JILA light&MATTER

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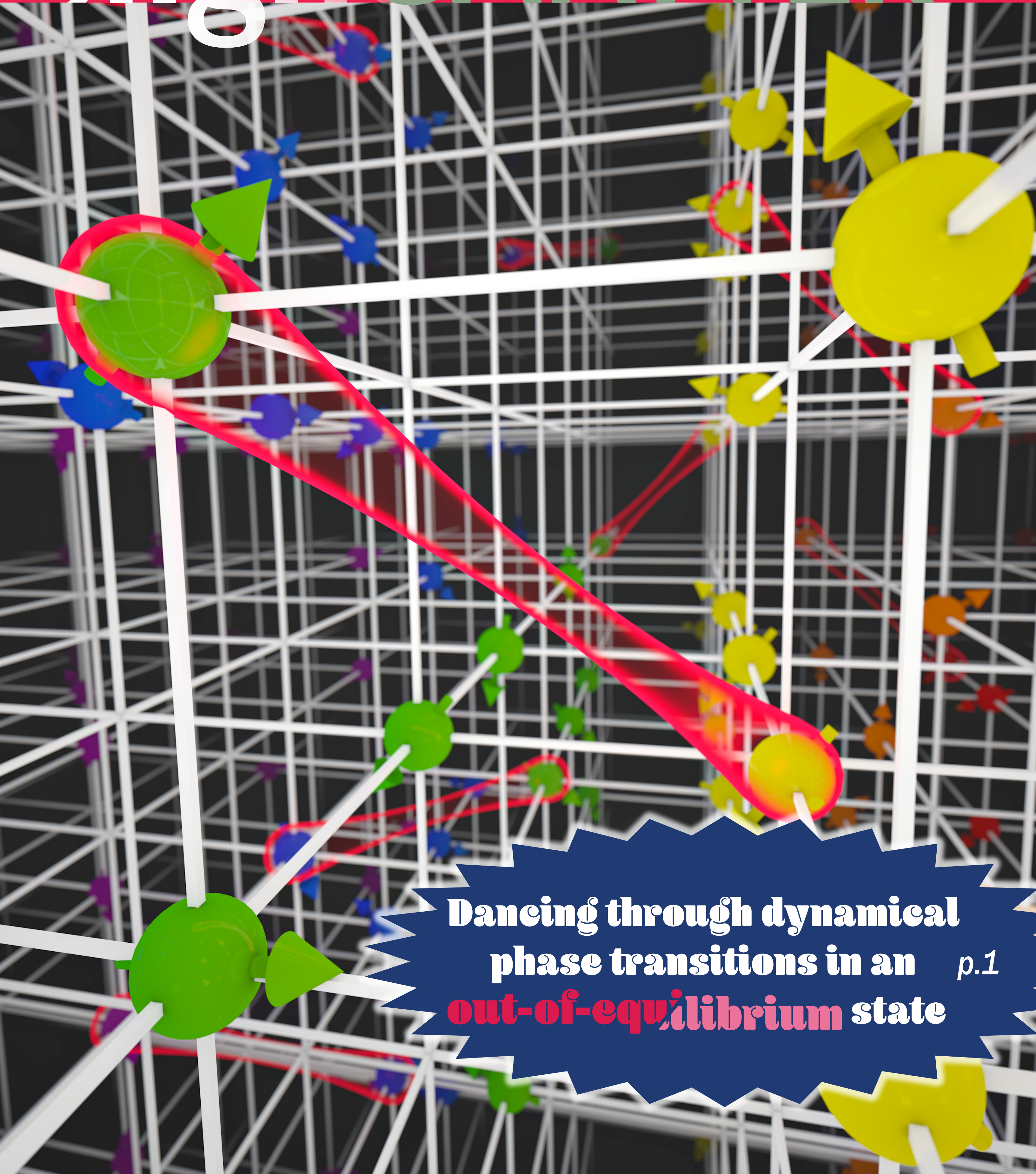

Dancing through dynamical phase transitions in an out-of-equilibrium state

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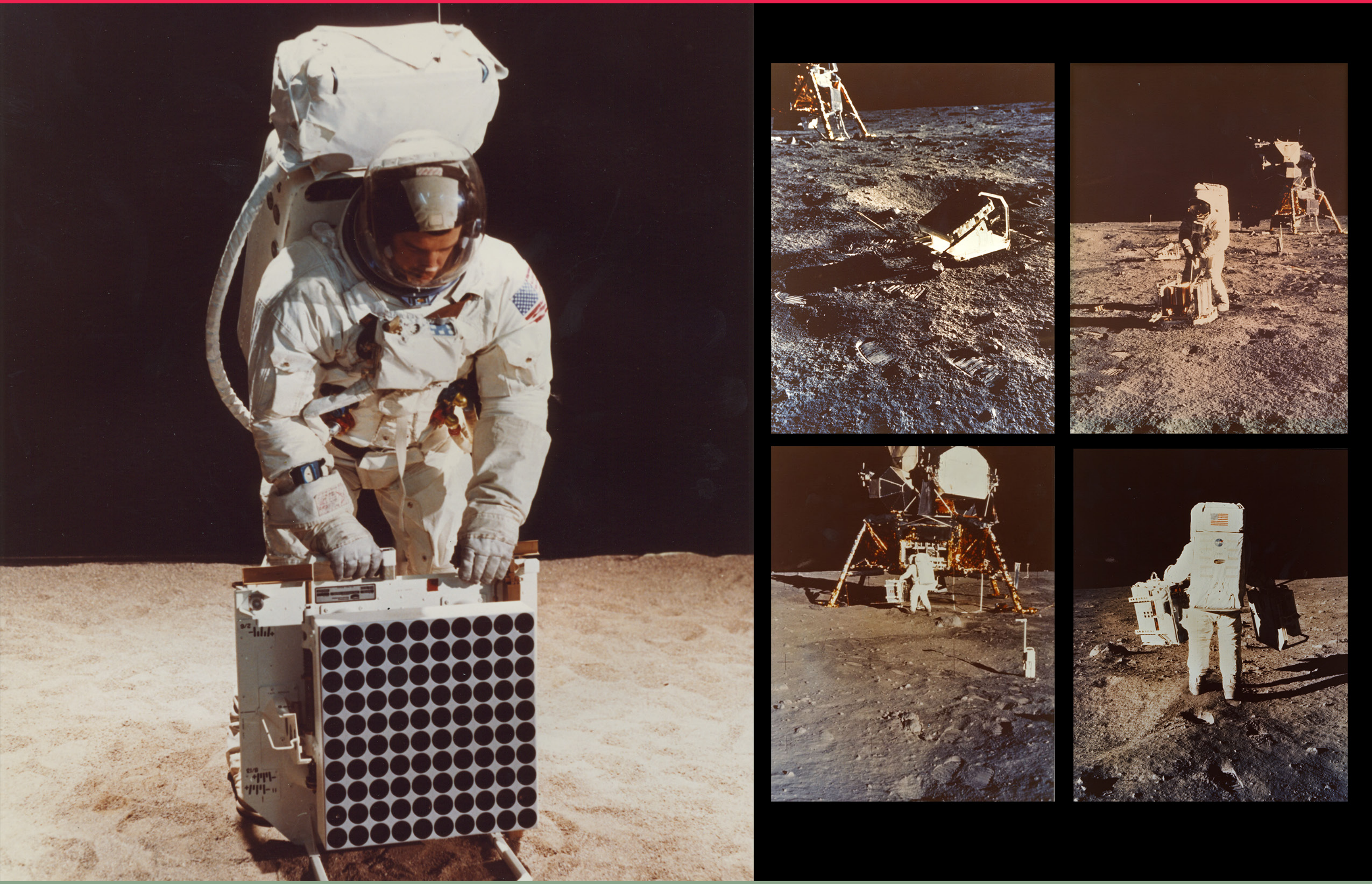

Apollo 11's last working experiment on the moon. "Houston, Tranquility Base here. The Eagle has landed," Neil Armstrong said as the Lunar Module landed on the moon, July 20, 1969. In the 50 years since the moon landing, most of those experiments have stopped working. Except one: Dr. James Faller's Laser Ranging Retroreflector, or LRR. Faller joined JILA, then the Joint Institute for Laboratory Astrophysics, as a fellow. Read more: https://jila.colorado.edu/news-events/news/apollo-11s-last-working-experiment-moon.

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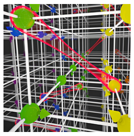
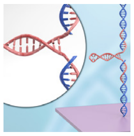
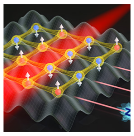
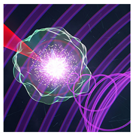
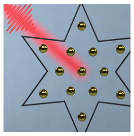







Features

Dancing through dynamical phase transitions in an out-of-equilibrium state

Using magnetic fields, physicists can control how fermions align themselves

In physics, it's always easier to study a system in equilibrium. A system in equilibrium is neat and orderly, everything in balance. But the real world is rarely so perfectly balanced.

> "Life is out-of-equilibrium. The weather is out-of-equilibrium," joked JILA Fellow Ana Maria Rey.

When things are out-of-equilibrium, it's hard to study a phenomenon called dynamical phase transitions. Phase transitions are ubiquitous in nature, like when water turns into ice, Rey explained. A dynamical phase transition is when an out-of-equilibrium system rapidly takes on different behaviors—just by changing one parameter, like a magnetic field.

These dynamical phase transitions are critical to understanding how our world works in the quantum realm. Controlling these phase transitions could help scientists build new and improved quantum mechanical technologies, like optical atomic clocks for experiments or better superconductors.

Dynamical phase transitions have been observed before in trapped ion arrays. But in those experiments, the ions didn't have the freedom to move around, and the electrically charged ions strongly interacted with each other over long distances. In theory, a dynamical phase transition could happen in other systems but it had never been seen before—until now.

At the University of Toronto, the experimental group of Prof. J. Thywissen, guided by the Rey group, observed a dynamical phase transition in an out-of-equilibrium weakly-interacting gas of fermionic potassium atoms for the first time. In contrast to electrically-charged ions with their strong long-range interactions, these neutral atoms interact much more weakly with each other and only over much shorter distances, needing to bump and collide to "see" each other.

"We're taking a system that apparently violates all the conditions satisfied by the ions," Rey said. "The system we have at hand (weakly interacting atoms), you never imagined would have the properties of this other system (strongly interacting ions)."

Building on Jin's work

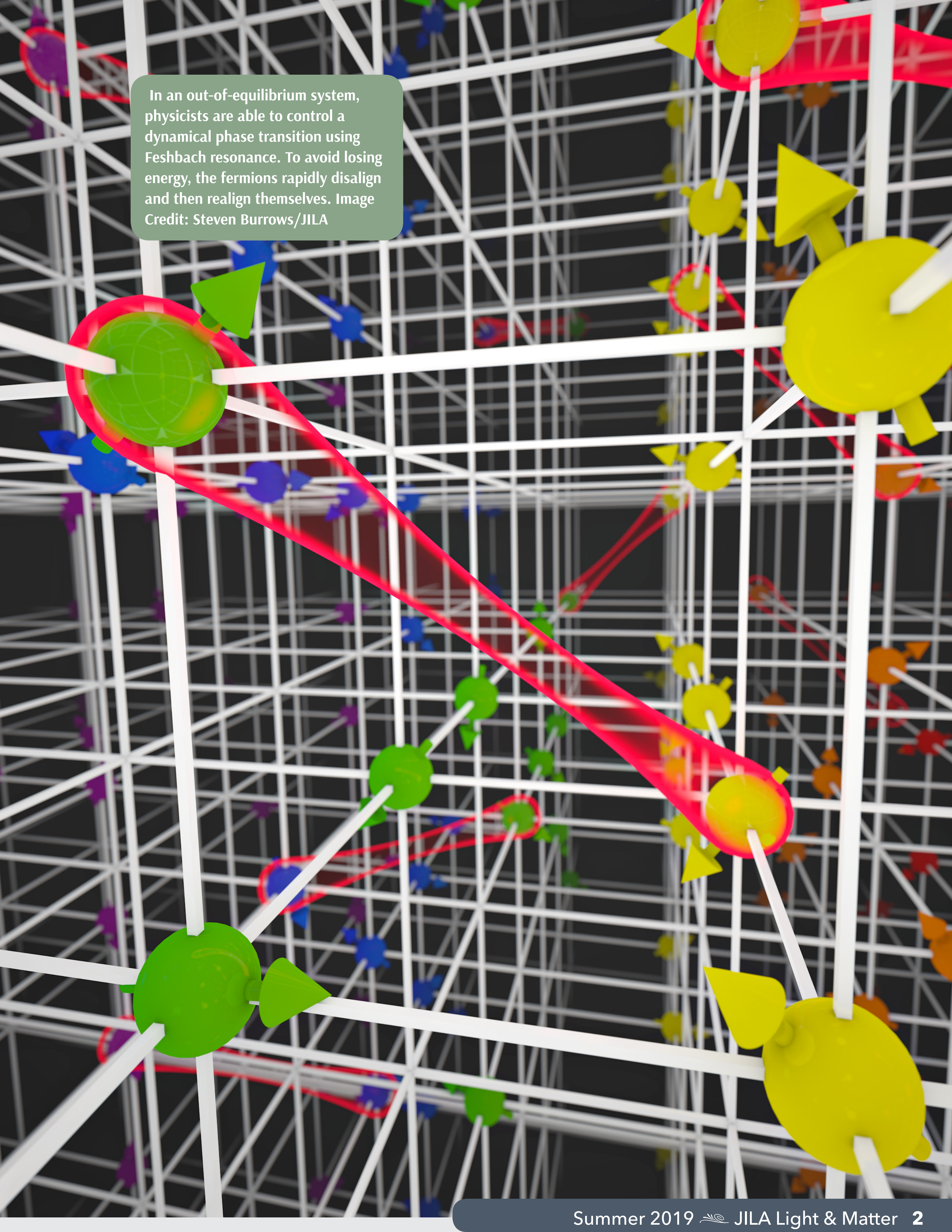
Their experiment built on late JILA Fellow Debbie Jin's work. Jin, who passed away in 2016, created the first degenerate Fermi gases. Her research laid the groundwork for understanding ultracold gases and Feshbach resonances. In a Feshbach resonance a magnetic field is used as a means to tune atomic interactions.

Using those tools, Rey's and Thywissen's groups were able to crank the magnetic field to turn interactions between fermions in a trap on and off.

Dancing to the quantum beat

Fermions are finicky particles. They don't like to touch. If they "bump" into each other, it costs them energy. To understand how this dynamical phase transition happens, think of fermions as dancers.

When Thywissen's team sets up their fermions, they are all aligned—all spins facing the same direction—in their lattice trap. At this point, everyone is on the dance floor facing the DJ as the music



In an out-of-equilibrium system, physicists are able to control a dynamical phase transition using Feshbach resonance. To avoid losing energy, the fermions rapidly disalign and then realign themselves. Image Credit: Steven Burrows/JILA starts. The dance is generated by a magnetic field that changes from site to site disorganizing the fermions. Each one moves to its own rhythm, and they fall out of alignment.

If their interactions are weak, when our fermion dancers start moving, they spread out on the dance floor. They start hitting each other as they groove to their own beat. They can also see their fellow dancers across the room, not just those immediately around them. Their energy penalty is minimal, so bumping into each other does not harm them, like our dancers occasionally bumping their neighbor's shoulders.

But when our physicist DJs turn up the Feshbach resonance and the interactions get stronger, the dancing fermions are in danger of becoming a violent mosh pit. Stronger interactions carry stronger energy penalties. A bump would cause the fermions to go flying off the dance floor in different directions.

Instead, to protect themselves from harm, the particles fell back into alignment just as quickly as they fell out of alignment. The fermions organized themselves into a line dance to avoid becoming a mosh pit. The dynamical phase transition had happened.

Turning and reversing

Rey's team found something else new. There was a sweet spot in this experiment where they could reverse the dynamics and undo what they had done. By tuning the Feshbach magnetic field, they could send all their fermions back to their initial alignment.

"The experiment can reverse both disorder and the interactions," she explained. "(Physicists) can completely be God and undo the dynamics, and we should recover what we started with."

Being able to undo those changes validates that their model is working. As a fully controllable quantum system, this will help us understand how world behaves on quantum scale.

Out-of-equilibrium superconductors

This experiment also models another physics phenomenon: a superconductor. Specifically, a superconductor out-of-equilibrium. When the fermions are aligned, they resemble a superconductor. So, what happened in that sudden misalignment?

"That's called quenching," Rey explained. Effectively, the superconductor suddenly shut off, and then turned itself back on. "The interactions that happen in our model, and the disorder that drives their dancing, are exactly the same processes that happen in a superconductor."

Jumpstarting these processes in a superconductor typically requires ultrafast pulses from a laser, and those changes happen in femtoseconds—that's one quadrillionth of a second, about a million billion times faster than you can blink. This experiment lets physicists see how a superconductor reacts when it's out of equilibrium on a more realistic time scale.

And all of this wouldn't have been possible without the work of Debbie Jin. When she gives presentations on this research, Rey takes a picture of Jin with her.

"She taught us so much," Rey said, and this is just one way that her legacy lives on.

More information on Dr. Jin's work: https://jila.colorado.edu/news-events/news/jin-fest-celebrates-legacy-deborah-jin ✺

S. Smale, He, P., Olsen, B. A., Jackson, K. G., Sharum, H., Trotzky, S., Marino, J., Rey, A. M., Thywissen, J. H., "Observation of a Transition Between Dynamical Phases in a Quantum Degenerate Fermi Gas" (submitted 2018). arXiv:1806.11044 [quant-ph]

JILympics

July found some JILAns taking a break to participate in the first annual "JILympics" contests. A fun time was had by all. Photos credit: Cynthia Torres and Rebecca Jacobson.

Pulling Apart HIV

Advance AFMs allow study of the HIV hairpin

> "It's particularly small, unfolds at low forces and refolds fast… This is about as challenging as it can get."

There are many molecules within the virus known as HIV, but only one is shaped like a hairpin. This molecule, aptly named the HIV RNA hairpin, allows the virus to create its own proteins from host resources, which is key to the virus's ability to take over an infected cell.

Scientists having been studying the details of this virus for decades in an attempt to improve diagnostics and treatments for AIDS and other HIV-induced diseases. And now, JILA researchers have demonstrated a much easier, faster and more precise way to understand the structure and function of the HIV RNA molecule, especially the HIV RNA hairpin. Furthermore, the techniques developed for this research promise to allow a wider range of users to study similar biological molecules, as they are built upon commercially available and user-friendly atomic force microscopes, or AFMs.

AFM Advances

AFMs are high-resolution microscopes that can resolve structures as small as atoms. But on top of imaging, AFMs can also pull apart, or unfold, biological molecules such as proteins and nucleic acids like DNA and RNA.

Over the last decade, JILA Fellow Dr. Thomas Perkins and his team have focused on improving AFM technology for biological applications. Their advancements in cantilever shape provided enhanced time resolution and force precision. Their advancements in chemistry enabled individual molecules to be stretched end-to-end. And their advancements in instrument automation allowed researchers to unfold and refold the same individual molecule over a thousand times (whereas previously molecules could refold only a handful of times).

According to Perkins, his team's advancements to AFM technology allow more researchers to probe biological molecules.

"It's a question about accessibility," said Perkins. "The benefit to doing these experiments on a commercial AFM is you can train an undergraduate to do the experiment."

Energy Landscapes

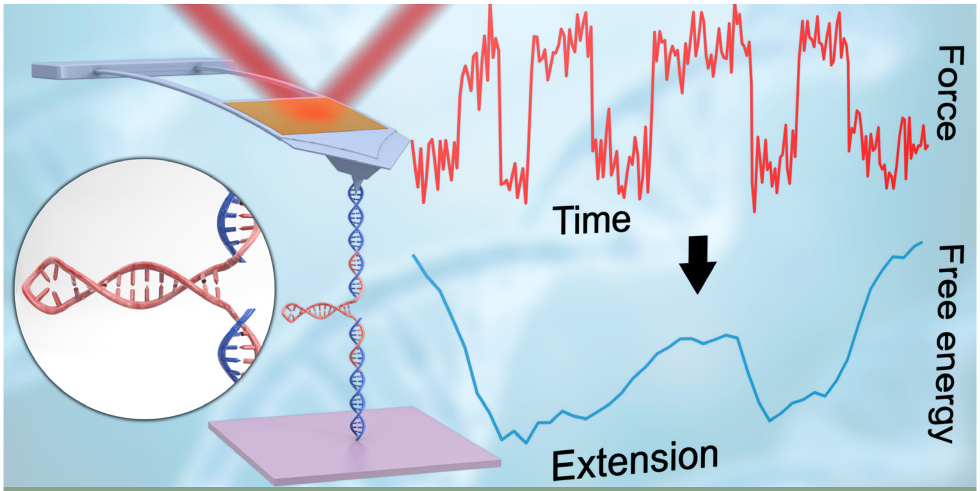
Equipped with an advanced AFM, Perkins quickly pushed past old limitations of biological probes.

"We've spent all of this time overcoming various technical issues—cantilevers, surfaces, alignment—and now it's this exciting time where we are doing applications, and we are doing things that people never expected you'd be able to do with an AFM," said Perkins.

And one of the things never expected from AFMs was the ability to probe a folding molecule with the precision required to map out the energy landscape, said Perkins.

The energy landscape of a molecule is like a 3D topographic map whose peaks and valleys represent the energy of the molecule's configuration. Because there are many ways a molecule can fold, there are many paths a molecule could take through this landscape.

And driving the molecule through this landscape is its desire to reduce its energy. Generally, a more folded molecule has a decreased energy. But some folding directions can be stymied by the equivalent of a high-mountain pass, or dam, in the landscape. Likewise, other foldings can be encouraged by sloping gullies. Understanding these complex landscapes–and how molecules navigate them–can help us understand why certain folds occur and why critical proteins may misfold and cause disease.



Using a cantilever AFM (gray), JILA researchers are able to unfold and refold the HIV hairpin, a bend in the HIV RNA molecule which helps the virus take over an infected cell's protein-making machinery. By leveraging a series of advancements to AFMs, researchers can now measure folding forces (red line) much more precisely and thereby determine free energy landscapes (blue line), which map the energy both of and between folded states. Image Credit: Perkins Group and Steven Burrows/JILA

But diseases are caused by more than just misfolded proteins. Some diseases, like HIV, are caused in part by proteins made by an RNA hijacker called a hairpin.

The HIV Hairpin

The HIV hairpin is a hairpin-shaped bend in the virus's RNA molecule that enables HIV to use a host's protein-making machinery to make copies of the virus rather than normal cell proteins. While many viruses have hairpins, HIV's is particularly elusive.

"This is a really hard hairpin to study," said Perkins. "It's particularly small, unfolds at low forces and refolds fast.... This is about as challenging as it can get."

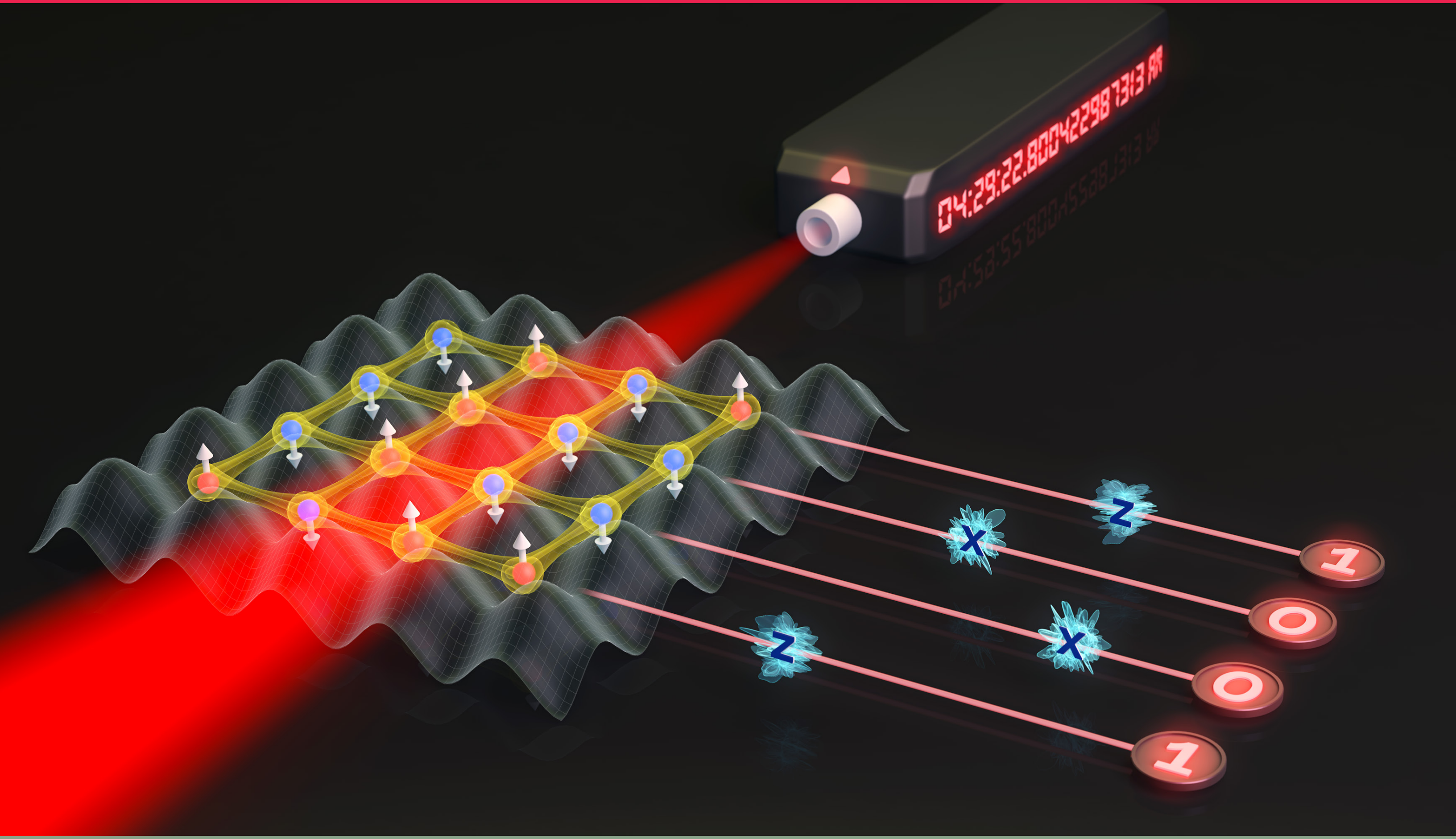
Perkins research, published last September, maps the first full-energy landscape of the HIV hairpin and demonstrates the first instance of an AFM-based probe measuring the full energy landscape of any nucleic acid.

Yet studying this hairpin is not, unfortunately, a direct answer to conquering HIV's effects on the human body.

"The hairpin is just one step along its life cycle," said Perkins, citing entrance, infection, and dormancy as other life cycle steps. "[But,] the better we understand the life cycle of HIV, the more opportunities there are to develop therapeutics."

In the future, Perkins hopes to understand the HIV hairpin at an even faster timescale. Currently, Perkins' group can observe the hairpin fold with 40-microsecond (40 millionths of a second) resolution. But with new advancements, Perkins expects to improve this resolution down to one microsecond. With this resolution, it would become possible to actually watch the RNA unfold.✺

R. Walder, Van Patten, W.J., Ritchie, D.B., Montange, R.K., Miller, T.W., Woodside, M.T., and Perkins, T.T., *Nano Letters* **18**, 6318–6325 (2018).



The optical atomic clock in Jun Ye's lab can create cluster states in milliseconds, which is necessary for quantum computing. Image Credit: Rey Group and Steven Burrows/JILA

TYING QUANTUM KNOTS WITH AN OPTICAL CLOCK

Researchers a step closer to the 'holy grail' of quantum science

When it comes to computers, quantum is the next big thing. Quantum computers could solve complex problems that even today's most sophisticated supercomputers cannot.

"One of the holy grails in the quantum world is to build that quantum computer," JILA Fellow Ana Maria Rey said. "You want a universal machine that uses quantum elements to model and understand the quantum world."

Let's back up and explain what makes a quantum computer different from a classical computer. Whether it's your smartphone or laptop, information in traditional computers is stored as single bits—a 1 or a 0. Those bits have to pass through a logic gate, which performs a simple calculation and spits out a single answer. Logic gates get combined into circuits which run calculations with thousands of bits of information.

But even supercomputers' enormous memory can only process so much. Running simulations with numerous variables or sorting through complex data sets takes a long time for our classical computers. At some point, their memory will overload. In a quantum computer, a qubit—like an atom—may exist in a superposition; it is both a 1 and 0 at the same time. Measure a qubit and it collapses into a 1 or 0. And when that qubit is entangled, its entangled partners will follow suit and collapse too. Pass those entangled qubits through a quantum gate and you can get all those possible combinations at once. Simply put, since a quantum computer can make operations in parallel, it can make calculations significantly faster than a classical computer.

That first step to creating the quantum computer is tricky. The qubits need to be in a cluster state, a neat configuration with all the atoms properly entangled.

"The hard part is connecting the qubits because that is necessary to generate entanglement" said Mikhail Mamaev, a JILA graduate student in Rey's group. "And experimentally it's very difficult to do."

Now there may be a quick and easy way to do it. In a paper published in Physical Review Letters this April, Mamaev proposed a way to create highly-entangled cluster states using an optical atomic clock.

Tying qubits in knots

All of the atoms need to be at just the right energy level for them to entangle with each other. Typically, entangling all of these atoms in the right configuration is a bit like knitting by hand, tying knots between each particle one by one in a row. It takes a long time, and it's pretty fragile. And just like knitting a sweater, getting a three-dimensional cluster of entangled atoms this way is a long and tedious process.

Thankfully, at JILA there's a tool sitting right under physicists' noses that could do the hard work for them. When visiting fellow Rainer Blatt saw the optical atomic clock in Jun Ye's laboratory, he suggested that the clock's laser could weave atoms into a cluster state for them.

"We have this clock with super-high coherence, super-clean, super-orderly. It is what lets us have a chance at making this thing" Mamaev said. "The tough part here is getting all these links to show up well enough and at the same time, and with a clock you can do that."

The clock can create those cluster states in a hundred milliseconds. Not only can it create these cluster states, it can keep them stable for ten seconds. That's a long time in the quantum world, long enough to run measurements. And by making a simple measurement, the entangled links break, giving physicists information.

"We can create them and have enough time to measure" Rey said.

Full speed ahead

Creating a quantum computer this way is on its way to the lab. The group published their work on arXiv and when Mamaev, lead author on this paper, presented it to the funding agency, they quickly created a grant to start running the experiment.

"Then it's going to be very exciting. Once you have the cluster state, you can start doing quantum computing with clocks. That's a new direction for the field" Rey said.✺

M. Mamaev, Blatt, R., Ye, J., and Rey, A.M., *Physical Review Letters* **122,** 160402 (2019).

THE FASTEST VORTEX IN THE WEST

Researcher have discovered a new property of light: self-torque

What do whirlpools, black holes, hurricanes, Jupiter's Great Red Spot, and the creamer you just put into your coffee cup have in common?

All of these things exhibit vortex phenomena, in which a fluid (e.g., gas, liquid, plasma, etc.) circulates around a common axis. Vortices such as these abound in nature, and can be found in macroscopic systems like those described above, or in microscopic quantum systems. And we now know that they can be produced in extreme ultraviolet (EUV) light beams, thanks to an international team of researchers at JILA and in Spain.

In a recent publication in Science, students and scientists from the Kapteyn-Murnane group at JILA, along with theoretical collaborators lead by the Grupo de Investigación en Aplicaciones del Láser y Fotónica at the University of Salamanca and with support from the Institut de Ciències Fotòniques (ICFO), in Salamanca and Barcelona, respectively, showed that they could create very unique EUV vortices via the highly nonlinear process of high-harmonic generation (HHG). Specifically, by adjusting the temporal separation of the two infrared vortex beams, they could generate optical vortices in the EUV that twist faster, and faster, and faster as they are produced, creating an optical version of a whirlwind.

This optical property had never been observed before, leading the team to discover a new property of light: self-torque—so named because its angular rotation, or momentum, increases with time.

Optical Donuts, Vortices, and the Orbital Angular Momentum of Light

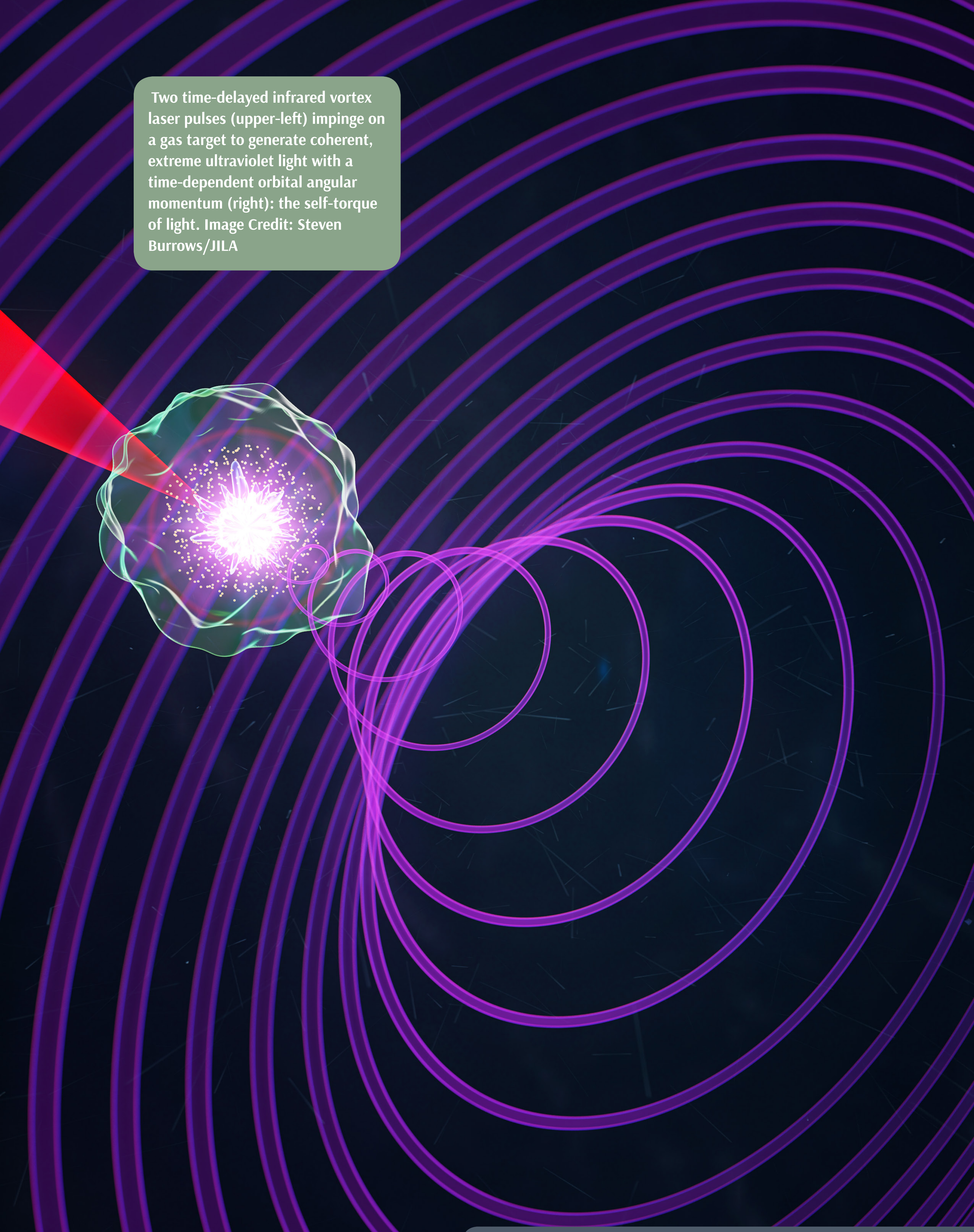
Vortices in nature, like tornados, are highly chaotic and often unpredictable. However, in 1992 researchers in the Netherlands showed that vortices of laser light could be produced and controlled with high precision, and that these optical vortex beams possessed quantized amounts of orbital angular momentum (OAM). This new property of light, OAM, is associated with a spatial twist of the laser wavefronts, and manifests as a "doughnut-like" intensity pattern. If you've ever watched water spiral down a drain, taking whatever is in the water with it, then you've witnessed OAM in action.

Since the discovery of OAM light beams, they have found diverse applications in fields ranging from super-resolution imaging, optical communication, optical manipulation, and even quantum-based computational logic. But until now, the OAM of light has always been observed to be a static property which does not vary in time.

Self-Accelerating Optical Vortices: Nature's Fastest Spanner Wrench

In order to realize this new optical property, the team exploited the quantum physics inherent to the high-harmonic generation (HHG) process. High harmonics of light have a nice analogy with harmonics of sound—pluck a guitar string gently and the string vibrates, producing a note. Pluck it really hard and you can hear overtones, or harmonics, of that frequency.

To create that high-harmonic generation with light, an intense, femtosecond laser pulse is upshifted to high frequencies of the driving laser by essentially creating a nanoscale radiating antenna from



Two time-delayed infrared vortex laser pulses (upper-left) impinge on a gas target to generate coherent, extreme ultraviolet light with a time-dependent orbital angular momentum (right): the self-torque of light. Image Credit: Steven Burrows/JILA an atom that is in the process of being ionized. When properly phase-matched, bright, coherent laser-like beams can be generated that span from the EUV to the soft x-ray regions of the electromagnetic spectrum.

The HHG process is coherent, meaning it must conserve both energy and momentum during the upconversion process, which is the secret to creating self-torqued EUV beams. This breakthrough by the Kapteyn-Murnane and Salamanca groups showed that EUV light produced via HHG can indeed possess a time-dependent OAM—and in doing so they have discovered self-torque, an entirely new property of light.

That self-torque is like a wrench speeding up as it's tightening a bolt. However, this wrench is composed of photons and twists around faster than an electron orbits a hydrogen nucleus.

From Optical Donuts to Optical Croissants: The Unique Physics of Self-Torqued Light Beams

"Normally, when HHG is driven with a 'doughnut' laser beam, the conservation rules dictate that each harmonic has an OAM equal to the harmonic number times the OAM of the driving laser. However, if we drive the HHG process with a time-delayed pair of laser pulses possessing different OAM, then things get really interesting," says corresponding author Kevin Dorney, a JILA postdoc who defended his Ph.D. thesis based partly on this work in March. "The time-delayed pulse pair results in the emission of EUV light with a time-varying OAM, which progresses smoothly through an octave of OAM states."

As the OAM content dynamically varies along the EUV pulse, the light beam continues to accelerate and thus possesses a self-torque. Such a property is rarely observed, and nearly never controlled, and to date has only been observed in electrodynamics or predicted to be in certain gravitational waves.

The resulting self-torqued EUV beams don't look anything like a donut at all, but instead resemble a croissant. Hiding behind this optical croissant is a variety of unique physics.

As you move across the EUV croissant, the frequency varies—like different colored petals of a pinwheel spinning in the wind. This is known as an angular frequency chirp. That chirp is directly induced by the self-torque, which was key to confirming the generation of this new property of light.

"It was really quite beautiful physics to have the azimuthal [angular] frequency chirp encode the presence of a time-dependent OAM," says JILA Fellow Margaret Murnane. "Without this connection, there would have been no way to verify the rapid, attosecond variation of the OAM, as such techniques simply do not exist."

The research team at JILA took this idea and ran with it, and set out to measure the azimuthal frequency chirp. In order to do this, the team exploited the physics of OAM beams to precisely control the direction in which the self-torqued beams were emitted, and in doing so were able to measure the azimuthal frequency chirp simply by sending the beam into a spectrometer.

"Once we laid out the plan to make the measurement, I remember thinking it would never work. However, with a bit of perseverance and some serious engineering, we were able to pull off the entire set of measurements in less than a week!", says Kevin Dorney. Even for a group that works continuously in the ultrafast lane, this was fast.

But the story wasn't over yet. The research team went on to show that not only could they produce beams with a self-torque, but that the self-torque could be controlled by simply varying the relative delay between the two visible OAM pulses. The beautiful agreement with theoretical calculations from the Salamanca team verified the presence self-torque in the EUV light, confirming the generation and control of an entirely new property of light.

Looking forward, the international team of experimentalists and theorists are excited to see what opportunities might be opened up by light with a time-varying OAM. Systems with dynamically varying OAM, like binary black holes, appear in nature as well as in emergent materials systems. The team believes that this new form of light can be used to observe and control some of the fastest nanoscale dynamics that nature has to offer, including magnetic and quantum excitations in molecules and nanostructures.✺

E. Pisanty, Rego, L., San Román, J., Picón, A., Dorney, K.M., Kapteyn, H.C., Murnane, M.M., Plaja, L., Lewenstein, M., and Hernández-García, C., *Phyical. Review Letters* **122**, 203201 (2019).

The annual, all-JILA photo was taken in June, on the lawn in front of the JILA Tower, on a beautiful sunny afternoon. Rebecca Jacobson, JILA Science Communicator, was this year's photographer. Photo credit, above: Cynthia Torres/JILA. Photo credit, below: Rebecca Jacobson/JILA.

CHAOS REIGNS IN A QUANTUM ION MAGNET

A proposed experiment would study rapid scrambling in the lab

Black holes still pose a lot of questions for physicists, especially when it comes to understanding what happens to the dust, particles and light they draw in. Nothing that crosses a black hole's event horizon can escape. When particles fall in, we can't read their information anymore and they appear to be lost. But the laws of physics tell us that information can't be truly lost. So what's happened to it?

According to JILA Fellow Dr. Ana Maria Rey, that information isn't gone; it's scrambled. Through the process of scrambling, particles share their information with other particles. And when particles share information, they become entangled, connected to each other.

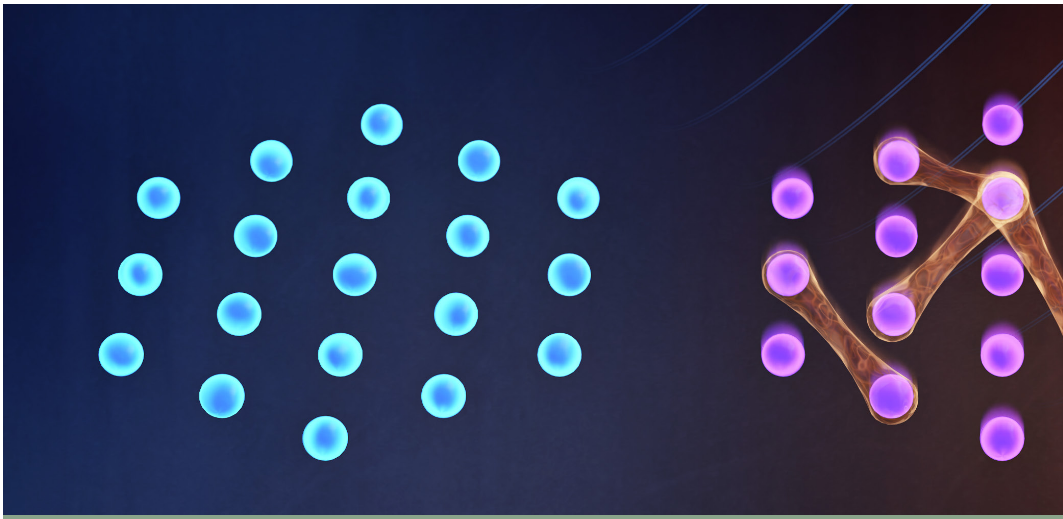
This whole process of scrambling is also tied to the idea of chaos, which is often called "the butterfly effect," the idea that if a butterfly flaps its wings in the Amazon, it may set off a tornado in Oklahoma. With chaos, any small change can exponentially ripple throughout the system.

In short, the information is still there, but it's all mixed up. When we try to read a small part of the system's information, we cut the entangled connections between those particles, and the information seems to disappear. "So we can't read it with simple measurements," Rey said. If we could, physicists could know what the original state of the particle or system was.

Physicists can't take a field trip to a black hole to test things like rapid information scrambling or entanglement. But we may be a step closer to being able to test these ideas in a lab. JILA theorists published a proposal to build, particle by particle, a microscopic system that acts like black hole and scrambles quantum information rapidly.

Driving through the scramble

To understand how to tackle this challenge, think of driving a car along a smooth road, Rey said. If you drive forward, stop and back up, you would end up in the same place. No information would be lost. If you turn the wheel of the car and back up, the car's position will change in a neat, linear fashion when you back up.



When a particle crosses the event horizon of a black hole, the quantum information of the

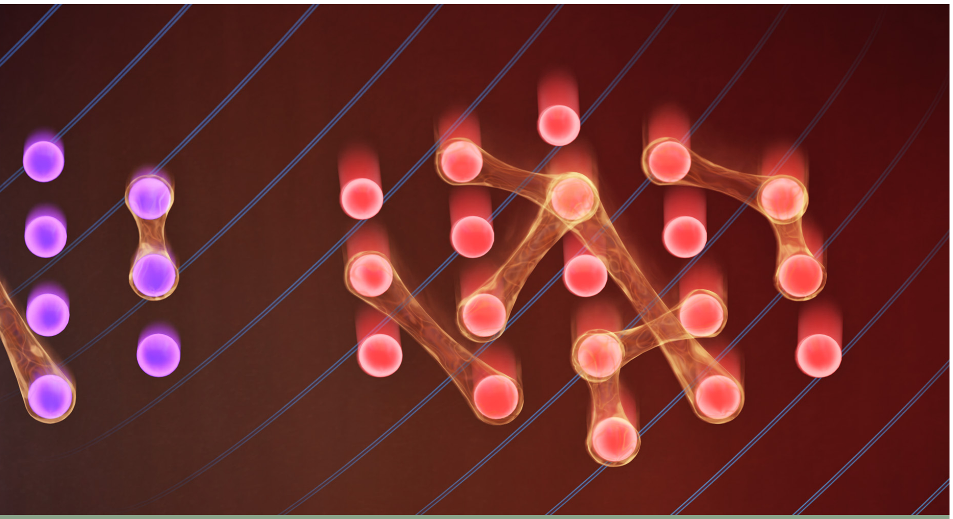
In the same way, information scrambling happens linearly over time, Rey explained. But it's slow, especially compared to a black hole. Black holes are the fastest information scramblers in existence.

"We don't have a black hole in the lab, but we are trying to emulate this scrambling of quantum information," Rey said. And then there's chaos.

If the car is no longer on a nice, smooth road, but a bumpy field full of rocks and trees, your position will change drastically when you turn the wheel and back up. "Then you're going to bump into many things, and then you are going to deviate exponentially from where you started," Rey explained. "This is a little bit like chaos."

Making a black hole(ish) in the lab

Most models of fast scrambling are too complex to be implemented in the lab. And solving the scrambling is extremely complicated, even with the most powerful computers. So the team had to think simple. Dr. Robert Lewis-Swan, a JILA postdoc and first author on a recent paper describing the team's ideas, said they can create this "black hole-ish" system using the Dicke Model, a simple model proposed by Robert Dicke in 1954.



particle is quickly scrambled and entangled. Image Credit: JILA/Steven Burrows

"The Dicke model is known to feature chaotic behavior and is relatively easy to experimentally realize," he said.

The scientists in the lab of Dr. John Bollinger at NIST use lasers to drive vibrations in a crystal made of trapped ions, like tapping the head of a drum. At the same time, they use microwaves to continuously flip the orientation of the quantum spin of the ions. Together, this realizes the Dicke model in the laboratory, allowing the scientists to generate chaos and scrambling of information in a matter of milliseconds.

To observe how information scrambles and the system becomes entangled, they hit the system with another laser to perturb the vibrations of the crystal. Then, by tuning the lasers and microwaves the experiment is put into reverse gear. By comparing how much the system is different to the state it started in, the scientists can characterize how information has been scrambled: a measurement they call a Fidelity Out-of-Time-Correlator or FOTOC.

Beyond theoretical

This experiment will help scientists better understand the rich and complex physics of black holes. But it will also tell us more about how chaos, entanglement and scrambling are all connected. And studying information scrambling will help us understand the limits of quantum information processing, which we need to develop quantum computers.

The proposed experiment would still be a lot slower than a black hole. Rey, the principal investigator, Lewis-Swan and their collaborators at NIST hope to add more complexity and increase its speed, going from rapid scrambling closer to the fast scrambling of a black hole.✺

R.J. Lewis-Swan, Safavi-Naini, A., Bollinger, J.J., and Rey, A.M., *Nature Communications* **10**, 1581 (2019).

The Snowflakes of Insulators

Electron calorimetry uncovers new insulating state

Falling on ice is never fun. A cold and slippery rink is as unforgiving as concrete. Falling into snow, however, is like falling into a pile of leaves. Fluffy, sometimes sticky, and soft enough to be the only substance societally acceptable to throw at another person's face, snow couldn't be more different than ice. But they're both solid H_2O, they're just in different states.

JILA researchers in the Kapteyn-Murnane group recently discovered the insulator version of snow. Using a new ultrafast electron calorimetry technique, the team discovered a never-before-seen state in an otherwise standard semiconductor. This state is insulating, yet its properties differ from the material's standard insulating state. This research, published on March 1st in Science Advances, is the group's most recent demonstration of using ultrafast lasers to uncover new understandings–and manipulate properties–of well-known materials.

Hot in a Femtosecond

Tantalum diselenide ($TaSe_2$) is a semiconductor built from one layer of atomically thin tantalum sandwiched between two layers of selenide. When cold, the atoms in this material bunch together into a star shape. This shape shackles the electrons to the atoms and impedes the flow of electricity, therefore rendering the material as an insulator. But warm this material and insulator melts into a conductor like ice melting to water.

Warm it quickly, however, and the insulator jumps into a previously-unknown insulating state. And by quick, they mean quick–the Kapteyn-Murnane team boosted the temperature tantalum diselenide's electrons more than 3000 Kelvin in just a few femtoseconds, or just a few millionths of a billionth of a second.

To jump the temperature this quickly the team used an ultrafast laser. According to JILA Fellow Dr. Margaret Murnane, a principal investigator of this experiment, such a fast speed ensures that the ultrafast laser heats only the electrons and not the atoms.

"The laser excites the electrons and smears them spatially. And now the insulator is destabilized, so the atoms, instead of being bunched up in a star, move away from each other to try to be equally spaced. But as the atoms rearrange, the material suddenly enters a new state that was previously hidden," said Murnane.

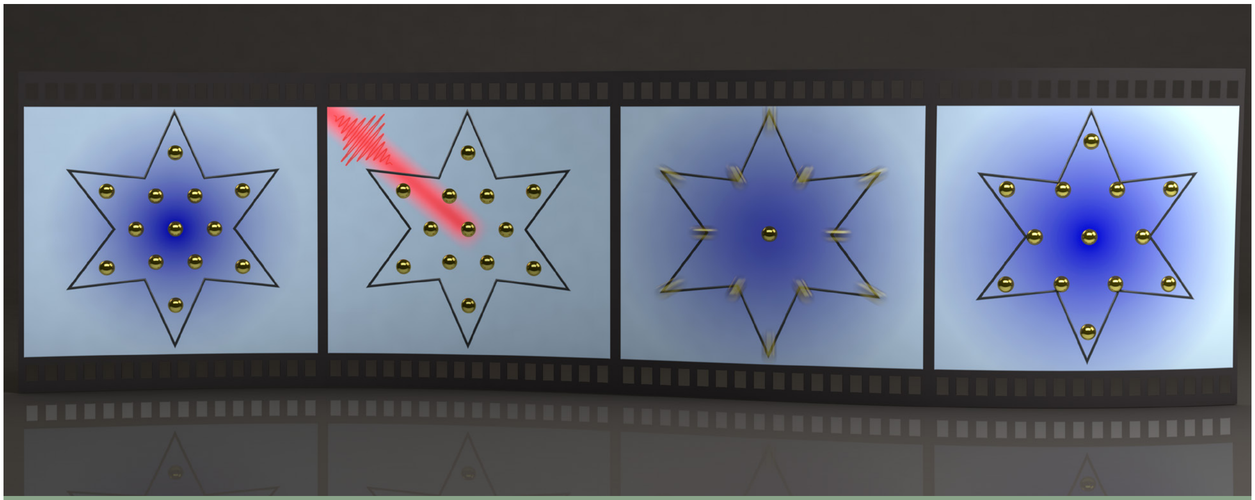
While this new state is still insulating, it has a much lower heat capacity than the usual insulating state. This means that the material requires much less energy to switch between states.

"A phase where the heat capacity drops to a third of its normal value–that's very surprising," said Murnane.

Gone in a Nanosecond

Dr. Xun Shi, the corresponding author of this research, mentioned another surprising find. "One reason that no one found this new phase is that it is not stable under normal equilibrium conditions… but it is metastable."

A metastable state is one with a lifetime, like snow on a warm sidewalk. This particular state lasts about



Using a new ultrafast electron calorimetry technique, JILA researchers in the Kapteyn-Murnane group discovered a new state in a standard material called tantalum diselenide. Starting in a standard insulating state (left frame), in which the atoms (gold) are arranged in a star formation, the group blasted the material with an ultrafast IR laser (red). This ultrafast laser heats the electrons, thus expanding their probability distribution (blue). This expansion destabilizes the insulator state and allows the atoms to rush out, eventually reaching a metastable insulating state (right frame). Image Credit: Kapteyn-Murnane Group and Steven Burrows/JILA

1 nanosecond, or a billionth of a second, before it drops back into the usual insulating state, said Shi. But despite how short this sounds, Shi assured that this is quite a long time in material science.

Long enough, in fact, for this state to have applications in computing and electronics. Ultrafast switches, for example, could be flipped within femtoseconds by using laser-induced state changes like the one found here.

The discovery of this state would not have been possible without the KM group's ultrafast electron calorimetry technique. This technique, in which extreme ultraviolet (EUV) light probes the temperature of electrons, previously enabled JILA researchers to study electron dynamics in magnetic materials and discover that electrons react ten times faster than previously thought.

"The [ultrafast electron calorimetry] technique is a way to systematically map when there is a change in phase and microscopic interactions in the material," said Murnane. "Not all kinds of interactions, but important ones for quantum materials that will be the basis of next-generation nanotechnologies."

Just as snow is different from ice, the team expects to find surprising differences between this new insulating state and the standard one. Thus far, the team has discovered that by tuning the laser power they can affect the lattice distortion, thus enabling them to study the properties of this state. In the future, the group plans to further study these interactions, specifically aiming to understand why the electrons preferentially couple to some lattice vibrations and not others. And looking beyond tantalum diselenide, they plan to use this same technique to explore and control new states in more materials.

Minding all their lofty goals, Murnane summarizes it well. "Learning how to manipulate a material with light, that's what we're trying to do."✷

X. Shi, You, W., Zhang, Y., Tao, Z., Oppeneer, P.M., Wu, X., Thomale, R., Rossnagel, K., Bauer, M., Kapteyn, H.C., and Murnane, M.M., *Science Advances* **5** (3), eaav4449 (2019).

IN THE NEWS

JILA Fellow Murray Holland wins Marinus Smith Award

JILA's greatest achievement is training the next generation of scientists and researchers. Recently, JILA Fellow Murray Holland was recognized for his role in shaping that future generation with a Marinus Smith Award.

In addition to his research at JILA on quantum gases and optomechanics, Holland teaches undergraduate physics classes at CU from introductory physics to the principles of electricity and magnetism. Each spring CU students and their families nominate faculty and staff who have inspired, mentored, and supported them. This year more than 80 nominations were made, and Holland was one of 16 CU staff and faculty who received an award on April 18.

“It is remarkable to be able to share the incredible stories from students and their families on how current faculty, staff and administrators positively influence the lives of our students during their time at CU Boulder. We are so proud and honored to host these annual awards and recognize the outstanding contributions of our campus community members,” Amber Cardamone, director of New Student & Family Programs, said in a press release.

Thomas Perkins wins Gears of Government Award

Sometimes, focusing on the little things can gain you recognition. Dr. Thomas Perkins won a Gears of Government Award for his work in atomic force microscopy. The President's Office gives the Gears of Government Awards to honor those in the federal workforce who have made a profound difference in American lives.

“Whether they are defending the homeland, inspecting our food, making scientific discoveries, or managing cyber risks, Federal employees underpin all the operations of our government and touch nearly every aspect of our lives,” Office of Management and Budget’s Deputy Director for Management Margaret Weichert said in a press release. “These awards recognize not just the front-line mission employees, but also those teams and individuals that are strengthening our country to be a more modern, effective government to better serve their fellow citizens.”

As a JILA Fellow and NIST physicist, Perkins' lab falls under the Department of Commerce. His lab has focused on single molecule measurements of biological systems, like proteins, DNA and RNA. To get those measurements, his team has advanced atomic force microscopy in the last decade. Their advances in AFM technology have led to better understanding of biology, such as completely mapping the energy landscape of a hairpin-shaped bend in HIV RNA, and understanding illnesses from cancer to brain disease. With this knowledge, scientists can develop better drugs and therapies. Perkins emphasized that their work is a team effort.

“I am delighted to receive this award that reflects a decade of innovation by members of my lab,” Perkins said. [See article on page 5 of this issue.]

JILA's Mike Bennett wins Anne K. Heinz Staff Award for Excellence in Outreach and Engagement

This week CU Boulder honored JILA's Mike Bennett with the Anne K. Heinz Staff Award for Excellence in Outreach and Engagement. As the director of educational outreach and research at JILA since August 2016, Bennett oversees the Partnerships for Informal Science Education in the Community (PISEC) program and other STEM outreach initiatives.

PISEC was founded in 2008 as part of the JILA-NSF Physics Frontier Center. The program works with Front Range schools to provide hands-on science programs for kindergarten through 12th grade—mostly underrepresented students. Recently, PISEC brought high school students to JILA for a poster session, followed by laboratory tours and question-and-answer time with

JILA scientists. Under Bennett's leadership, the PISEC program has expanded, reaching nearly 100 students and involving 30-plus university participants ever week.

The program benefits CU Boulder's students as well, CU Boulder physics researchers Noah Finkelstein and Eric Cornell wrote in their nominating letter. Through PISEC undergraduate, graduate and postdoctoral students train and mentor these young students.

"Mike continually improves PISEC, which, under his supervision, demonstrates positive impacts for youth, communities, CU undergraduate and graduate students, and partnering institutions–both CU and school communities," Finkelstein and Cornell wrote.

Not only has Bennett's leadership been valuable, educators said he also has an amazing way of connecting with students.

"Our students benefited tremendously. From getting feedback on projects by real engineers and scientists to learning more about CU students' research, the experiences gained through these mentors will not be forgotten quickly," Skyline High School in Longmont and St. Vrain Valley School District educators wrote in a support letter.

"I'm extremely humbled to have received this award, and I think it speaks predominantly to the importance of the work we're partnering with local community members to undertake with PISEC," Bennett said in an email. "In my mind, our partnership-focused model creates a more equitable landscape for students to engage in authentic scientific practice, providing real opportunities for them to participate as members of the scientific community. At the same time, our volunteers benefit from opportunities to engage with members of the public, learning and practicing pedagogy and communication skills that are valuable at all levels of the scientific enterprise. Ultimately, through creating this blended community, the hope of the PISEC model is that all participants' scientific worldviews will be expanded, creating a more robust and inclusive scientific culture."

As part of the award Bennett received $5,000 to support the program's outreach activities.

CHRIS GREENE, FORMER JILA FELLOW, NAMED TO NATIONAL ACADEMY OF SCIENCES

Former JILA Fellow Chris Greene received one of the highest honors for a scientist in the United States. Greene, professor of physics and astronomy at Purdue University, was named to the National Academy of Sciences this week. He is one of 100 new members invited to join the academy on April 30.

Greene's work includes studying ultracold few-body and many-body quantum systems, ultrafast laser interactions with atoms and molecules, novel and multichannel Rydberg molecules, electron-molecule collisions and dissociative recombination.

The National Academy of Sciences was created in 1863 by an act of Congress to advise the nation on scientific and research matters. The National Academy of Sciences is a private, nonprofit society of distinguished scholars engaged in scientific and engineering research, dedicated to furthering science and technology and their use for the general welfare. There are currently 2,347 active members and 487 foreign associates.

CUBIT MEETS WITH CONGRESS

On April 17–18, 2019, the University of Colorado Boulder met with leadership at the White House, federal research agencies and in Congress to discuss the university's unique strengths in quantum information sciences, as well as its support for fully funding federal quantum activities authorized in the National Quantum Initiative enacted last year.

Quantum information science and technology is a top priority for United States' research investment dollars. CU Boulder launched its CUbit Quantum Initiative earlier this year to synergize quantum efforts on campus, at NIST and with industry partners. The CU Boulder delegation highlighted this effort and discussed not only the university's research strengths in quantum and rich history of collaboration with NIST, but also new efforts to improve workforce development, convene regional and national stakeholders and accelerate commercialization of new quantum technologies.

The CU Boulder delegation–which included Terri Fiez, Vice Chancellor for Research and Innovation, and Jun Ye, Director of CU Boulder's CUbit Quantum Initiative and a Fellow at JILA–met with Kelvin Droegemeier, Director of the White House Office of Science and Technology Policy and his policy team, leadership at the U.S. Departments of Energy and Defense, and several Colorado congressional offices, including U.S. Senator Cory Gardner and U.S. Representatives Joe Neguse and Ed Perlmutter. Gardner and Perlmutter each serve on their chamber's respective science committees, which have jurisdiction over federal science policy, and Neguse represents CU Boulder in Congress.

PISEC HIGH SCHOOL POSTER SYMPOSIUM BRINGS REAL SCIENCE TO STUDENTS

From enrichment tools for otters and ocean clean up to recycled computer monitor light displays, high school students got a chance to show off their scientific research this week at the PISEC High School Poster Symposium. Students from Englewood High School, Northglenn High School, and Skyline High School proudly displayed their research posters at JILA on April 19, 2019, giving their presentations to JILAns and other students.

PISEC was founded as part of the JILA NSF Physics Frontier Center in 2008. Graduate and undergraduate students at JILA volunteer to work with students throughout the semester. They focus on giving the students real scientific experience, from designing an experiment to presenting their research on a poster.

Events like the poster symposium give students an opportunity to start interacting with CU's science community, said Mike Bennett, director of PISEC. They may be young but "this is real authentic science," he told attendees.

After presentations, students were treated to a show at the Fiske Planetarium, followed by tours of laboratories at JILA, ATLAS and the Duane Physics Building. Then they got an opportunity to ask scientists questions about working in research.

Englewood High School physics teacher Rosemary Wulf was excited to see this project evolve from just a campus lab tour to a more interactive experience.

"This year is amazing," she said. "I definitely saw my students shining. They had an opportunity to show their research and learn how to be a scientist."

MARIT FIECHTER WINS SPIN PRIZE FOR BEST UNDERGRADUATE PHYSICS THESIS

One of JILA's former students was awarded high honors at Netherland's Physical Society's annual FYSICA conference this April. Marit Fiechter, an undergraduate student at the University of Groningen in the Netherlands, won the Students of Physics In the Netherlands (SPIN) prize for her bachelor's project, which included a 500 Euro cash prize from the Dutch Society of Physics.

Most undergraduate students in the Netherlands complete a three-month project at the end of his or her degree. Fiechter's prize-winning thesis on narrow-line cooling of yttrium monoxide grew out of her work in Jun Ye's lab at JILA. She says JILA's collaborative spirit not only helped her research, it helped her grow as a scientist.

"I'm very grateful Jun gave me the opportunity to join his group; I really enjoyed my time at JILA," she said in an email. "Not only did I like the project, I also got along with my coworkers (Ian Finneran, Yewei Wu and Shiqian Ding) really well. They are the reason I've learned as much as I have now, by always answering my questions and then enthusiastically explaining even more!"

She added, "I feel like I was surrounded by talented and hard-working people, who are eager to push their experiment forward while at the same time not stressing out about it."

Fiechter will start her master's degree in physics at ETH Zürich this September.

10 differences. Circle them and be the first to show Kristin Conrad, X415, to win a $25 gift card.

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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