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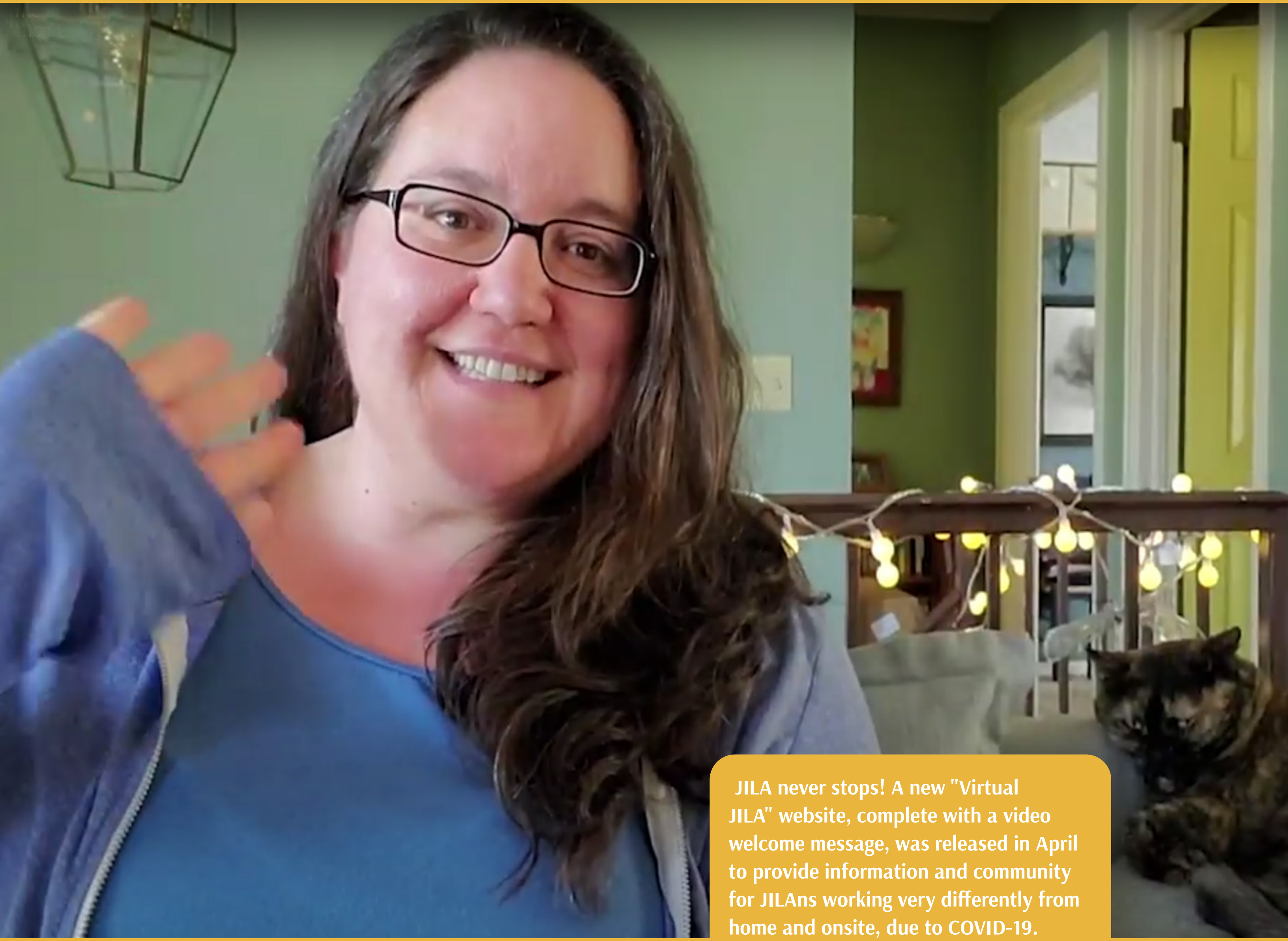
Guiding Electrons with Gold Nanostars p. 1



JILA never stops! A new "Virtual JILA" website, complete with a video welcome message, was released in April to provide information and community for JILAns working very differently from home and onsite, due to COVID-19.

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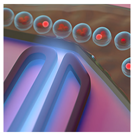

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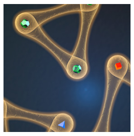

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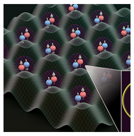

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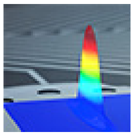

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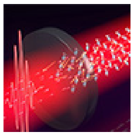

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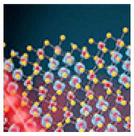

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Guiding Electrons with Gold Nanostars

In nearly 80 years, computers have shrunk from electronic behemoths that filled 50-by-30-foot rooms to smartphones that fit in the palm of your hand.

That's largely because transistors have shrunk down to the nanoscale—ten to one-hundred billionths of a meter, which is a thousand times smaller than the width of a human hair. Those transistors control current in computer chips; they store the binary 1s and 0s your computer uses to process information. But recently scientists have run into a problem.

"We're getting about as small as we can go. Recently we've been approaching the limit where transistors can't get much smaller because you're nearing the few-atom regime," said Jake Pettine, a graduate student in the Nesbitt Lab at JILA.

But, if computers can't get much smaller, why not make them faster? Today's computers operate at a few gigahertz, with electrons moving around as fast as they can through the transistors, Pettine pointed out. At a few gigahertz, a computer goes through a cycle a few billion times a second.

"That's pretty fast, but visible light is about a hundred thousand times faster," he said. "So, one way to go faster, instead of controlling those electrons with typical electronic means, is to control them with light."

"You can process information on a much faster timescale, as opposed to just having slow, lumbering voltages coming in from wires," said JILA Fellow David Nesbitt.

To do that, you need to use light to steer electric currents in nanoscale circuits. Pettine and the Nesbitt Lab may have found a means of guiding that light using gold nanostars. Their findings were published recently in *Nature Communications*.

The golden touch

Gold is a key to the nanostar's usefulness. The first thing you notice about gold is its brilliant shine, Nesbitt said, and that effect only gets stronger as the particles get smaller.

"It's the material that provides a terrific hook to bring photons into it…Gold has these marvelous properties that allow it to have exceptionally strong interactions with light in the visible [spectrum], where many ultrafast lasers operate. As you shrink [gold] down to the nanoscale, it interacts more strongly per volume."

Scientists have exploited this unique characteristic since the days of alchemy. Tiny particles of gold were embedded in glass to create red stained glass for medieval cathedrals. When white sunlight hits the particles in the glass, the gold absorbs blue light and transmits deep ruby red light.

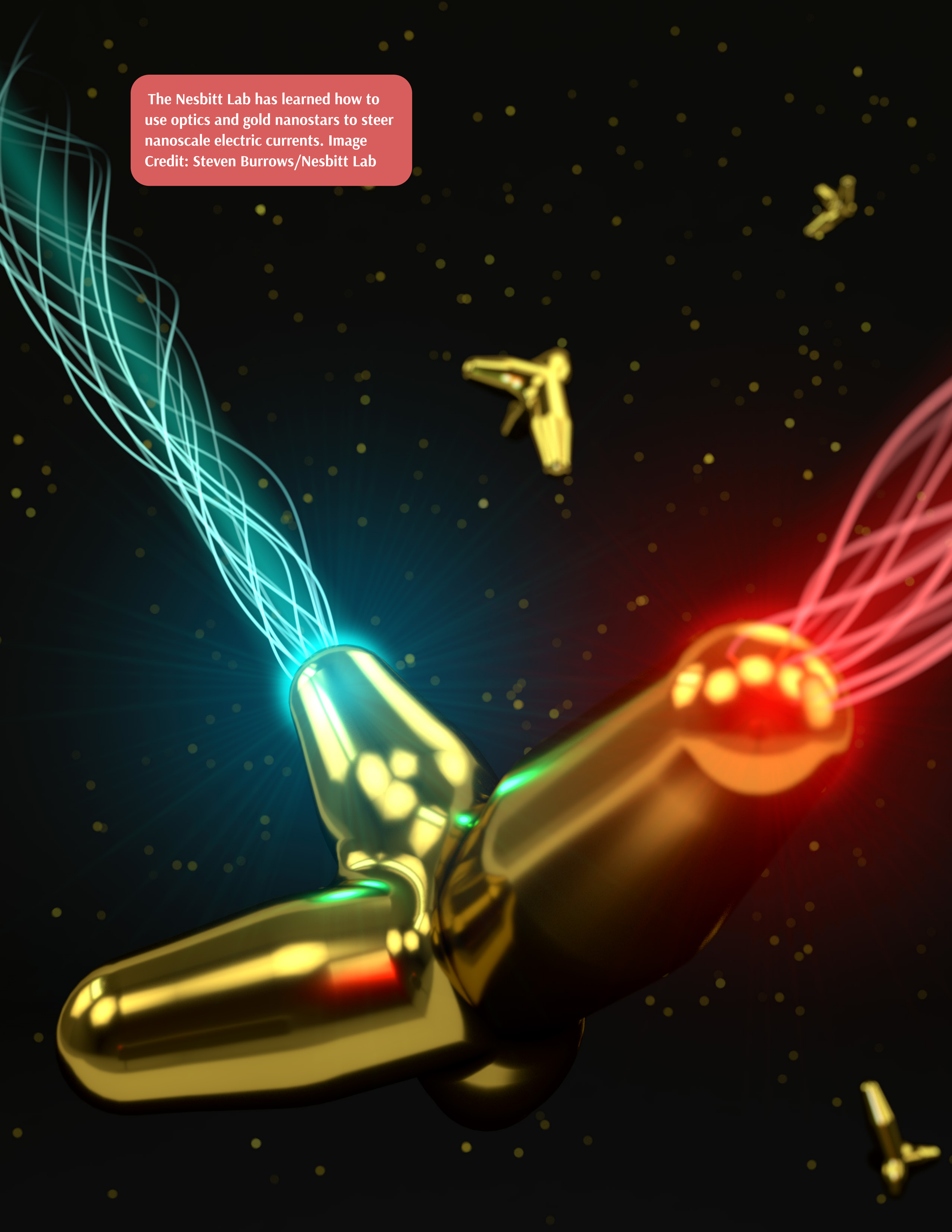
Unlike light through a stained-glass window, Pettine and Nesbitt need to draw light into the gold nanostars and concentrate it at specific "hot spots." That's where the nanostars' shapes come in handy.

A star is born

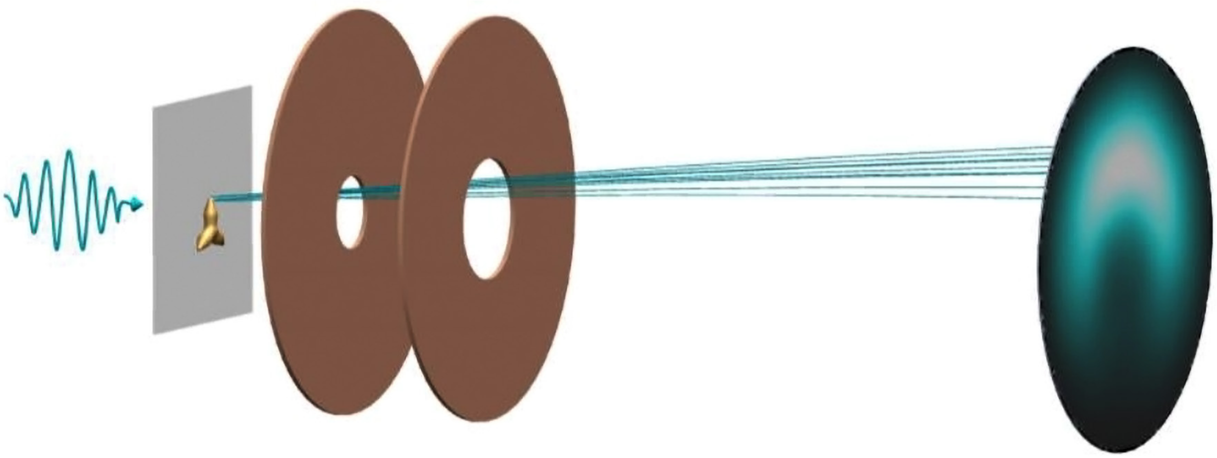
The gold nanostars in the Nesbitt Lab are shaped like toy jacks or caltrops, with pointy arms protruding from their small center. With a specialized "recipe", the lab's collaborators at Northwestern University grow the nanostars like crystals in a cave to reach the right size and shapes.

No two stars are exactly alike, with different arms of different lengths pointing in various directions. Those arms act like antennas, drawing in light from the laser, Nesbitt explained.

"Think of the nanostar just as being an old-style television antenna…pointing in different directions and able



The Nesbitt Lab has learned how to use optics and gold nanostars to steer nanoscale electric currents. Image Credit: Steven Burrows/Nesbitt Lab



Experimental setup, in which photoelectrons are mapped onto a microchannel plate detector. Image Credit: The Nesbitt Group

to bring in different stations as a result," Nesbitt said. "The stations that these nanostars are communicating with are different colors of laser light."

The electrons at the tips of these antennas are able to "tune in" to the energy coming from the laser light. But now, they need some direction.

Steering on the Fermi sea

There are millions of free-floating electrons inside the gold nanostars, collectively known as the Fermi sea. Hit the electron sea with light and it creates waves. Without direction, the electrons will just bob up and down in place, like a cork on the ocean.

That's why the asymmetric antenna-like arms of the nanostars are so important. Electric fields collect near their sharp points, Nesbitt pointed out. As electrons slosh along the elongated arms, they pile up at the sharp tips and create a hot spot.

The electrons stream off this hot spot in a process called photoemission, or the photoelectric effect.

"When electrons build up at these really sharp tips, they can shoot out in a certain direction…If the electrons were just going back and forth, the electrons have energy but we can't do much with it. Once you actually kick them off in a certain direction, that's when you get useful current," Pettine explained.

Pettine found that by changing the polarization and/or color of the laser, he could change which tips the current flowed through, and how many electrons spilled out.

"This is where the steering idea comes in," Pettine added. "For instance, we change the angle of the light–the polarization of the light–and we see that as we do that, the angle of the emitted electrons changes."

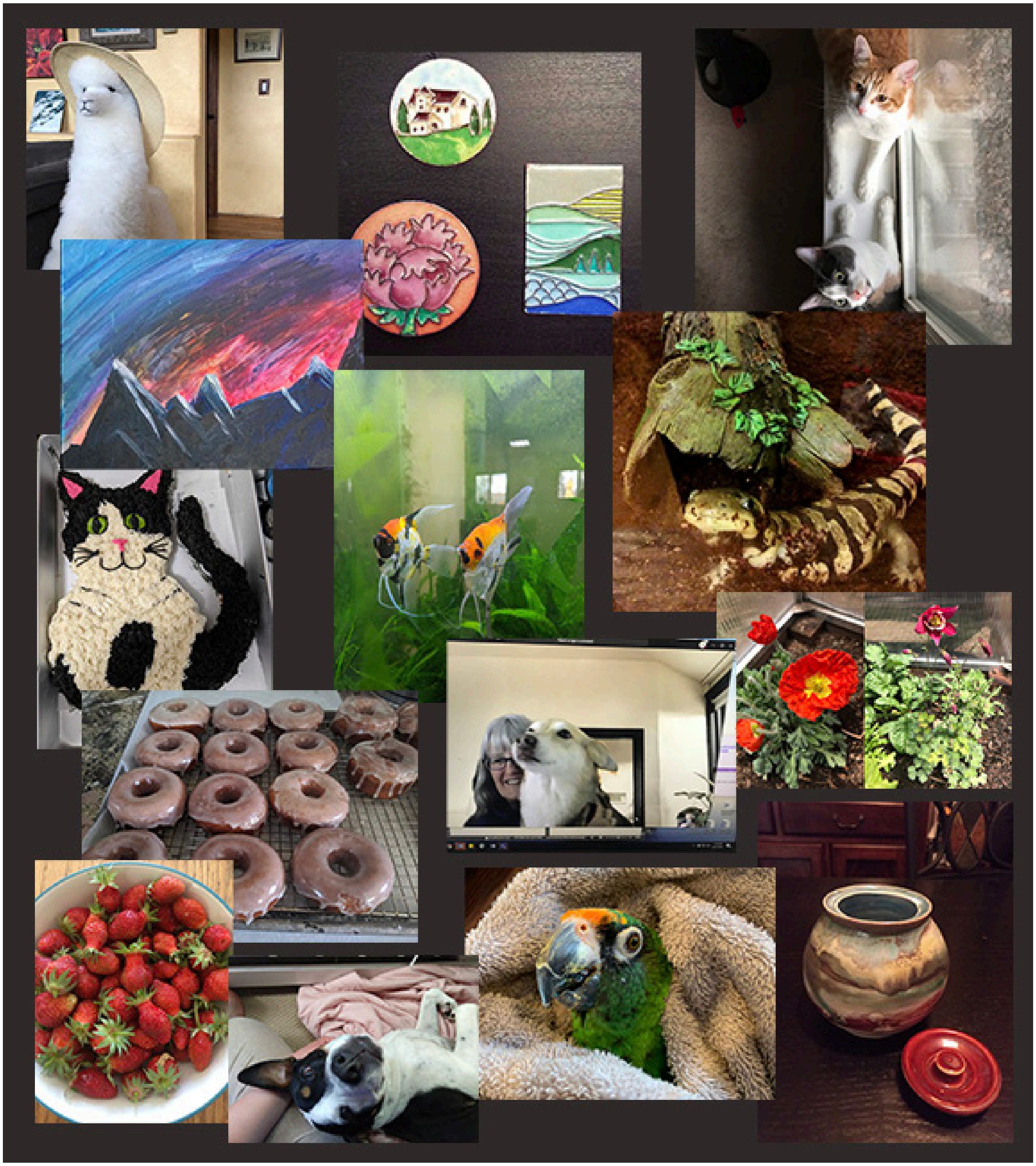
In this study, Pettine and his group created a detailed map to show exactly which light colors/polarizations couple to any particular tip. This kind of control is promising as a step toward new computers and technologies using electron beams, such as electron microscopy or electron diffraction.

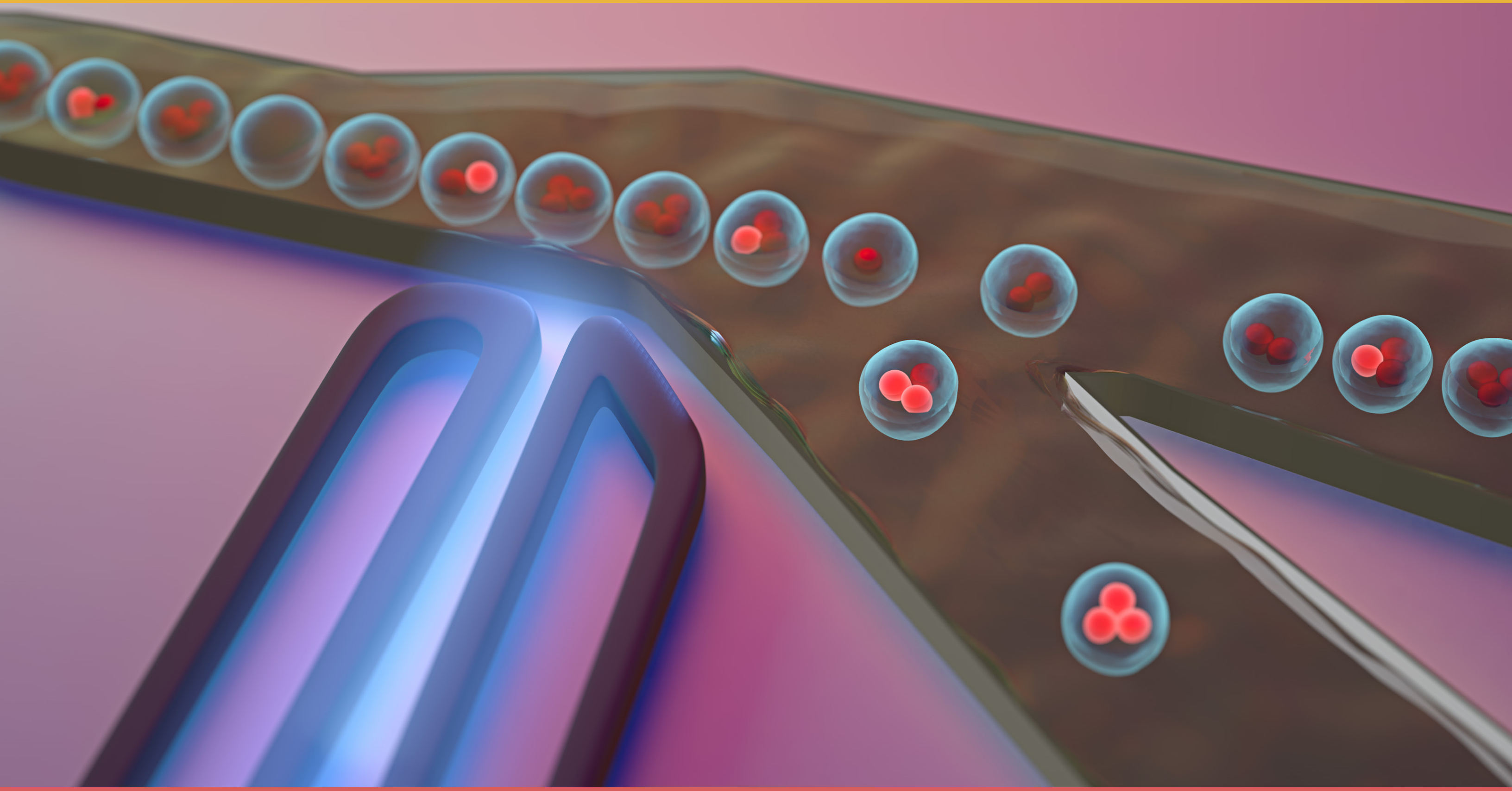
"Part of this paper is showing that we can do this experimentally, and the other part is introducing a full model that we can then apply to other nanoscale systems…So, the nanostars are just a good prototypical system to illustrate these behaviors," Pettine said.

J. Pettine, Choo, P., Medeghini, F., Odom, T. W., and Nesbitt, D.J., *Nature Communications* **11**, 1–10 (2020).

COVID-19: JILAns Work from Home

In March 2020, the majority of JILAns began working from home as a safety response to the unprecedented threat of a new virus. One way of maintaining JILA's strong sense of community has been the use of online collaborative tools to share technical issues, project coordination, and even pets and hobbies.





The Jimenez Lab has built a fast flow cytometry system which quickly sorts fluorescing cells from non-fluorescing ones. Image Credit: JILA/Steven Burrows and the Jimenez Lab

SORTING THE GLOW FROM THE FLOW

How do you find a single cell in sea of thousands? You make it glow.

Adding fluorescence helps track movement and changes in small things like cells, DNA, and bacteria. In a library of millions of cells or bacteria, flow cytometry sorts the glowing material you want to study from the non-glowing material.

In short, "it's a fluorescence filter," said Srijit Mukherjee, a graduate student in the Jimenez Lab at JILA.

With the help of JILA's electronics shop and clean room, the Jimenez Lab has found a way to take droplet sorting time from days to hours. Their new setup not only improves the time it takes, you can better sort your material by how long, or how brightly, it glows.

"You gain an enrichment off a population in a matter of a few hours," Mukherjee explained. "Then you can repeat the process again and again to enrich this population of a very rare event."

Drop by drop

Here's how flow cytometry works: You have a large library of material–cells, for example–which have been genetically modified so the cells with the traits you want to study glow. You encapsulate a group of those cells (and the medium they're floating in) into individual droplets of water in oil. The droplets flow through a tube past a focused laser beam. When a glowing group is detected, it is separated out with an electric field which "pushes" it into the "keep" pile.

There are two obstacles scientists run into with flow cytometry systems. First, there's a lot of junk floating around with the glowing material you want to study. The odds of getting any fluorescent cells at all in your droplet are low, Mukherjee pointed out–at single cell loading, fewer than 10% of the droplets have a cell, glowing or not. The other 90% are just oil and water.

"Even in that 10%, the probability that you have a fluorescent droplet is even lower, so your throughput is really, really low," Mukherjee explained.

Second, flow cytometry can be really tedious. That low throughput means it can take a long time to sort through with a large library of material, even with good flow cytometry systems.

The Jimenez Lab wanted to sort fluorescing *E. coli* bacteria. For their experiment, they needed to not only sort out the glowing bacteria, but sort by the lifetime of that fluorescence. The flow cytometry system they were using could only sort 50 cells a second; sorting through millions of bacteria would have taken days. Plus, the system was complicated to use.

"To most of us, it was just a black box…it was just a cobweb of Labview codes," Mukherjee said. "Getting it to sort was a challenge."

Pumping up the drops

The group took a mathematical approach, Mukherjee said: if you increase the number of cells in each droplet, the probability that a droplet contains a fluorescing cell increases too.

"It's basically dumping out most of the non-fluorescing junk and selecting out the fluorescing population," Mukherjee said.

Then, they repeat the flow cytometry process with the traditional single-cell per droplet approach–but this time, they sort out the material by more specific characteristics, such as a fluorescence lifetime or brightness.

The power of collaboration

To do that, they needed faster electronics and clean, precise tools. Those were all available in house at JILA, and the Jimenez Lab built their fast flow cytometry system completely at JILA.

JILA's electronics shop was able to craft field-programmable gate array (FPGA) electronics which operate on a nanosecond scale–much faster than what they could order elsewhere. The clean room at JILA was used to fabricate all the microfluidic chips, so they were super clean. Being able to make everything in house also made this new system extremely cost-effective, Mukherjee added.

As a result, the Jimenez Lab enriched the proportion of fluorescing cells in their samples from 10% to 94%. They went from sorting 50 cells per second to about 2500 droplets per second–greater than a hundredfold improvement, Mukherjee said.

This type of system could make a difference not only to labs, but to anyone who needs to sort through a large library for a particular event, such as biomedical researchers who need to find the few abnormal cells in a pool of millions.

"We are trying to use it to approach fluorescent protein libraries, but this is a very general approach to enrich any fluorescent event in a library of events."

S.-T. Hung, Mukherjee, S., and Jimenez, R., *Lab on A Chip*, **20**, 834–843 (2020).

How Universal is Universality?

"Atoms aren't like protons. They're full of pulleys and bells and whistles. Sometimes, those 'guts' matter." –Eric Cornell

We understand pretty well how a single atom behaves. Two atoms interacting with each other? Still solvable. But it becomes exponentially more complicated to characterize how three atoms or particles interact with each other, explained Xin Xie, a graduate student in the Cornell Group at JILA.

Those interactions–whether particles will repel each other, smash together or just orbit each other in perfect harmony–dominate the quantum world. Understanding how those forces work inside a simple hydrogen atom, with its single positive proton and negative electron, is relatively easy, explained JILA Fellow Eric Cornell. But most atoms are much more complicated.

"We study three-body physics because there are still mysteries in this interaction." - Xin Xie

"Atoms aren't like protons. They're full of pulleys and bells and whistles," he said. All of those structures in the "guts" of each species of atom meant that when three atoms got too close to each other, no mathematical formula could predict how all three would interact, Cornell said.

But years of experimental data found there was a sweet spot, a universal range in which the behaviors of three atoms can be decomposed into the more solvable two-atom problem. At that range, the atoms are stopped en route to each other, keeping them at just the right distance.

That range was dictated by the van der Waals force. And by knowing the strength of the van der Waals force between two atoms, we can easily predict the shortest distance that three atoms can get without either smashing into each other or repelling each other. It didn't seem to matter which species of atoms you looked at; the van der Waals force always dictates three-atom interactions.

For the last decade, this van der Waals universality had been pretty widely accepted…until now. Xie and the Cornell Group recently found this universality has a limit. Their findings raise an important question: When it comes to three-body interactions, just how important are those pulleys, bells and whistles, those innate structures that make up an individual species of atom?

"A long time ago people thought these structures were so important. Then people found that maybe they're not that important," Xie explained. "But then we claim that they still matter… it can cause some deviation from the van der Waals universality."

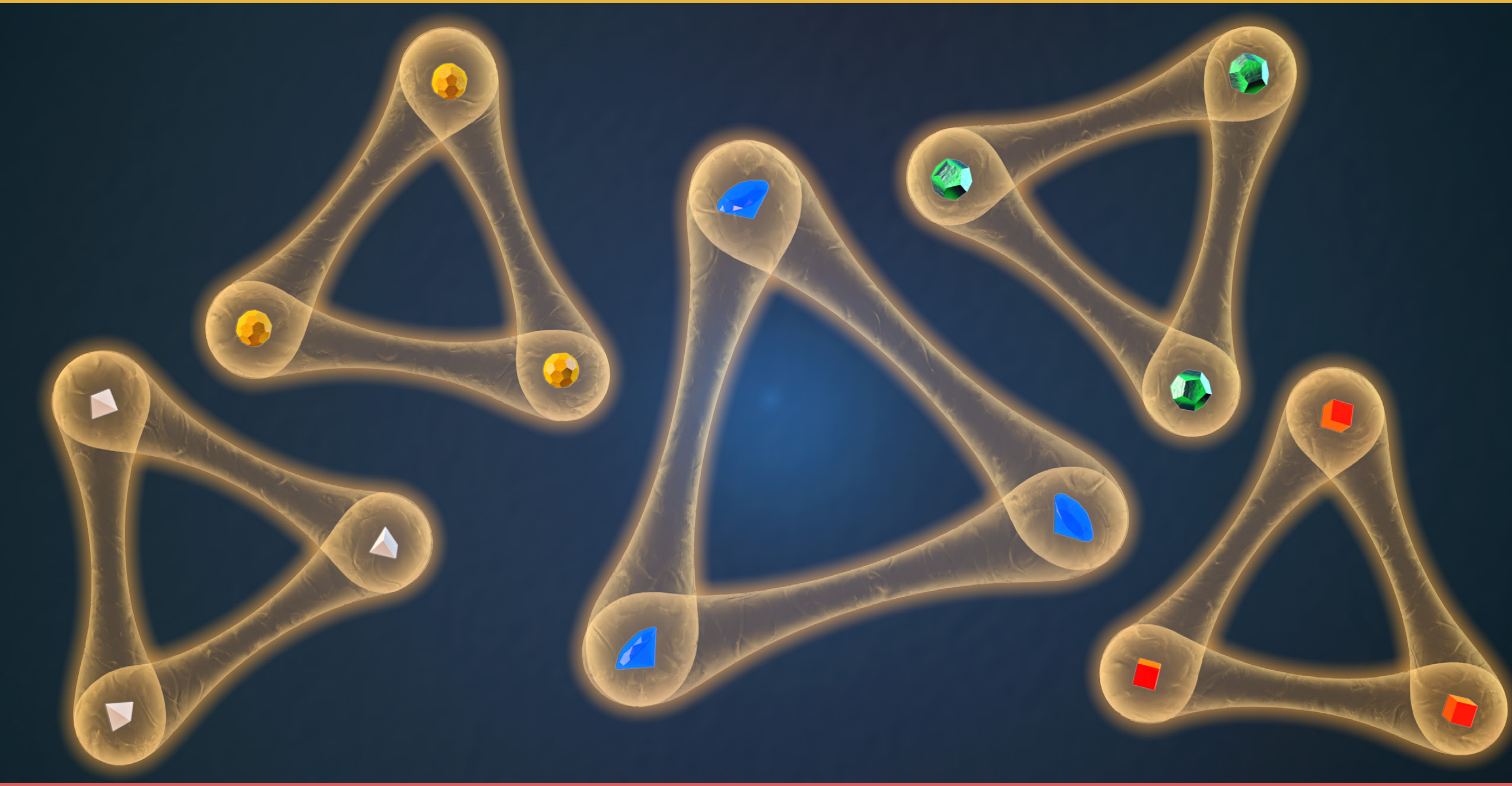
Take it to the limit

To find the limit, you have to really dig down and look at the atoms very closely, Cornell said. When they're warm, atoms in a gas cloud bounce around like billiard balls. To measure their interactions, you need to slow the atoms down, and that means making them cold–really cold.

Xie and her team used lasers to bring a cloud of potassium atoms down to 300 nanoKelvin, about -459 degrees Fahrenheit, hovering just above absolute zero.

Then they change the magnetic field around the atoms to force them to interact. As the atoms interact, the cloud decays. The more strongly the atoms interact, the faster it decays. The decay rate reveals information on the spatial extent of a three-atom system.

But Xie and her team found their potassium atoms does not quite fall into the universal group, and within a very narrow margin of error. Clearly, van der Waals universality was not as universal as it seemed.



The van der Waals universality is a sort of "sweet spot", a distance at which three atoms' interactions can be predicted with simpler two-body equations. The Cornell Group has found that distance may not be so universal after all, and that the species of atom may change that "sweet spot." Image Credit: Steven Burrows/ JILA

"Sometimes, those 'guts' of the atom matter," Cornell concluded.

"We study three-body physics because there are still mysteries in this interaction." –Xin Xie

Cold atoms in space

The next step for this experiment lies beyond the Earth's atmosphere. In the vacuum of space, the atoms can reach even colder temperatures, and possibly reveal some new information. So, in December 2019 a refrigerator-size version of this experiment started operation on the International Space Station.

Finding the limits of universality has greater implications for physics. Ultracold atoms are often at the center of precise metrology, like optical atomic clocks which use cold strontium atoms. If those atoms start interacting with each other in an unpredictable way, it could throw off your clock, and you wouldn't know why, Xie said.

"You can't account for all the degrees of freedom in a physical system," Xie pointed out. But experiments like this show what "ingredients" are important to understand these interactions. Testing the limits of universality helps physicists better predict how other atoms will behave.

"If we understand this species (potassium), we can apply our model to a different species," Xie added.

R. Chapurin, Xie, X., Van de Graaff, M.J., Popowski, J. S., D'Incao, J.P., Julienne, P.S., Ye, J., and Cornell, E.A., *Physical Review Letters* **123**, 233402 (2019).

The Power of the Dark Side

Atoms could live in their excited states forever by reaching a dark state.

How long can a unique atomic state live?

Atoms normally live in their ground state, where its electrons are sitting in their lowest possible orbits. But when the atoms are hit with some extra energy, their electrons are kicked into a higher energy level, orbiting further from the nucleus of the atom. That's an excited state.

Long-lived excited states are appealing to physicists for several reasons. At JILA, sophisticated optical atomic clocks need long-lived, excited strontium atoms for precise timekeeping.

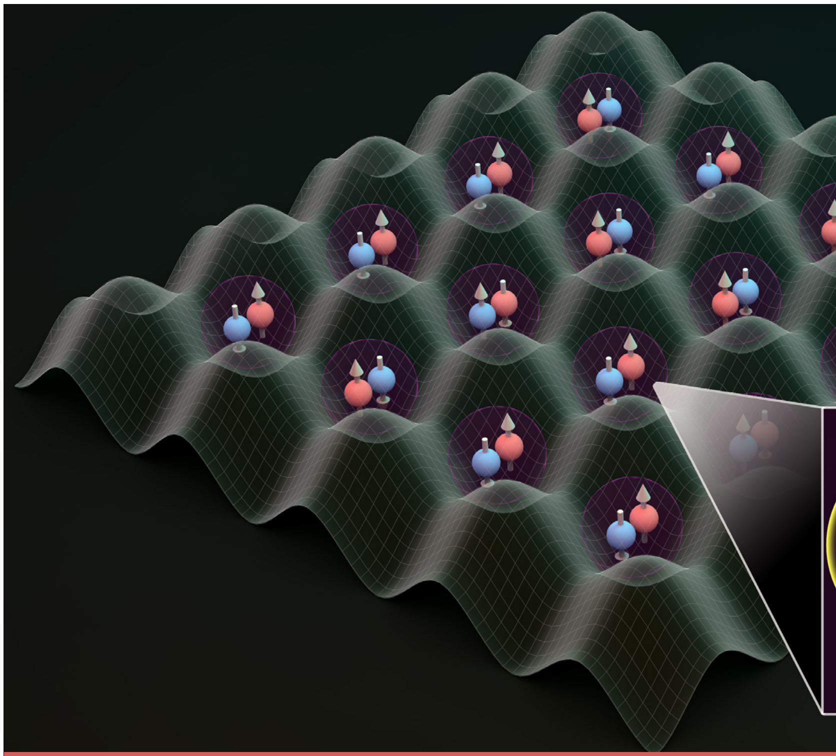
> **"Dark states are stable and they do not decay. There is the possibility that they live forever." —Ana Maria Rey**

Nevertheless, a single atom does not remain excited forever. How long that excited state will last depends on the species of atom, but eventually the atom shoots out the excess energy via a burst of light or collision with another atom or surface. Then the electrons decay back to their ground state.

And reaching a very long-lived state is tricky. Very long-lived states are hard to excite and typically require very sophisticated laser technologies to hold atoms in vacuum. Ideally, scientists would like to work with states that are both easily excitable and live for a long time.

Quantum mechanics offers hope that atoms could live longer in an excited state–the creation of a dark state. "Dark states are stable and they do not decay," said JILA Fellow Ana Maria Rey. "And there is a possibility that they live forever…this idea has caught a lot of attention in physics."

After playing around with some material, Asier Piñeiro Orioli, a research associate in the Rey Theory Group at JILA, found a way to harness the power of the dark state.



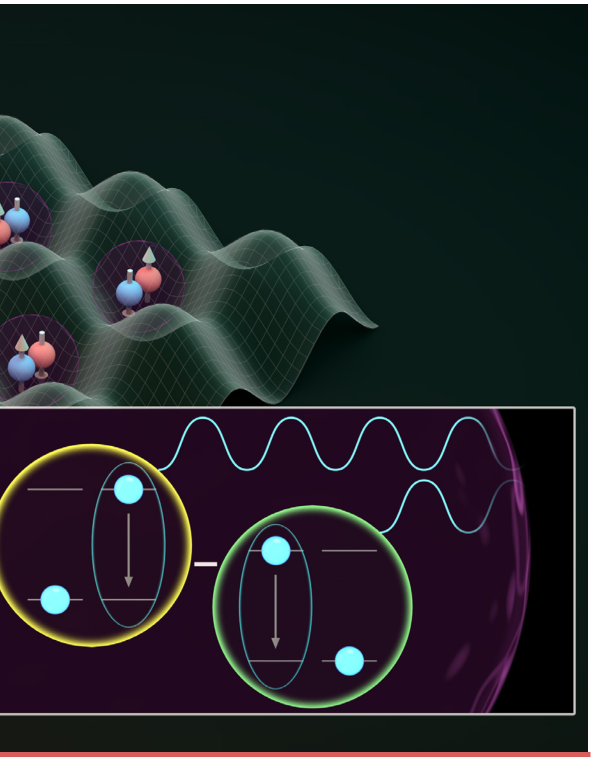
The Pauli exclusion principle dictates that atoms with the same space. By preparing and pairing up atoms, Asier Piñeiro Orioli in to use this principle so that atoms will stay in their high-energy

It takes two

A dark state requires symmetry, Rey said–a balance between two atoms. In an optical atomic clock, strontium 87 atoms are held in an egg-carton-like lattice, one atom per well. So, the first step to create a dark state is to add a second atom to each well. Reaching that desired balance within atom systems relies on the Pauli exclusion principle and destructive interference. The Pauli exclusion principle says that no two identical fermions can have the same quantum number.

"You have one atom in the ground state and one atom in an excited state," Piñeiro added. "The lower atom is blocking the atom upstairs…If it decayed, you would have two atoms in the ground state and that cannot be."

Destructive interference means that the two emitted photons would see each other and cancel out their own radiation, said Piñeiro. "In a sense, it's like the photons cannot escape. It's like two prisoners bound together and going in opposite directions," he explained.



quantum number cannot share the same
the Rey Theory Group has devised a way
state. Image Credit: Rey Theory Group

The term dark state is literal; the atoms can't absorb or emit light as photons. And that is powerful. However, atoms need more than two energy levels for destructive interference to happen. In strontium 87 atoms, the ground and excited states have substructure and contain at the least 10 different internal levels, giving the photons more ways to maneuver and cancel each other.

Baby steps for stubborn atoms

Atoms can be very stubborn. In a dark state, they can remain in an excited state for a relatively long period of time, but getting the atoms into that state is tricky.

"They don't like to decay but they don't like to be prepared either," Piñeiro said. Starting with both atoms in the ground state, it would be almost impossible to excite them.

Rather than struggling to push these atoms directly into the right energy levels, Piñeiro proposes moving the atoms up in two separate steps to prepare a dark state. Adding this intermediate step will let the experimentalists tame the stubborn atoms and force them into a dark state.

New opportunities for clocks

While the Ye Group's optical atomic clock is one of the best in the world, long-lived atoms would offer opportunities to explore new ideas. Rey and Ye have been looking at using the Pauli blockade to prolong the life of strontium's other excited states when Piñeiro found a way to achieve completely dark states.

"I wasn't looking for it. I was just playing around a bit with some very easy program that I wrote to understand how these atoms behave. And then suddenly I saw something that was not decaying," Piñeiro said.

The other beauty of this proposal? The geometric arrangement of the atoms doesn't matter, Rey said. As long as there are two atoms per site, it doesn't matter the shape or pattern of the optical egg carton.

"As long as you have a dark state here, a dark state here, we don't care anything about the geometry," Rey said. "So it's really robust."

If Piñeiro's proposal works, the Ye Group could eventually build a clock that runs forever. A longer lasting clock would open up new experiments that will let us understand quantum mechanics and the world around us.

A. Pineiro Orioli and Rey, A.M., *Physical Review Letters* **123**, 223601 (2019).

Meadolark Optics, SPIE and the University of Colorado Announce $2.5 Million Endowed Chair in Optics and Photonics at JILA

Thanks to generous donations, JILA will have its first-ever endowed chair position for optics and photonics research. The Baur-SPIE Endowed Chair in Optics and Photonics will be funded by a gift of $1.5 million from private donors Tom and Jeanne Baur of Meadowlark Optics, and a $500,000 matching gift from SPIE, the international society for optics and photonics. In addition, CU Boulder is contributing $500,000 from the university.

By providing comprehensive support for a faculty chair, the $2.5 million fund will enable JILA to expand its research and education capacity in optical physics and photonics. The chair is designed for early-to-mid-career researchers affiliated with groups historically under-represented at CU Boulder, as well as academics who have an established interest in teaching and mentoring.

> **“We have a strong respect for the hard work of the optical research community at JILA that we are supporting. We hope that our contribution will inspire others to contribute to the advancement of optical research at JILA and elsewhere.” —Tom Baur**

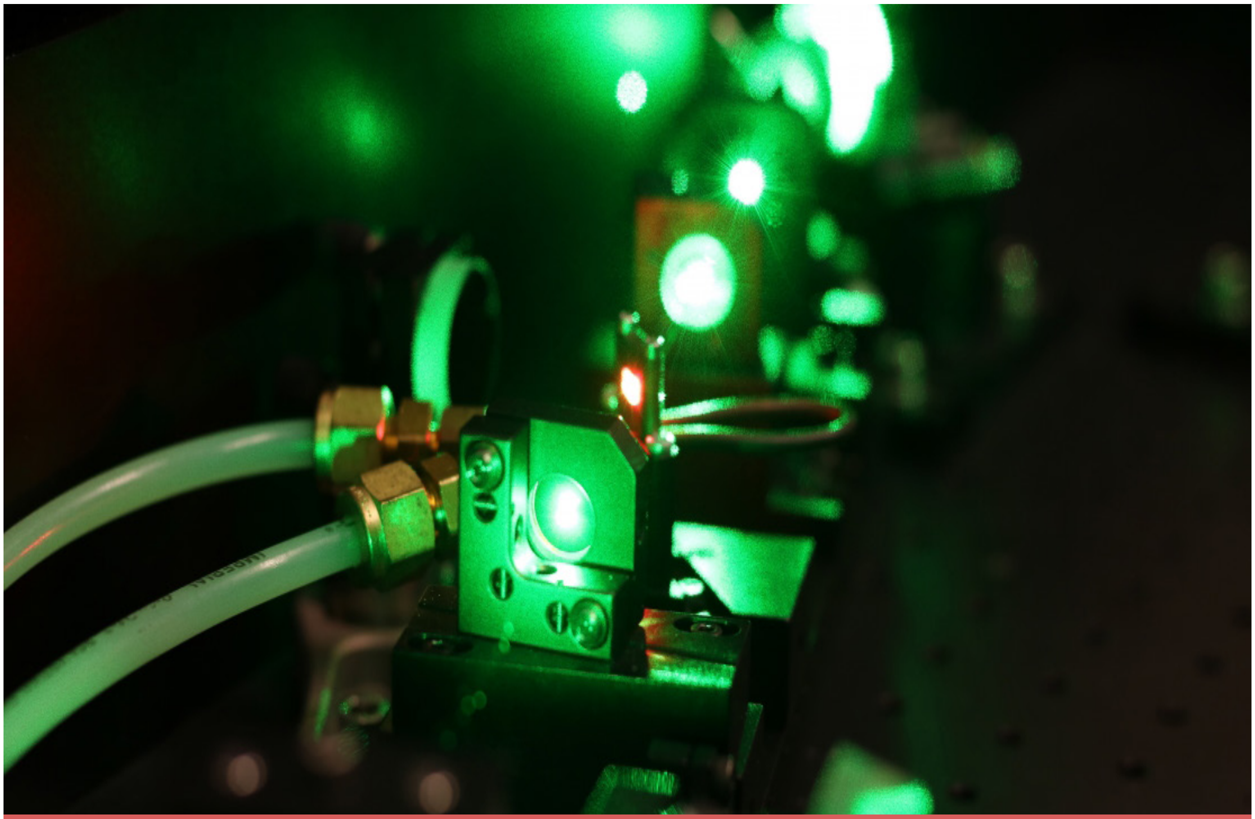
Tom Baur, a first-generation college student at the University of Michigan, received a master’s in astro-geophysics in 1969 from CU Boulder and then worked for 13 years as an observational astronomer at the High Altitude Observatory, a division of the National Center for Atmospheric Research in Boulder. He later founded Meadowlark Optics, now located in Frederick, Colorado.

The company has benefited from its partnerships with JILA and CU Boulder faculty and students. Both institutions have been a significant source of employees for Meadowlark Optics, and the company has had successful joint research programs with the university and with NIST. In 2018, Baur was the recipient of the SPIE G.G. Stokes Award for a lifetime of leadership in polarization optical components, and for revolutionizing the polarization field through commercialization of liquid crystal variable retarders.

“Jeanne and I have been lifelong learners, and much of that learning has been outside the classroom,” Baur noted. “We have a strong respect for the hard work of the optical research community at JILA that we are supporting. We hope that our contribution will inspire others to contribute to the advancement of optical research at JILA and elsewhere.”

The Baur’s gift is matched by SPIE as part of the SPIE Endowment Matching Program. Established in 2019, the SPIE Endowment Matching Program is a $2.5 million, five-year, educational-funding initiative designed to increase international capacity in the teaching and research of optics and photonics. SPIE supports optics and photonics education and the future of the industry by contributing up to $500,000 per award to college and university programs with optics and photonics degrees, or with other disciplines allied to the SPIE mission.

“This generous gift from Tom and Jeanne will give JILA the opportunity to expand its optics and photonics focus by hiring from the best and the brightest of teaching researchers,” said SPIE President John Greivenkamp. “We



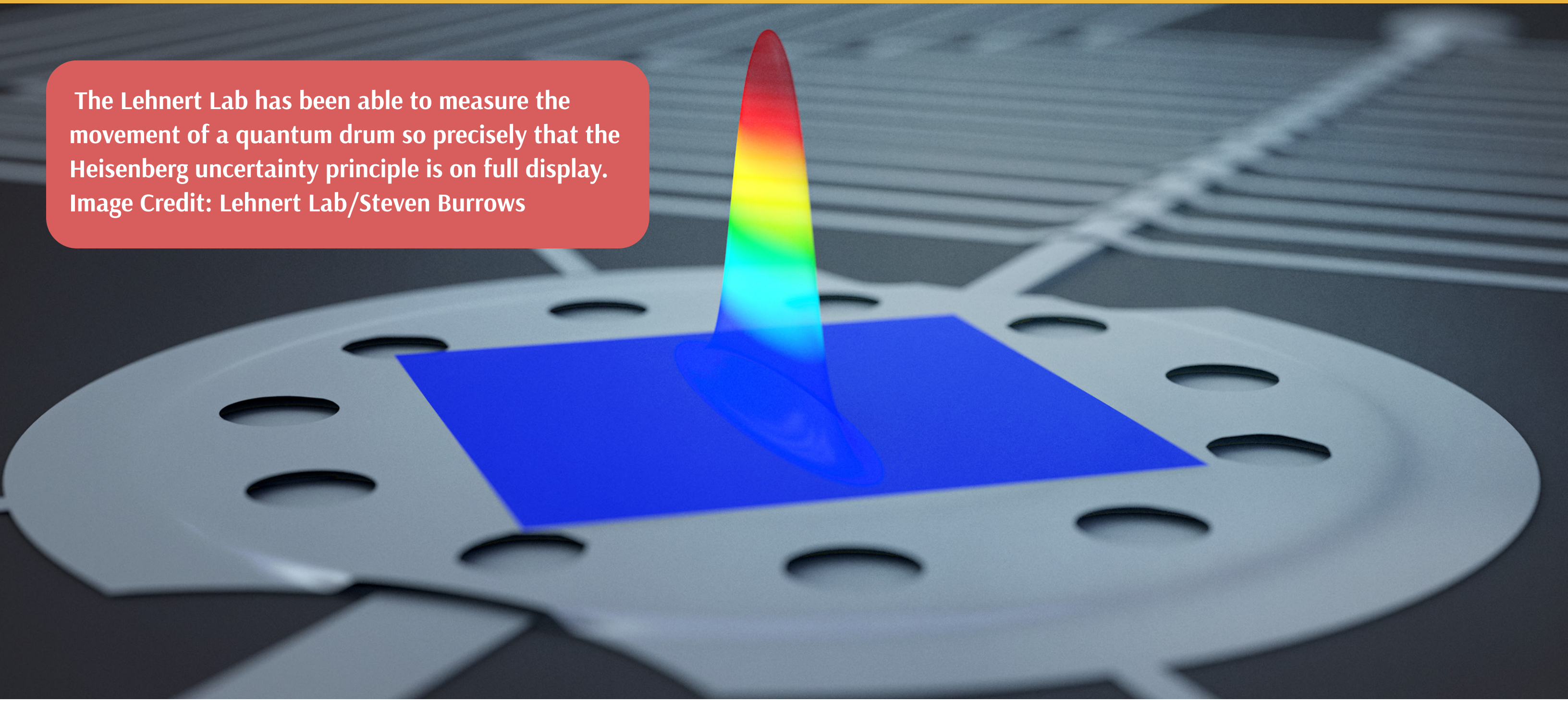
Laser oscillator in the KM Lab at JILA. A $2.5 million gift from Tom and Jeanne Baur, SPIE and CU will fund the first Endowed Chair at JILA in optics and photonics. Image Credit: Rebecca Jacobson/JILA

are delighted to support higher education and research – a core purpose of SPIE – by creating this endowed faculty position with the Baur family. The chair holder will be a critical supporter of current and future generations of optics and photonics scientists and engineers, and we are excited to be a part of this far-reaching effort."

"We are very excited about a partnership that will support our continued emphasis on diversity and inclusion in STEM fields," said CU Chancellor Philip P. DiStefano. "JILA's contributions to optics and photonics research have led to advances in basic research and to practical applications for industry and technology. As a joint part of JILA, we're proud to support this endowed chair, which prioritizes teaching and mentoring."

JILA's optics and photonics researchers are leaders in the field, particularly in creating ultrafast laser pulses. JILA researchers have developed lasers that deliver pulses in the femtosecond (10–15 second or one quadrillionth of a second) and attosecond (10–18 second or one quintillionth of a second) pulses. Those speeds are fast enough to capture phenomenon like the formation of molecules and the movement of electrons. JILA's optics research has also advanced scientists' control of new, powerful wavelengths of light, such as ultraviolet and x-ray.

"JILA is extremely grateful for this generous gift by Tom and Jeanne Baur, CU, and SPIE. We are thrilled for their support of the research and teaching activities in optics and photonics at JILA," says JILA Chair Andreas Becker. "This endowed Chair position will truly make a difference in our abilities to attract the best educators and brightest scientists in this area now and in future."



The Lehnert Lab has been able to measure the movement of a quantum drum so precisely that the Heisenberg uncertainty principle is on full display. Image Credit: Lehnert Lab/Steven Burrows

Drumming to the Heisenberg Beat

At JILA, scientists work on mechanical oscillators which are the size of a grain of salt. They may be tiny, but they are the heartbeat of quantum technology, and are currently a promising technology for networking quantum computers.

"If you push on a mechanical oscillator, it's going to move," said Robert Delaney, a graduate student in the Lehnert Lab. The oscillator vibrates like a tiny drum. As it moves it translates information from one signal to another, a crucial task for devices from cell phones to computers.

"You'd take information from the microwave domain, convert it to motion, and then convert it to the optical domain," Delaney said.

> **"It's not noiseless but in principle it could be noiseless, and in practice it's approaching that limit." —Robert Delaney**

And in principle these mechanical oscillators could do that almost perfectly, he added, if it weren't for noise. Not all noise can be picked up by your ears. In physics, any unwanted fluctuation in the medium around your equipment is noise. Noise can come from a lot of sources: heat, other electric signals, etc.. Miniscule fluctuations called zero-point fluctuations are present even in the vacuum of space. Just measuring the movement of the drum creates noise. No matter where it's coming from, noise can distort the signals both to and from the oscillator.

Now the Lehnert Lab at JILA has found a way to quiet that noise around their measurements. And it turns out when you do that, you get more than a quieter drum. This method also beautifully illustrated one of the most famous tenets of quantum mechanics–the Heisenberg uncertainty principle.

Squeezing out the noise

No system will ever be perfectly noiseless, but JILA Fellows Cindy Regal and Konrad Lehnert have made great progress reducing the noise around these mechanical oscillators. In order to use these oscillators in larger applications, they need to be prepared in precise state, and that involves measuring it.

But that's where they were hitting a snag. Measurements in a quantum system can be tricky. A grain-of-salt size drum seems tiny, but that's a large object to measure in the quantum world. And this is where Heisenberg comes in. The Heisenberg uncertainty principle says you can either perfectly know an object's position or its momentum at any given point in time, but never both. According to this fundamental principle of quantum mechanics, a simultaneous measurement of both the position and momentum of the drum adds a lot of noise relative to that of fragile quantum signals.

However, measuring either the position or the momentum on its own can—at least in principle—be done perfectly, without any added noise. Other techniques for measuring the motion of a mechanical oscillator have mainly focused on continuously monitoring its position. But most of these techniques have had other sources which added noise, or made the mechanical oscillator's motion unstable, preventing efficient measurement of the quantum state of motion.

Delaney and his team decided to create that instability in a way they could control. And to do that, they used microwaves to squeeze the oscillator.

"If those zero-point fluctuations were like a blob in phase space, you might stretch out that blob so that the area's the same, but it's very long in the momentum axis and very short in the position axis. That's squeezing," Delaney said.

Then, rather than measuring continuously, Delaney and his team used short, pulsed measurements to amplify the drum's motion and measure it at a single instant in time. This technique turned out to be really quiet, reducing the noise by a factor of six over other methods.

"It's not noiseless but in principle it could be noiseless, and in practice it's approaching that limit," Delaney added.

The Heisenberg beat

Not only is the measurement quiet, you can understand the quantum motion of the mechanical oscillator so precisely that the Heisenberg uncertainty principle is on full display. Using this method, Delaney found that they were able to tell the drum's position or its momentum with great precision.

"The uncertainty principle only tells you things about the product of two variables. It doesn't tell you about them individually. So if you are very certain about the position, you better be very uncertain about the momentum," Delaney explained. "One of the things is that it's often challenging in a lot of systems to even get down to the point where the Heisenberg uncertainty principle is relevant because often things like thermal noise are going to dominate over the uncertainty principle."

The beating heart of quantum technology

Mechanical oscillators are already at the heart of modern technology. Cell phones, for example, use a mechanical oscillator to turn the vibrations from your voice into an electrical signal, which is then converted to radio waves and sent flying through the air to your friend's phone on the other end.

Quantum computers and quantum networks will need to do the same thing to send information, and these tiny drums will help them do it. Making them quieter will help those signals travel loud and clear.

Beyond its application for new technologies, seeing the Heisenberg uncertainty principle demonstrated so perfectly is its own reward, Delaney said.

"That's really what I found appealing about it," he said. "I really like fundamental physics, but it's also nice to have it have some connection to something that may be a reality in the future."

R.D. Delaney, Reed, A.P., Andrews, R.W., and Lehnert, K.W., *Physical Review Letters* **123**, 183603 (2019).

Phases on the Move: A Quantum Game of Catch

The world is out-of-equilibrium, said JILA Fellow Ana Maria Rey. All around us systems are constantly in flux, from our living bodies to the weather and the stock market. These systems aren't settled in a final state.

Equilibrium systems are stationary; they don't change in time, said JILA Fellow James Thompson. And after a hundred years of research, we have developed tools to understand what happens in a system at equilibrium, Rey added. But when it comes to understanding an out-of-equilibrium system, many questions remain.

> **This is just a stepping stone. We're paving the ground for something really cool to happen. —Ana Maria Rey**

"We are out of theory," Rey said. "One of the challenges that we have at the moment is trying to understand out-of-equilibrium matter and how it tends to organize."

Rey and Thompson teamed up to create a controllable, non-equilibrium macroscopic system in the lab, so they can study how it behaves when you tune individual parameters. What they found could pave the way for a new foundation in our basic understanding of physics.

Atoms playing catch

Studying the organization principles of out-of-equilibrium systems requires a highly tunable system, Rey said, so Thompson put a million atoms in a one-dimensional lattice inside an optical cavity. In this setup, the atoms have the opportunity for all kinds of interactions.

By shining a laser onto the cavity, they are able to inject photons that act like baseballs, and the atoms start playing a quantum game of catch. If they catch the photon-baseballs, they start spinning. If these atoms couldn't interact with each other, they would spin freely, flipping over, Rey explained. But each atom is interacting with all others in the array—and if their partners aren't catching the photons and flipping over, then they won't either.

In this case, atomic interactions occur by exchanging virtual cavity photons, which act slightly different than the injected photon-baseballs.

"Essentially an atom throws a photon into the cavity mode. It bounces back and forth and any atom is able to reach up and grab it," Thompson said, and throw it back.

Interactions between atoms want to keep them pointing all at the same direction. "If he's down, I want to be down. So, in principle, the atoms want to be aligned," Rey explained.

In a quiet cavity the atoms don't want to play catch. But when the intensity of the injected photons (i.e., the number of photon-baseballs per second) increases, the atoms' behavior changes.

"If you just throw enough photons, eventually atoms start catching these photons, ignoring others. Catching the baseball is equivalent to start spinning up and down," Thompson explained. "If they don't have a ball in their hand, they prefer to remain aligned with their peers and point down."

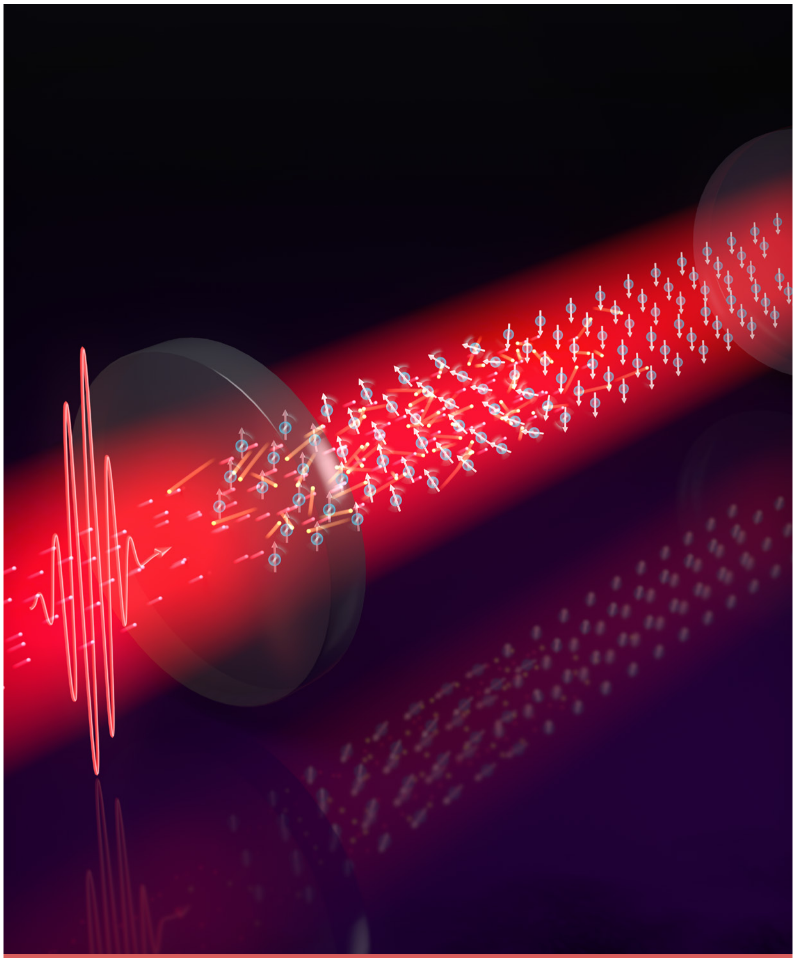
Changing phases

When the atoms decide to spin, they do so simultaneously and instantaneously. That abrupt change in behavior is interesting, Rey said. It is a dynamical phase transition. In many respects, it resembles the transitions we are used to seeing in our daily life but in a dynamical system.

"Think of it like trying to understand what you need to change to turn water into ice or into a gas," Rey elaborated. You fiddle with the temperature or the pressure until you reach a critical point where the water freezes, boils, or melts.

But in this non-equilibrium system, the starting phase really affects what the atoms would do next. Watching and understanding how these transitions happen helps shed light on organizing principles of systems in motion.

As the team turned the dials, they could identify the complete phase diagram-all of the different phases this system could display–all of which Rey's group had predicted. To confirm the dynamical nature of the phases, Thompson and Rey showed a surprising symmetry: changing the sign of the interactions-plus to minus or vice versa–does not affect the phase diagram. That doesn't happen in equilibrium systems, Rey explained. This demonstrated that "the organization principles of out of equilibrium matter can be very different to what we're used to," Rey summarized. "There are different rules that govern out-of-equilibrium systems and how they organize."



The rules of non-equilibrium systems are a mystery. JILA's Thompson Laboratory and Rey Theory Group collaborated to study how new types of phases of matter emerge in a non-equilibrium system made of atoms and light. Image Credit: Steven Burrows/JILA

Learning new rules

These results give scientists new clues to the rules that govern an out-of-equilibrium system. And coming up with rules to explain these complex systems is exactly the point of basic research like this, Thompson added.

"When thermodynamics was being developed, they didn't know PV=NkT [the ideal gas law]. They had to figure that out," Thompson said. "What are the rules of the game for this kind of regime that we're operating in? What are the emergent properties that describe these systems?"

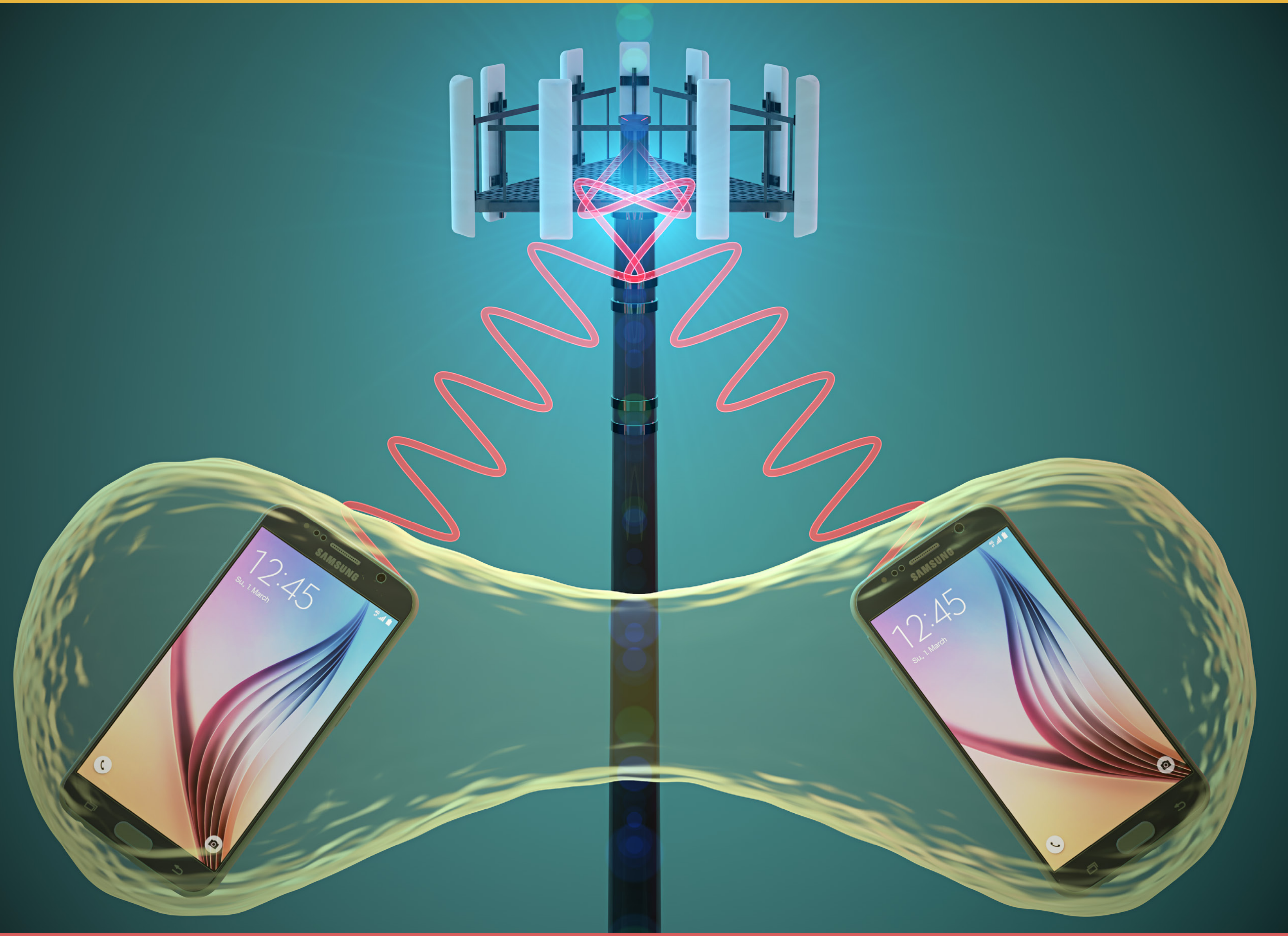
Rey hopes that this type of experiment can help them understand more complex systems featuring chaos and information scrambling behavior also exhibited by black holes, but at extreme scales.

There are a lot of opportunities to build on this experiment, Rey and Thompson pointed out, but this is a crucial starting point.

"This is just a stepping stone," Rey concluded. "We're paving the ground for something really cool to happen."

The study was published in *Nature* on April 30, 2020, and was supported by the Physics Frontier Center grant from the National Science Foundation.

J.A. Muniz, Barberena, D., Lewis-Swan, R.J., Young, D.J., Cline, J.R., Rey, A.M., and Thompson, J.K., *Nature* **580**, 602–607 (2020).



The Smith Theory Group has found that quantum entanglement could improve our mobile communication systems, allowing them to faithfully transmit more information. Image Credit: Steven Burrows/Smith Group

Playing Games with Quantum Entanglement

When you text your friends across the city, you aren't sending messages directly to each other. Your phones send signals to the nearby cell phone tower, which takes all of these signals and redistributes them to the proper recipients.

This basic setup—multiple senders transmitting to one recipient—is known as a multiple access channel or MAC. And if you've had to wait impatiently for the network to send a five-minute video of your adorable cat, you know that MACs have a fundamental limit on how much information they can handle.

As we continue to transmit more data through our MAC networks, scientists are looking to the quantum world to raise those fundamental limits. But before we start building new technology, we need to understand how quantum will work with these MACs.

That is where mathematicians and theory come in. A recent study from the Smith Group used logic games to test how quantum entanglement could improve MACs—and revealed that these communication systems are surprisingly sophisticated.

"The question is: is there a deeper understanding of quantum theory we can gain from studying these (MAC) models?" said JILA Fellow Graeme Smith. "How can we put a quantum overlay on our existing communications networks?"

Shall we play a game?

What do games have to do with quantum mechanics and communication? A lot, actually. Using just paper and pen, mathematical logic games, like the magic square game, mimic the way a MAC operates, Smith explained.

Here's how the magic square game works: two players (we'll call them Alice and Bob) have to fill a three-by-three square—Alice with plus signs and Bob with negative signs—while a single referee decides which row or column they are filling out. Alice needs to have an even number of plus signs in each row. Bob needs an odd number of negative signs in each column.

But there's a catch: Alice and Bob are separated. You can think of them as being separated by a wall, Smith said. They cannot communicate, which means that one won't know which column and the other won't know which row they are filling out at any time.

If Alice or Bob fails, the information is wiped out, which mimics noise in a MAC communication system. Even if our imaginary players agree on a strategy ahead of time, the best Alice and Bob can do is win eight out of nine games, Smith explained.

Getting entangled

In quantum mechanics, particles exist in all possible states at once until you observe them. When particles physically interact with each other they can become entangled. Entangled particles are connected forever, until noise or measurement disrupt them. Whatever happens to one instantaneously affects the other, even if they are separated by great distances.

With entanglement Alice and Bob can peak around the wall. Though they cannot communicate with each other, Alice and Bob can use the quantum correlations to win with certainty, Smith said. Apply that to a MAC and you could create a channel that can handle more data, with much less noise or interference, he added.

Coding for the future

Furthermore, the MAC's capacity increased regardless of how much entanglement is created. The Smith Group found that even creating a little bit of entanglement can improve the rates on a classical system, i.e. in principle we could apply new quantum tools to our existing communication networks and improve them.

And they also found our classical MACs are more complex than we thought. Mathematicians had believed that without quantum mechanics, it was possible to find single, computable formula that let's Alice and Bob win the game every time. Smith and his team found that finding a perfect strategy for Alice and Bob is "NP-hard"—that is, finding a solution would take such an incredibly long time as to be impractical.

This work is just the start. With this knowledge, the Smith Theory Group can start working on finding the limits on coding strategies for these MACS, both classically and with quantum entanglement.

F. Leditzky, Alhejji, M. A., Levin, J., Smith, G., *Nature Communications* **11**, 1497 (2020).

Breathing Stars and the Most Beautiful Scalpel

The ultrafast laser had previously been seen as a hammer, but it's actually the most beautiful scalpel. –Margaret Murnane

Look at any material on an atomic level and you see a dynamic world of interconnected atoms and electrons. Negatively-charged electrons throughout the material swarm around the positively-charged ions, and the electrostatic force between them holds the material together.

At a nonzero temperature, the ions in the material vibrate around their equilibrium positions. Those collective vibrations are called phonons. As the ions move, the electron cloud–as well as its quantum properties–sways accordingly, and vice versa. We call this electron-phonon coupling.

For many quantum materials, the electronic properties, such as whether it will conduct electricity or not, depends on how phonons and electrons are coupled–in other words, how they interact with each other. Understanding those interactions–and manipulating them–is crucial to understanding the world around us.

"How the electrons talk to phonons is a very fundamental physical problem. It determines the properties of many materials, including superconductivity," said Xun Shi, a postdoctoral researcher in the Kapteyn-Murnane Group at JILA. "People always want to learn how electrons connect to phonons, and it's a challenge to measure or calculate."

To study those interactions, you need a very fine scalpel to peel through the jumble of phonons and electrons in a material, and isolate the important ones that determine how the material behaves. And Xun Shi, Yingchao Zhang and Wenjing You in the Kapteyn-Murnane Group have found that scalpel.

In a study published on April 2, 2020 in the *Proceedings of the National Academy of Sciences*, the team found that by using ultrafast laser pulses, they can precisely pinpoint how electrons and phonons interact, transforming nearly 50 years of theory and understanding.

"We had simple ways of understanding materials since the 1970s, and now we can see that the charges and the lattice are coupled in very intriguing ways," said JILA Fellow Margaret Murnane. "The ultrafast laser had previously been seen as a hammer, but it's actually the most beautiful scalpel."

The tangled phonon-electron web

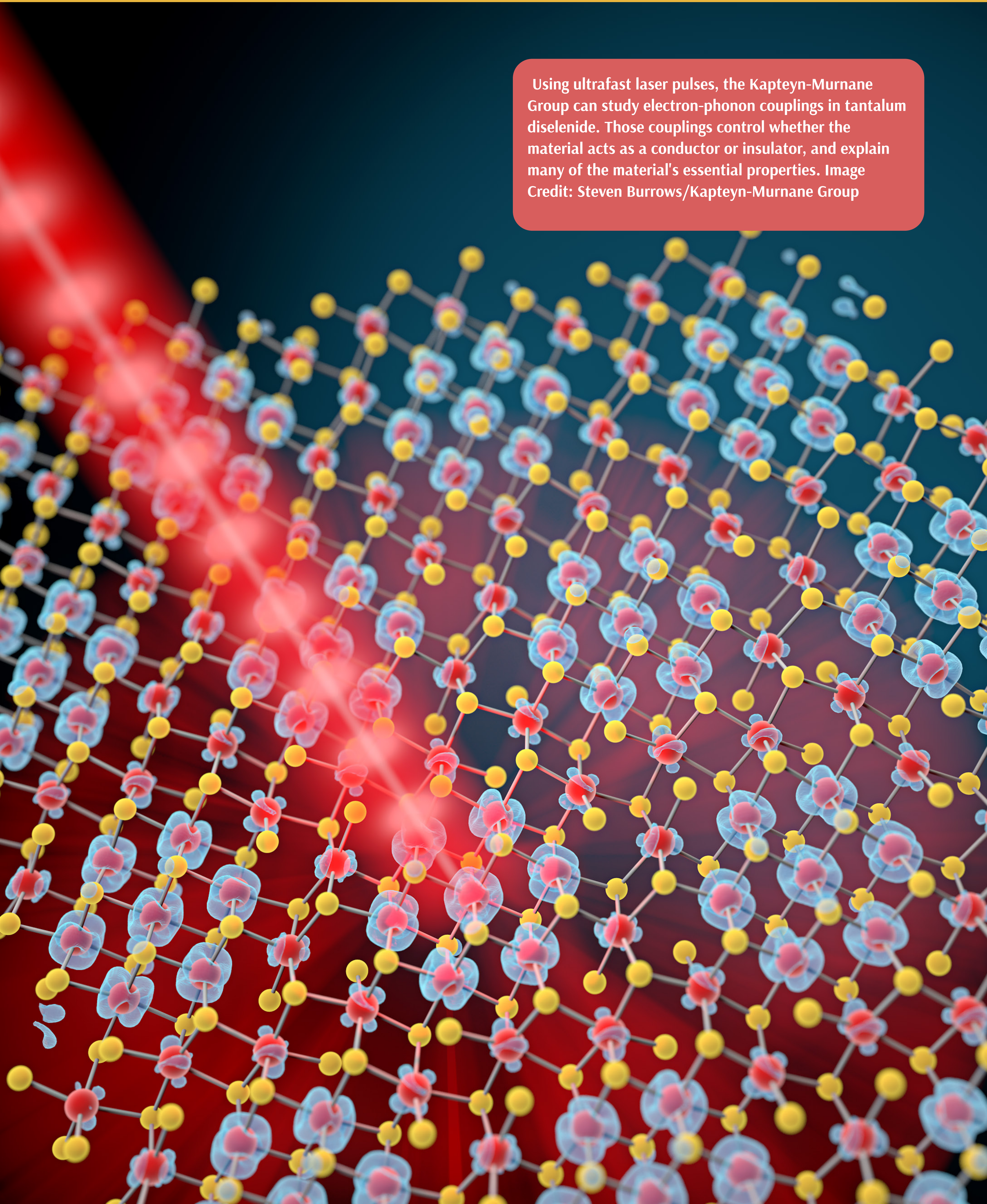
Materials have a jumble of phonons–vibrations of different periods and wavelengths. And when it comes to understanding the properties of a material–say whether an exotic material will act as an insulator or a conductor–not all of those phonons matter, Murnane pointed out.

Isolating the right electron-phonon couplings has been tricky to date. Think of it this way, Shi said: if we heat something up, everything inside the material goes from low temperature to high temperature. All of the phonons and electrons heat up at the same rate, at the same time. You can't distinguish the ones that are important from the spectators.

For these investigations, ultrafast lasers were usually seen as big hammers, Murnane added–a big burst of energy which violently excites all the electrons, ions, and phonons in a material. Physicists thought ultrafast lasers were great for creating out-of-equilibrium physics, but not for delicately manipulating individual electron-phonon couplings.

But the Kapteyn-Murnane Group found exactly the opposite.

"This is a dream that people have been struggling with for a long time. It turns out that at a high-level, ultrafast pulses were always a scalpel," Murnane said. "We just could not see how they were changing and manipulating the material."



Using ultrafast laser pulses, the Kapteyn-Murnane Group can study electron-phonon couplings in tantalum diselenide. Those couplings control whether the material acts as a conductor or insulator, and explain many of the material's essential properties. Image Credit: Steven Burrows/Kapteyn-Murnane Group

Breathing Stars of David and the beautiful scalpel

Shi, Zhang, and You looked at tantalum diselenide, where the ions are held together in six-pointed, Star of David-shaped formations. It's a very unique material, and makes sorting the important phonons from the unimportant ones easier. That's where the ultrafast lasers come in.

"If we use an ultrafast laser pulse, we can selectively excite electrons, not the atoms," Shi said.

Rather than smashing energy into the entire electron-ion web, ultrafast lasers put energy into just the electrons, he explained. The electrons are smaller and faster than the ions, and they spread out, moving away from the ions in the Star of David.

With the electrons spread out, the atom formation began expanding and contracting; the star starts to "breathe," Murnane explained. When the star expands, it became more metallic, and when it shrinks, it became more insulating. As it breathes, Shi, You, and Zhang could see that the electron temperature oscillates—swings back and forth—which had never before been seen experimentally. Moreover, the electron-phonon coupling also oscillates.

By preciously tuning the laser power, they can manipulate the material to change it from an insulator to a metal, and finally into a new metastable state never observed previously, Murnane said. That metastable state lasts for a nanosecond—100 million times faster than you can blink—and that's a long time in non-equilibrium physics, Shi pointed out, giving scientists the opportunity to study how they can control those electron-phonon interactions.

A gentle nudge means big changes

Finding this new transitional regime led the team to a new discovery about how electrons and phonons are coupled—and how they can manipulate the material.

As the star breathes, the temperature of the electrons oscillates at the same frequency as the atoms, Zhang explained, like a piston in a can of compressed gas.

"When you compress the piston, the gas in the piston will create a higher temperature and heat it up. When the piston expands it will go to a lower temperature," Zhang explained. "The lattice is also like this."

Theoretically, the stronger the laser pulse, the cooler the star would be when it expanded, Zhang went on. But in this new transition mode, they noticed something that made their jaws drop. With the pump laser power around a critical value, a gentle nudge from the laser power could change whether stars were hot when they expanded or cold. In other words, the electron temperature oscillation exhibits a 180-degree phase change relative to the breathing vibration, when the material enters the new transitional regime.

"That is not predicted by any theory," Zhang said. "We are still looking for how to explain this."

"Normally when you heat up electrons, they lose energy to the lattice—to the phonons—and it's unidirectional or monotonic. You heat them up and then they cool down by heating up the lattice," Murnane explained. "But in this exotic quantum material, they are so coupled that in this weird transition state, you can switch how the electrons talk to the phonons."

Which means that scientists can control electron-phonon couplings in a material by changing the laser power.

"We still have a lot of work to do to control this interaction," Shi said, but this transitional regime opens a world of possibilities. Changing a material's properties could be useful in new technologies, especially ones that need to quickly change their conductivity or become superconductors.

Y. Zhang, Shi, X., You, W., Tao, Z., Zhong, Y., Kabeer, F. C., Maldonado, P., Oppeneer, P. M., Bauer, M., Rossnagel, K., Kapteyn, H., Murnane, M., *Proceedings of the National Academy of Sciences* **117**, 8788–8793 (2020).

IN THE NEWS

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JILA HELPS DESIGN ALARMS FOR VENTILATORS IN THE COVID-19 PANDEMIC

Patients with severe COVID cases struggle to breathe, and ventilators pump their lungs for them. As the disease progresses, the amount of pressure needed to keep a patient breathing properly increases. Modern, sophisticated ventilators are equipped with sensors that can trigger alarms when unsafe conditions for the patient develop, such as when the air pressure is too high or too low.

As the novel coronavirus quickly spread through the United States in February and March, health care providers realized their intensive care units might not have enough ventilators to treat a surge of COVID-19 patients. Hospitals tried to buy more, but couldn't.

That's when the San Francisco VA hospital reached out to Rafael Gómez-Sjöberg, Director of Bioengineering at the Chan Zuckerberg Biohub, a San Francisco-based biomedical research institute. The hospital had a stock of very basic "transport" ventilators on hand that could be used in an emergency. However, those ventilators lack any alarms, so using them would have required a person to sit by each machine around the clock to manually monitor it and adjust its settings to ensure safe operation for the patient—staff the hospital couldn't spare in the midst of a surge of cases. So, the chief of anesthesiology asked the engineers at the Biohub if they could make some kind of simple alarm device to improve the safety of the transport ventilators.

The bioengineering team immediately started designing the electronics for the device, and had a basic design ready in a few days. However, the team was heavily taxed by other urgent requests related to the virus and, since time was of the essence, extra help was needed. Gómez-Sjöberg decided to ask Ed Marti, a biophysicist at Stanford, if he could help review the existing design to make sure it was correct and design a printed circuit board. Marti has experience with electronics and had mentioned that he could get his JILA ex-colleagues to help.

The design principle of the alarm is very simple. The device monitors the pressure in the tube that goes from the ventilator to the patient and calculates the most basic breathing parameters: the peak inspiration pressure, the peak end-expiration pressure, and the breaths per minute. These parameters are displayed on a small screen on the device, and an audible alarm is triggered when the pressure goes above a user-set threshold, when the pressure stays too low for a certain amount of time, or if the breathing cycle stops. This audible alarm, coupled with screen messages explaining the cause for the alarm, alert staff to check on the patient and adjust the ventilator. The device would allow some of these basic ventilators to be useful in case of a shortage.

ANDREW WILSON JOINS JILA AS NEW NIST QUANTUM PHYSICS DIVISION CHIEF

JILA has a new NIST Quantum Physics Division Chief, so join us in welcoming Andrew Wilson!

Wilson's path has intertwined with JILA's for years. Prior to coming to JILA on May 24, Wilson was down the road at NIST working on trapped-ion quantum information processing. Before joining NIST 10 years ago, he was on the faculty of the Physics Department at the University of Otago in his home country of New Zealand. JILA is well-known at the University of Otago, with various connections over the years; Wilson was even a visiting Fellow at JILA during his time there. Wilson completed his post-doctoral work at Oxford University; coincidentally in the same research group that JILA Fellow Murray Holland was a doctoral student. His research has also covered a wide range, from neutral atom experiments to high-resolution laser spectroscopy.

Moving from neutral-atom to trapped-ion experiments was a big shift, but that range of experience will be helpful coming to JILA, Wilson says. Apart from his duties as NIST Quantum Physics Division Chief, he plans to continue some research with the NIST Ion Storage Group.

When he's not in the lab, Wilson enjoys the beauty of the Colorado Rockies, camping and hiking with his family. He's also a music lover, attending concerts and practicing the guitar.

STROBE'S Nico Hernandez-Charpak Wins CU President's Diversity Award

Jorge Nicolas (Nico) Hernandez-Charpak, STROBE'S Assistant Director of Research and Knowledge Transfer, has been recognized for his outstanding work to diversify the field of physics. The CU President's Diversity Award recognizes CU faculty, staff and students who work to develop a culturally and intellectually diverse university community.

Throughout his career, Hernandez-Charpak has worked to diversify the field of physics–from mentoring graduate and undergraduate STEM students to organizing panels of LatinX scientists to speak about STEM careers. As part of STROBE, he helped secure a six-year, $4 million National Science Foundation award between Fort Lewis College (a non-tribal Native American Serving Institution in the Four Corners region), Norfolk State University (a member of the Historically Black Colleges and Universities), and the STROBE NSF Science and Technology Center for Real-Time Functional Imaging at CU Boulder. This led to the Partnership for Education and the Advancement of Quantum and nanoSystems (PEAQS), a new partnership with the STROBE Science and Technology Center.

Department of Defense Awards Konrad Lehnert Prestigious Vannevar Bush Faculty Fellowship

JILA Fellow Konrad Lehnert has been awarded the Vannevar Bush Faculty Fellowship, the Department of Defense's most prestigious single-investigator award. With up to $3 million in funding, the VBFF is a five-year fellowship which supports basic research with the potential for transformative impact.

Formerly known as the National Security Science and Engineering Faculty Fellowship, the program changed its name in 2016 to commemorate the late Dr. Vannevar Bush, who was the director of the Office of Scientific Research and Development during WWII and the author of "Science, The Endless Frontier." Bush was an ardent advocate for basic research who made innovative contributions to the national security. JILA Fellow Margaret Murnane won this Fellowship in its inaugural competition in 2008.

JILA Fellow Adam Kaufman wins Office of Naval Research Young Investigator Award

The Office of Naval Research has awarded JILA Fellow Adam Kaufman one of its prestigious 2020 Young Investigator Awards. The ONR program rewards early career scientists "who show exceptional promise for doing creative research"–and Kaufman is a most deserving recipient.

"This selection recognizes both his past accomplishments and his vision for developing optical tweezer arrays for demonstrating useful quantum computing," said Tom Perkins, acting NIST Quantum Physics Division Chief.

JILA Fellow Jason Dexter Wins 2020 Sloan Fellowship

The Alfred P. Sloan Foundation announced on February 12 that JILA Fellow Jason Dexter has won a 2020 Sloan Fellowship.

Dexter joined JILA in 2019. Dexter's work revolves around black holes, specifically how gas falls into black holes and their use as probes of strong gravity. He is a core member of the Event Horizon Telescope Collaboration, which captured the first image of a black hole last year.

"I'm honored to receive this prestigious award," Dexter said. "Images and movies of gas falling into black holes hold tremendous promise for learning how they grow and for understanding their nature. The Sloan Fellowship will support our group's work in maximizing the science return on these breakthrough observations using state of the art computational models."

JILA Fellows Margaret Murnane and Henry Kapteyn Win the Benjamin Franklin Medal for Physics

A husband-and-wife team at the forefront of laser science at the University of Colorado Boulder has followed in the footsteps of the Curies, winning a prestigious Benjamin Franklin Medal.

The Franklin Institute announced today that Henry Kapteyn and Margaret Murnane would receive this year's medal in physics—one of several awards handed out annually by the center named after the scientist and founding father.

Kapteyn and Murnane are fellows at JILA, a joint research institute between CU Boulder and the National Institute for Standards and Technology (NIST). They have pioneered new advancements in X-ray lasers, devices that shoot out incredibly fast pulses of X-ray radiation.

The researchers, also professors in the Department of Physics, are only the third married couple to receive a Benjamin Franklin Medal. The first were Marie and Pierre Curie who took home the prize for chemistry in 1909.

FELLOWS JUN YE AND DEBORAH JIN NAMED MOST HIGHLY CITED RESEARCHERS FOR 2019

JILA Fellows Deborah Jin and Jun Ye have been named Most Highly Cited Researchers for 2019 by Clarivate Analytics. This is the sixth year in a row that Jin and Ye have been given this honor.

Clarivate operates Web of Science and the Science Citation Index. Their list of Highly Cited Researchers recognizes scientists across the world who have demonstrated significant influence through publication of multiple highly cited papers during the last decade. Researchers on this list have multiple papers whose citations rank in the top 1% in the Web of Science collection of journals. The 2019 list encompasses 6,216 researchers from around the world, 194 of whom are published in the field of physics.

QUANTUM PHYSICS: ATOMIC RESEARCH DISCOVERIES SHOW THERE'S MUCH MORE TO LEARN

This month on *CU on the Air* we welcomed CU Boulder Professor Ana Maria Rey, a theoretical physicist and fellow at JILA. Professor Rey has earned multiple awards for her groundbreaking research, including the coveted MacArthur Genius Fellowship and the Presidential Early Career Award for Scientists and Engineers. She earned the Alexander Cruickshank Award in 2017 and 2019, and became the first Hispanic woman to win the Blavatnik Award for Young Scientists. Professor Rey studies the interface between atomic, molecular and optical physics, condensed matter physics, and quantum informational science. Listen to the podcast: http://cuontheair.blubrry.net/2019/11/01/quantum-physics-atomic-research-discoveries-show-theres-much-more-to-learn/

JILA TEAM DEMONSTRATES MODEL SYSTEM FOR DISTRIBUTION OF MORE ACCURATE TIME SIGNALS

JILA physicists and collaborators have demonstrated the first next-generation "time scale" - a system that incorporates data from multiple atomic clocks to produce a single highly accurate timekeeping signal for distribution. The JILA time scale outperforms the best existing hubs for disseminating official time worldwide and offers the possibility of providing more accurate time to millions of customers such as financial markets and computer and phone networks.

The novel time scale architecture combines a super-reliable, advanced atomic clock with an ultrastable device for storing time signals and is a "blueprint for the upgrade of time scales worldwide," as described in the journal Physical Review Letters.

FORMER JILA RESEARCH ASSOCIATE WINS 2019 PACKARD FELLOWSHIP

The David and Lucile Packard Foundation announced the 2019 class of Packard Fellows for Science and Engineering. This year's class features 22 early-career scientists and engineers, including Shimon Kolkowitz.

Kolkowitz, a former research associate in the Ye group at JILA, now has his own lab at the University of Wisconsin. His group works with optical atomic clocks to make them more precise and accurate. Ultra precise and accurate atomic clocks have the potential to understand dark matter and the connection between quantum mechanics and gravity.

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

University of Colorado **Boulder**

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

About JILA

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

JILA's faculty 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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