molecular, Cellular, and Developmental Biology, as well as in the School of Engineering.

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 eight broad categories: Astrophysics, Atomic & Molecular Physics, Biophysics, Chemical Physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information Science & Technology.

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