LIGHT + MATTER

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Scientists Develop New, Faster Method for Seeking out Dark Matter

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JILA
CU Boulder and NIST

Furry friend enjoying the springtime snow!
Image Credit: Kristin Conrad

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Stories

Feature Articles

Scientists Develop New, Faster Method for Seeking Out Dark Matter

For nearly a century, scientists have worked to unravel the mystery of dark matter—an elusive substance that spreads through the universe and likely makes up much of its mass, but has so far proven impossible to detect in experiments. Now, a team of researchers has used an innovative technique called "quantum squeezing" to dramatically speed up the search for one candidate for dark matter in the lab.

The findings, published 10 February 2021 in the journal *Nature*, center on an incredibly lightweight and as-of-yet undiscovered particle called the axion. According to theory, axions are likely billions to trillions of times smaller than electrons and may have been created during the Big Bang in humungous numbers—enough to potentially explain the existence of dark matter.

Finding this promising particle, however, is a bit like looking for a single quantum needle in one really big haystack.

There may be some relief in sight. Researchers on a project called, fittingly, the Haloscope At Yale Sensitive To Axion Cold Dark Matter (HAYSTAC) experiment report that they've improved the efficiency of their hunt past a fundamental obstacle imposed by the laws of thermodynamics. The group includes scientists at JILA, a joint research institute of the University of Colorado Boulder and the National Institute of Standards and Technology (NIST).

"It's a doubling of the speed from what we were able to do before," said Kelly Backes, one of two lead authors of the new paper and a graduate student at Yale University.

The new approach allows researchers to better separate the incredibly faint signals of possible axions from the random noise that exists at extremely small scales in nature, sometimes called "quantum fluctuations." The team's chances of finding the axion over the next several years are still about as likely as winning the lottery, said study coauthor Konrad Lehnert, a NIST Fellow at JILA. But those odds are only going to get better.

"Once you have a way around quantum fluctuations, your path can just be made better and better," said Lehnert, also a professor adjoint in the Department of Physics at CU Boulder.

HAYSTAC is led by Yale and is a partnership with JILA and the University of California, Berkeley.

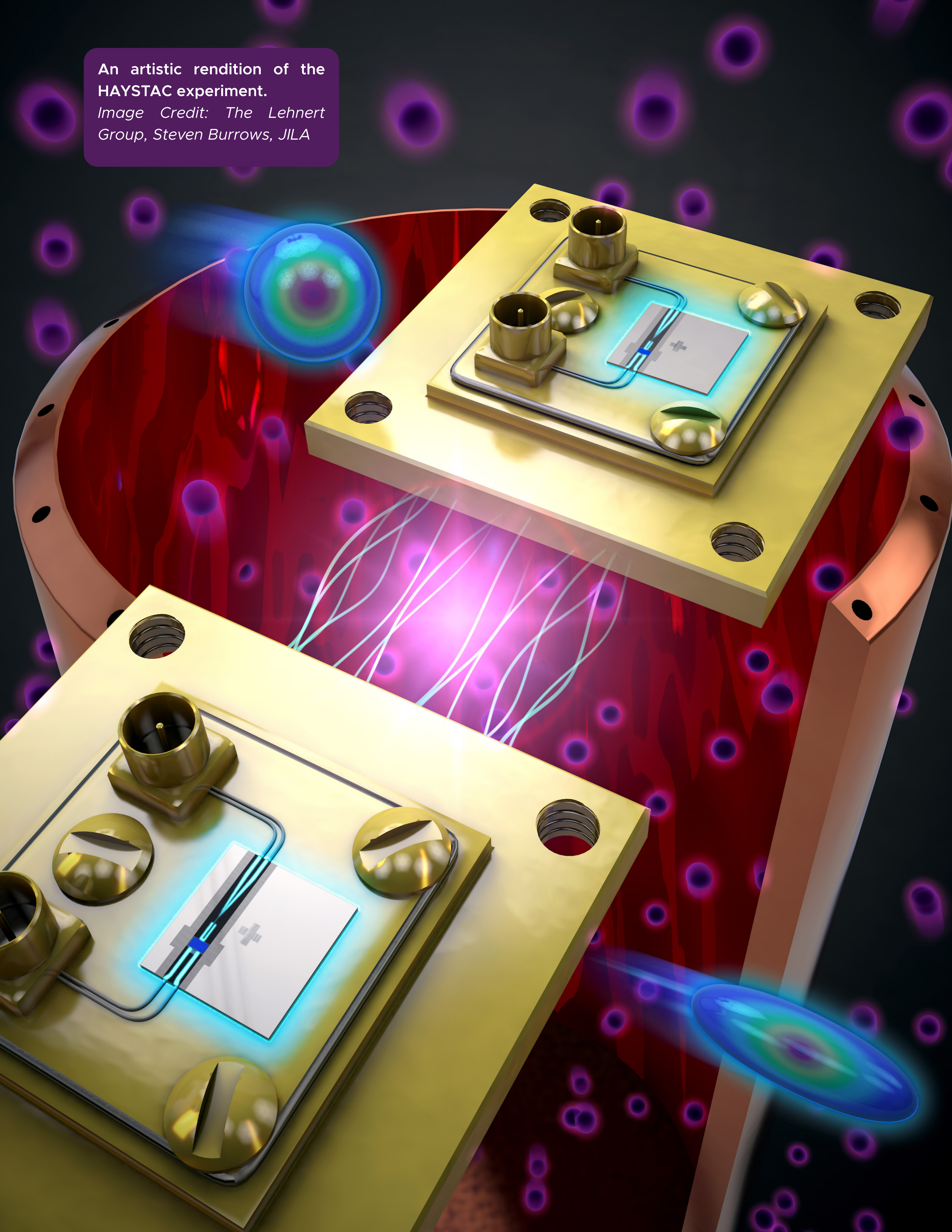
Quantum laws

Daniel Palken, the co-first author of the new paper, explained that what makes the axion so difficult to find is also what makes it such an ideal candidate for dark matter—it's lightweight, carries no electric charge and almost never interacts with normal matter.

"They don't have any of the properties that make a particle easy to detect," said Palken, who earned his PhD from JILA in 2020

But there's one silver lining: If axions pass through a strong enough magnetic field, a small number of them may transform into waves of light—and that's something that scientists can detect. Researchers have launched efforts to find those signals in powerful magnetic fields in space. The HAYSTAC experiment, however, is keeping its feet planted on Earth.

The project, which published its first findings in 2017, employs an ultra-cold facility on the Yale campus to create strong magnetic fields, then try to detect the signal



An artistic rendition of the HAYSTAC experiment.

Image Credit: The Lehnert Group, Steven Burrows, JILA of axions turning into light. It's not an easy search. Scientists have predicted that axions could exhibit an extremely wide range of theoretical masses, each of which would produce a signal at a different frequency of light in an experiment like HAYSTAC. In order to find the real particle, then, the team may have to rifle through a large range of possibilities—like tuning a radio to find a single, faint station.

"If you're trying to drill down to these really feeble signals, it could end up taking you thousands of years," Palken said.

Some of the biggest obstacles facing the team are the laws of quantum mechanics themselves—namely, the Heisenberg Uncertainty Principle, which limits how accurate scientists can be in their observations of particles. In this case, the team can't accurately measure two different properties of the light produced by axions at the same time.

The HAYSTAC team, however, has landed on a way to slip past those immutable laws.

Shifting uncertainties

The trick comes down to using a tool called a Josephson parametric amplifier. Scientists at JILA developed a way to use these small devices to "squeeze" the light they were getting from the HAYSTAC experiment.

Experimental electronics in the dilution refrigerator. These components ensure that quantum noise dominates the experiment.
Image Credit: Kelly Backes, Yale University

Palken explained that the HAYSTAC team doesn't need to detect both properties of incoming light waves with precision—just one of them. Squeezing takes advantage of that by shifting uncertainties in measurements from one of those variables to another.

"Squeezing is just our way of manipulating the quantum mechanical vacuum to put ourselves in a position to measure one variable very well," Palken said. "If we tried to measure the other variable, we would find we would have very little precision."

To test out the method, the researchers did a trial run at Yale to look for the particle over a certain range of masses. They didn't find it, but the experiment took half the time that it usually would, Backes said.

"We did a 100-day data run," she said. "Normally, this paper would have taken us 200 days to complete, so we saved a third of a year, which is pretty incredible."

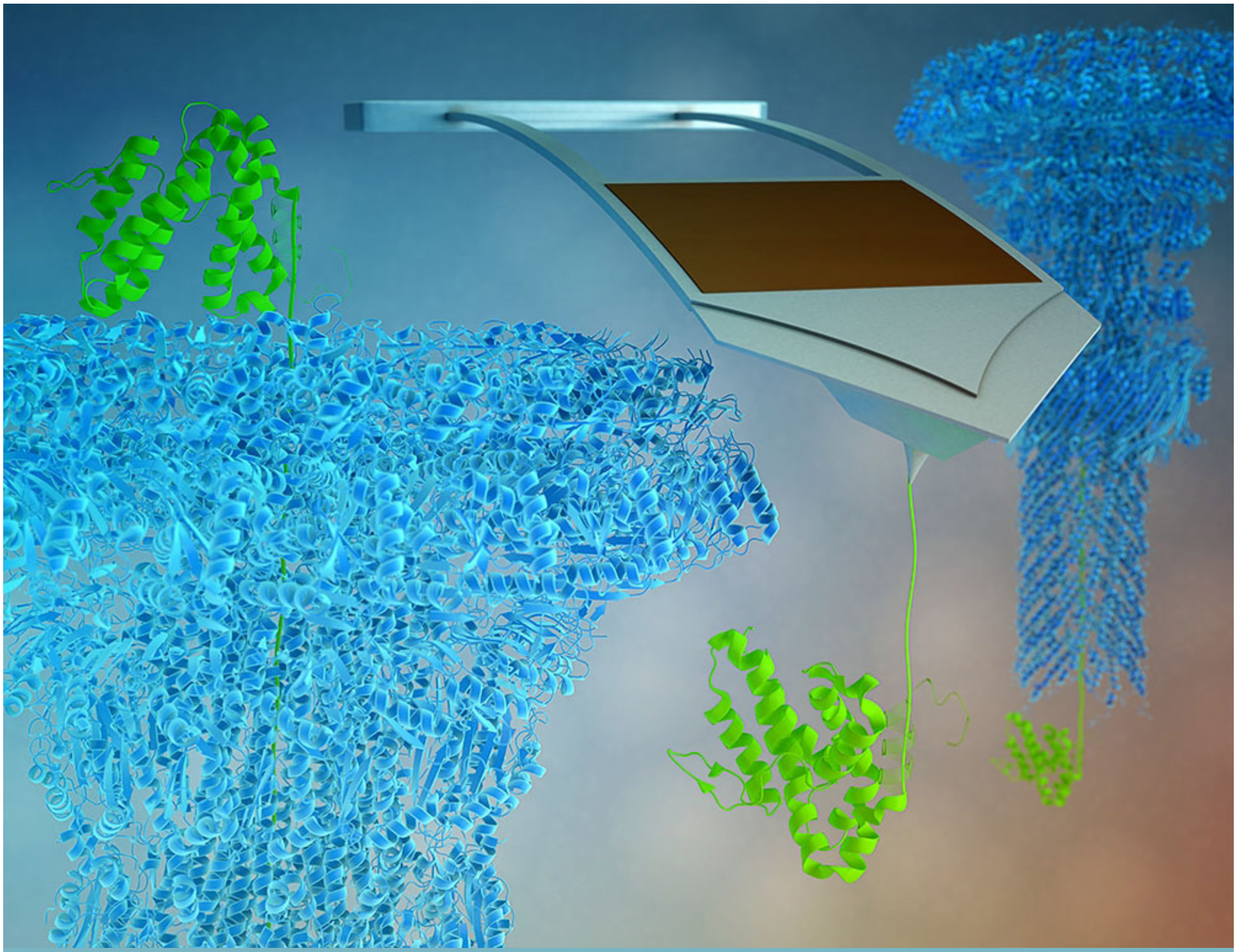
Lehnert added that the group is eager to push those bounds even farther—coming up with new ways to dig for that ever-elusive needle.

"There's a lot of meat left on the bone in just making the idea work better," he said.

Written by Daniel Strain

Backes, K.M., Palken, D.A., Kenany, S.A. *et al.* A quantum enhanced search for dark matter axions. *Nature* **590**, 238–242 (2021).

The Forces Involved in Folding Proteins



Model of the type III secretion system in Salmonella bacteria
Image Credit: The Perkins Lab, Steven Burrows, JILA

Washing your hands after cracking an egg or touching raw chicken may seem like common sense, as the possible resulting bacterial infections have been thoroughly studied. Yet, researchers at JILA have found something surprising and ground-breaking about the physics of bacterial infections. In a new paper, JILA physicist Thomas Perkins collaborated with CU Biochemistry professor Marcello Sousa to dissect the mechanisms of how certain bacteria become more virulent. The research brings together the Perkins lab expertise in single-molecule studies and the Sousa lab expertise in the type III secretion system, a key component of Salmonella bacteria.

The type III secretion system is shaped like a syringe, with a needle that's only two nanometers in diameter (for reference, an atom is around 0.1 to 0.5 nanometers in diameter). Through these needle-like structures, bacteria pump effector proteins directly into host cells, humans or livestock for example, to take control of various host cell functions, including suppressing the cell's immune system or hijacking its DNA and RNA machinery. In order for effector proteins to pass into the host cell, the proteins must be partially unfolded as the 2-nm pore is only a few atoms wide.

Proteins that don't unfold clog the needle leading to the prevailing model that effector proteins have low thermodynamic stability (and so are often unfolded) while proteins that clog the needle have high stability.

Protein folding and protein stability

Protein folding has been studied for decades. In general, proteins fold into their most stable state. Historically, protein stability is measured using thermodynamics. According to JILA Fellow and adjoint professor in Cellular, Molecular and Developmental biology, Thomas Perkins, "The classic way biochemists measure protein stability is either to increase temperature or a denaturant, like urea, to a high level and then lower it back down. If a protein unfolds and refolds under these conditions, then you can measure the thermodynamic stability of the protein."

When applying this technique to effector proteins, the team found effector proteins have typical thermodynamic stabilities. Indeed, thermodynamic stabilities are indistinguishable from proteins that clog the needle. The team then looked to see if mechanical force might play a role

Applying Force to Unfold Proteins

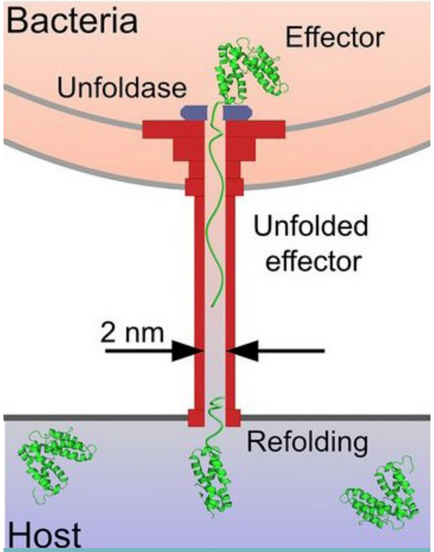
The Perkins lab has lots of experience unfolding proteins using atomic force microscopy (AFM). They developed modified cantilevers that have improved force precision and stability. Nonetheless, it still took four years of effort to develop the ability to reliably apply force to the two model effector proteins (SptP and SopE2), larger and more complicated proteins than the model proteins the Perkins lab has studied in the past. The team needed to anchor the protein down to a surface—without it randomly sticking—and then pull on it from a specific point. After this development, they were finally able to look at the mechanics of effector protein unfolding.

Their data showed that the two model effector proteins were mechanically labile, meaning that they would easily unfold at low forces. Perkins said: "What is remarkable is that these proteins unfold at very low forces compared to a peer set of other proteins. That led us to the hypothesis that it is the mechanical unfolding of these proteins that governs whether a protein can actually make it through the type III secretion system." Prior work by others showed that proteins known to clog the needle unfold at high force. Perkins goes on to say "If our hypothesis is correct, most, if not all, effector proteins should unfold at low force."

Evolution and Unfolding Forces

From their data, the team realized that the mechanics of how these proteins unfold might shed light on another outstanding question in the field. Proteins that have the same structural fold and carry out the same function are homologues. Homologues usually have very similar protein sequences, the linear list of amino acids that make up the protein. However, protein sequences of effector proteins have virtually no similarity with homologues that are not secreted.

First author Marc-André LeBlanc suggests that it is the evolutionary pressures for these proteins to unfold at such low forces but maintain typical thermodynamic stabilities so they refold efficiently that causes their sequences to look so different. Perkins added. "Looking forward, one of the things we're planning to investigate is if homologues that don't go through the type III secretion system are more mechanically robust."



Schematic depiction of protein transport through the T3SS showing effector proteins, which are at least partially folded in the bacterial cytoplasm.
Image Credit: The Perkins Lab

If these non-secreted homologues are more mechanically robust, then there was likely evolutionary pressure for these effector proteins to diverge from their homologues in the case of folding mechanics.

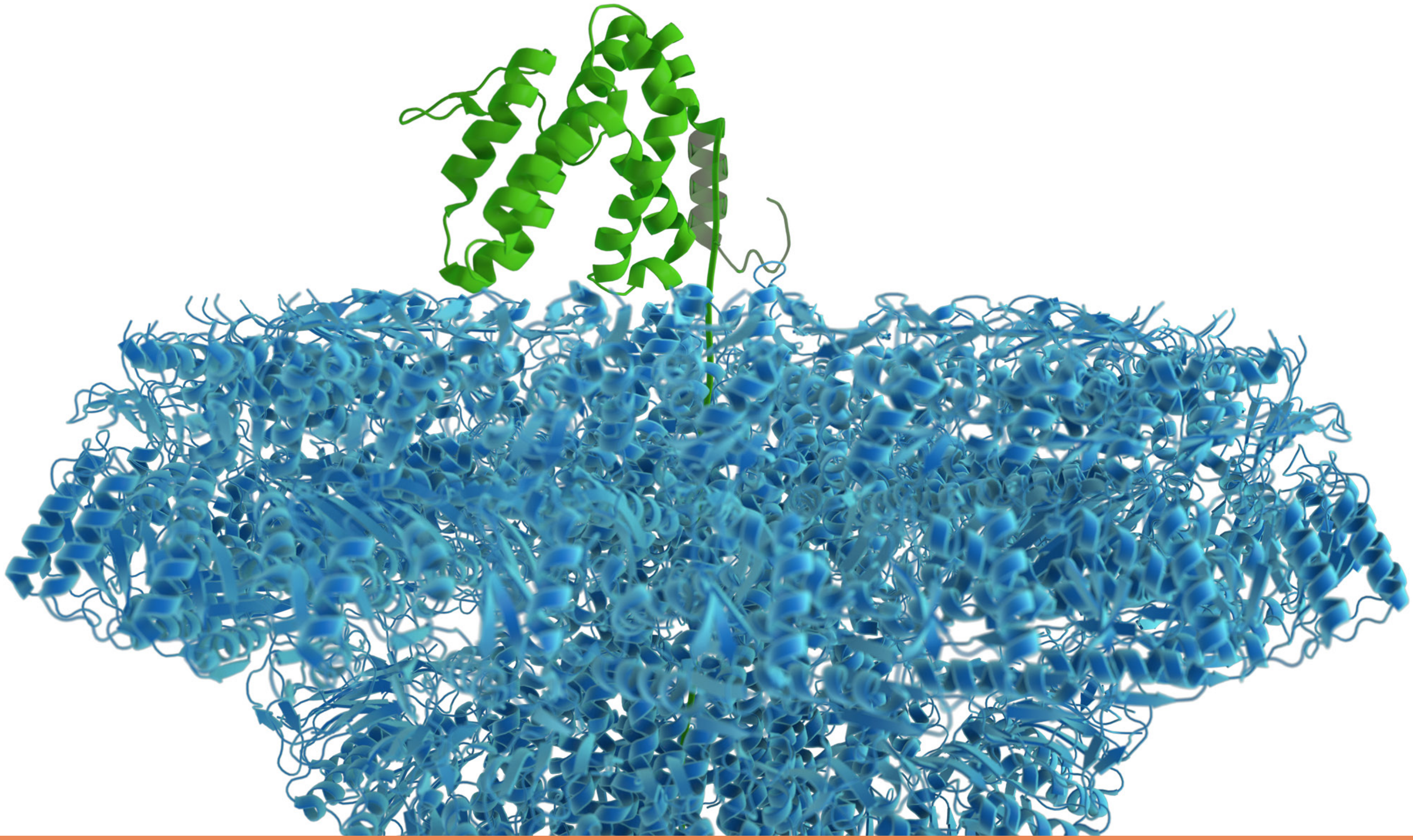
This possible evolutionary pressure may provide insight into the factors that control protein folding and stability, which is what the Perkins and Sousa Labs are currently studying by using AFM to investigate targeted mutations in their model effector proteins.

The research is still ongoing. LeBlanc is looking forward to using the newly developed technology to not only expand the research, but give the study possible medical applications.

“Everything is based on basic research at this point.” LeBlanc said. “But you can play that forward and start to think about applications. There are some labs using the type III secretion system as a protein delivery mechanism. You can certainly imagine if you have a protein that you want to get into another cell, this might be a good way to do it.”

While the study is still in early development, the researchers are excited to see the applications of their newly developed technologies and the impacts of their work on the field of biophysics as a whole.

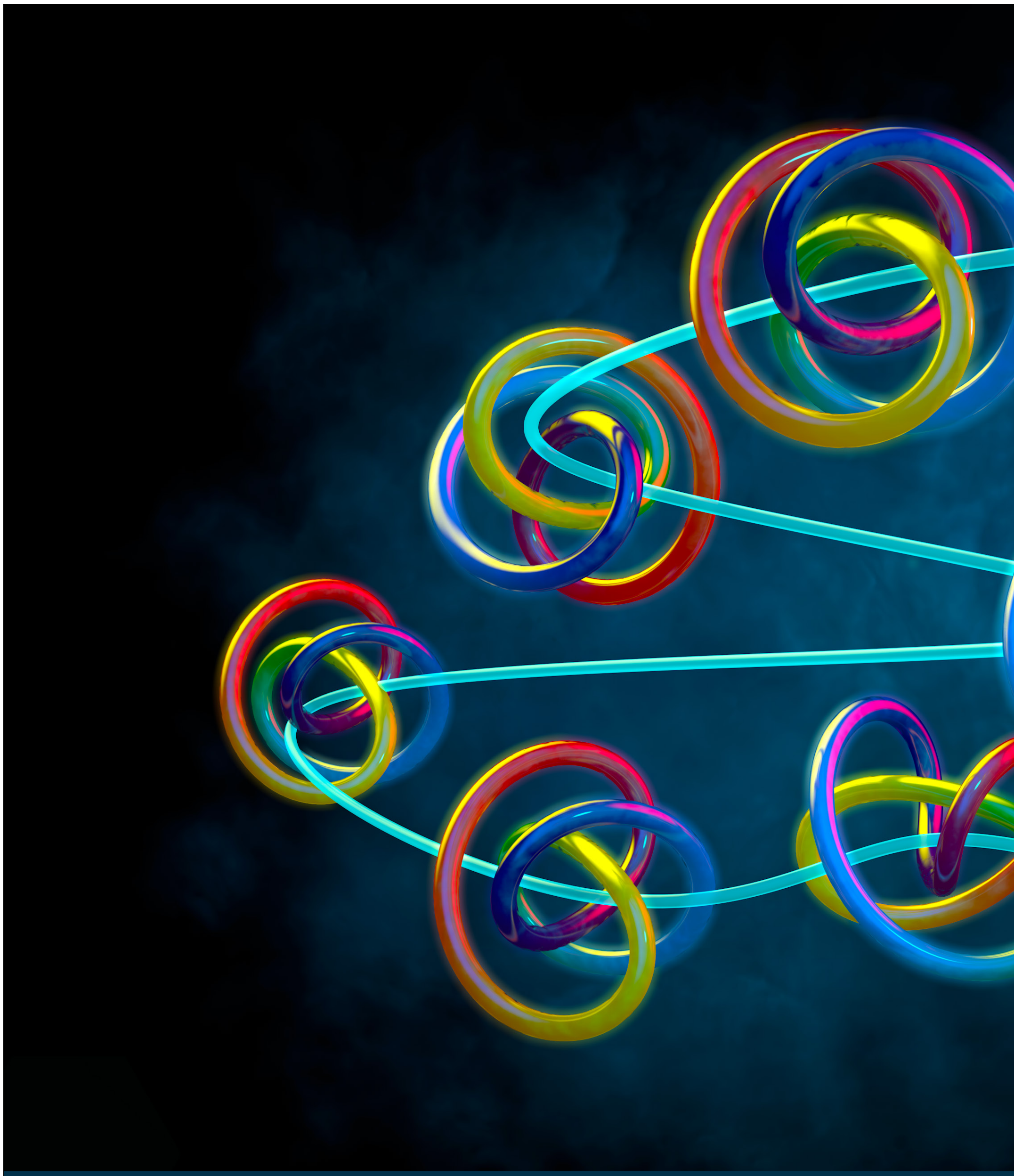
Marc-André LeBlanc, Morgan R. Fink, Thomas T. Perkins, Marcelo C. Sousa. Type III secretion system effector proteins are mechanically labile. *Proceedings of the National Academy of Sciences* **118 (12)** e2019566118 (2021).



Using Quantum Knots to Build a Secure Internet

In this era of the COVID-19 pandemic, the amount of internet hacking has increased dramatically. Hackers threaten our security, taking information before anyone realizes the network has been compromised. These threats are serious and require creative and immediate action to resolve.

For scientists at JILA, a quantum internet is one way to resolve these actions. Essentially, a quantum internet connects different quantum computers or different quantum users into a network to achieve coordinated quantum tasks, explains Shuo Sun, a University of Colorado Boulder Assistant Professor of Physics and JILA Associate Fellow. A quantum internet can enable secure communication, distributed quantum computing, and distributed sensing. In order for a quantum internet to work, it must be built using the principles of quantum mechanics. A quantum internet is a very broad concept and there are many fascinating things that researchers are looking into to use it.



By entangling photons, scientists tie little quantum knots be
resent the information to be delivered.
Image Credit: The Sun Group, Steven Burrows, JILA

Photons and Encryption:

When looking within a quantum internet, the Sun Lab is looking specifically at photons. Photons—tiny packets of light—can exist in two states at once. If a photon is like a computer bit (which is in binary code), it's both a 1 and a 0 until it is observed; then it collapses into either a 1 or 0 upon observation. This quantum superposition of photons allows a receiver to know immediately if their message has been read by a hacker, once the photons' superpositions collapse.

etween them, so they jointly rep-

There are some complications within photons being used as vehicles for encryption, as they can get lost by being absorbed by material in fiber optic cables. When the photons get lost, their valuable information is lost as well. And, thanks to quantum mechanics, scientists can't just make copies of the information.

Entanglement and Quantum Knots:

Instead, scientists can use quantum mechanics, specifically entanglement, to protect the photons from being absorbed. Entanglement connects quantum particles, stated Professor Sun. By entangling these photons, scientists tie little quantum knots between them, so they jointly represent the information to be delivered. The photons aren't just paired off within these quantum knots. They're connected to hundreds of other photons in a tree-shaped pattern. The robust redundancy of these photons means that scientists can still read the information, even if a few photons are lost.

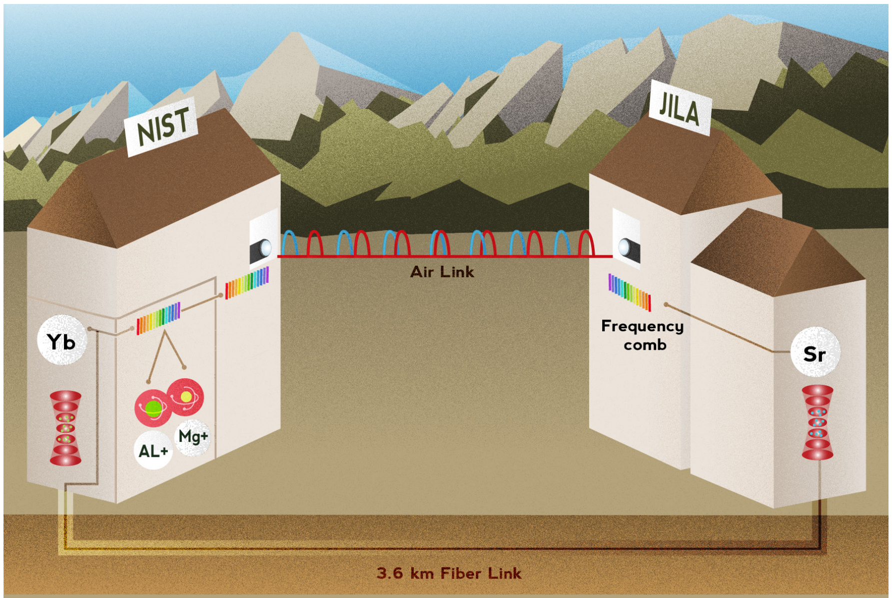
Using a mirror and a photon emitter, the Sun Lab at JILA has devised a means of quickly tying the quantum knots. The emitter sends a particle of light toward the mirror. It bounces off the mirror and passes back through the emitter, entangling itself with the next particle of light.

According to Shuo Sun, the lab is planning to experimentally realize this photon generation scheme as an efficient way to encrypt information. They believe that their solid-state quantum emitter, combined with nanophotonics, offer a very promising approach to realizing this scheme. "It is possible to realize a source of multipartite entangled photons on a semi-conductor chip" stated Sun. Overall, a quantum internet allows us to connect remote and isolated quantum systems into a larger system that can be more powerful.

The Sun Lab paper was published in *Physics Review Letters* on 24 November 2020.

Yuan Zhan and Shuo Sun. Deterministic Generation of Loss-Tolerant Photonic Cluster States with a Single Quantum Emitter. *Physical Review Letters* **125**, 223601 (2020).

NIST Team Compares Three Top Atomic Clocks with Record Accuracy



Model of Atomic Clock Comparisons between JILA and NIST. *Credit: N. Hanacek/NIST*

In a significant advance toward the future redefinition of the international unit of time, the second, a research team led by the National Institute of Standards and Technology (NIST) has compared three of the world's leading atomic clocks with record accuracy over both air and optical fiber links.

Described in the March 25 issue of *Nature*, the NIST-led work is the first to compare three clocks, each based on different atoms, and the first to link the most advanced atomic clocks in different locations over the air. These atomic clock comparisons place the scientific community one step closer to meeting the guidelines for redefinition of the second.

"These comparisons are really defining the state of the art for both fiber-based and free-space measurements—they are all close to 10 times more accurate than any clock comparisons using different atoms performed so far," NIST physicist David Hume said.

The new measurements were challenging because the three types of atoms involved "tick" at vastly different frequencies, because all of the many network components had to operate with extreme accuracy, and because the wireless link required cutting-edge laser technology and design.

The study compared the aluminum-ion clock and ytterbium optical lattice clock, located in different laboratories at NIST Boulder, with the strontium optical lattice clock located 1.5 kilometers away at JILA, The team's measurements were so accurate that uncertainties were only 6 to 8 parts in 10^{18}—that is, errors never exceeded 0.000000000000000008—for both fiber and wireless links.

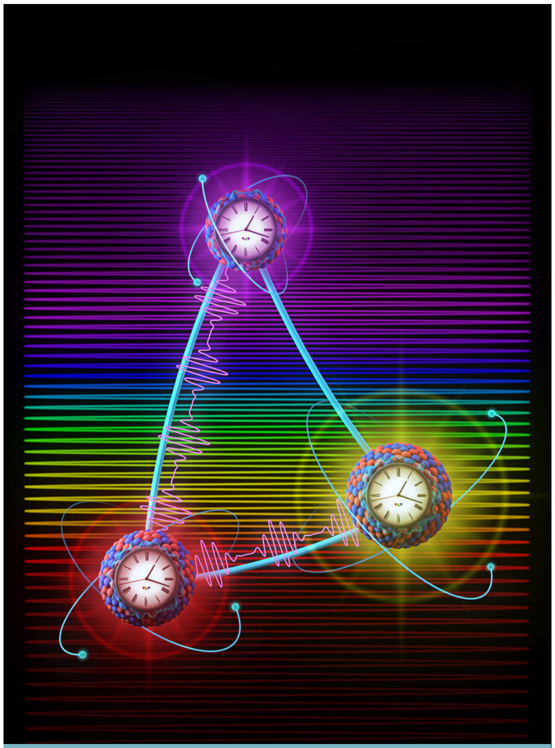
NIST researchers previously described in detail how they transferred time signals over the air link between two of the clocks, the NIST ytterbium and JILA strontium clocks, and found the process worked as well as the fiber-based method and 1,000 times more precisely than conventional wireless transfer schemes. This work shows how the best atomic clocks might be synchronized across remote sites on Earth and, as time signals are transferred over longer distances, even between spacecraft.

The key to the air link was the use of optical frequency combs, which enable accurate comparisons of widely different frequencies. NIST researchers developed two-way transfer methods to precisely compare optical clocks over the air, even in conditions of atmospheric turbulence and laboratory vibrations. The comb-based signal transfer technique had been demonstrated previously but the latest work was the first to compare state-of-the-art atomic clocks.

Since 1967, the second has been defined based on the cesium atom, which ticks at a microwave frequency. The atomic clocks used in the new comparisons tick at much higher optical frequencies, which divide time into smaller units and thus offer greater precision. Comparisons are crucial to the international community's selection of one or more atoms as the next time standard.

The new NIST results reported in *Nature* also set other important records. Frequency is the most accurately measured single quantity in science. The NIST team measured frequency ratios, the quantitative relationships between the frequencies of the atoms as measured in three pairs (ytterbium-strontium, ytterbium-aluminum, and aluminum-strontium). The results are the three most accurate measurements ever made of natural constants. Frequency ratios are considered constants and are used in some international standards and tests of fundamental physics theories.

Frequency ratios offer an important advantage as a metric for evaluating optical atomic clocks. A direct measurement of an optical clock frequency in the usual units of hertz is limited by the accuracy of the current international standard, the cesium microwave clock. Frequency ratios overcome this limitation because they are not expressed in any units.



Artist's conceptual illustration of the linked Atomic Clocks.
Image Credit: The Ye Group, Steven Burrows, JILA

Frequency ratios are usually measured over long distances by use of fiber networks, which are few and far between, or in some cases with microwave data transferred over satellite links, which tend to be unstable.

Guidelines for redefinition of the second recommend the demonstration and verification of multiple frequency ratio measurements with uncertainties approaching the best optical clock performance. All three types of clocks in the new study offer superlative performance now and promise further improvements. NIST's ytterbium clocks, for example, represent the natural frequency of the atoms (a value known as systematic uncertainty) to within a possible error of just 1.4 parts in 10^{18}—about one billionth of a billionth.

NIST's new frequency ratio measurements, while record-setting, are not quite that good yet. But the research team is working on improving measurement stability and clock performance, Hume said.

Beyond their role in the next generation of international standards, optical atomic clocks can be used as sensitive probes for new physics, such as the dark matter believed to constitute most of the "stuff" in the universe. Technological applications for optical clocks include improved timing and navigation systems and measuring Earth's gravitational shape (geodesy).

Boulder Atomic Clock Optical Network (BACON) Collaboration*., Beloy, K., Bodine, M.I. *et al.* Frequency ratio measurements at 18-digit accuracy using an optical clock network. *Nature* **591**, 564–569 (2021).

Scientists Dig Deeper into Subject of First-ever Image of a Black Hole

An international team of scientists, including a University of Colorado Boulder researcher, has taken the most detailed look yet at the supermassive black hole at the center of a galaxy called Messier 87. The results suggest the celestial object is surrounded by strong magnetic fields—key ingredients that could help generate galaxy-length jets of particles that shoot out around it.

A new image of M87*, the supermassive black hole at the center of a galaxy called Messier 87, shows this mysterious object in more detail than ever before.
Image Credit: EHT Collaboration

The research, published in two studies 24 March 2021 in The *Astrophysical Journal Letters*, is the latest to emerge from the Event Horizon Telescope, a collaboration that includes more than 300 scientists from five continents drawing on observations from several telescopes around the world.

In April 2019, the team made international headlines when it released the first-ever image of the immediate vicinity of a black hole. That now-famous portrait of this object shows a dark shadow the size of our entire solar system ringed by a swirling mass of ultra-hot, magnetized plasma called an "accretion disk."

CU Boulder astrophysicist Jason Dexter is a member of the Event Horizon Telescope collaboration and coordinating author of one of the new papers. He said that the 2019 image finally gave a face to black holes. But for scientists like him who want to understand how the bodies behave, it was just the beginning.

"I think these new papers are going to be a major step forward in using Event Horizon Telescope data to look at how black holes grow," said Dexter, a JILA fellow and assistant professor in the Department of Astrophysical and Planetary Sciences.

The team's latest images look at the same black hole, but in polarized light. That's a term researchers use to describe the orientation of light waves as they travel through space. (Polarized sunglasses work by blocking light with certain orientations, while allowing other light through). Such data, Dexter said, may help scientists to dive deep into the belly of a black hole.

"We're seeing strong magnetic fields near the black hole," he said. "These fields may be able to extract energy from the black hole itself and use it to power these jets."

Rings of fire

That hot and volatile environment is Dexter's specialty.

He explained that the tricky thing about studying objects like M87*, the black hole at the center of M87 more than 50 million light-years from Earth, is that they're impossible to see on their own. The gravity produced by black holes is so strong that even light can't escape their grasp if it gets too close.

But scientists can view the area just outside of a black hole and, in particular, its accretion disk. As Dexter put it, "We can't see inside a black hole, but we can study what's all around it."

There's a lot to study: Accretion disks form when massive central objects gobble down humungous clouds of gas from the surrounding space. Like water circling a bathtub drain, that material will begin to spin around the black hole the nearer it gets. Scientists have long suspected that this churning matter could, under the right circumstances, generate magnetic fields—similar to what makes the field that causes compasses point north on Earth.

"We have two broad theories for what those magnetic fields can look like," Dexter said. "Some research has suggested that they could be weak and are simply dragged along with the gas. The other idea is that they can become really strong near the black hole and actually push back against that motion."

To probe the nature of those fields, the Event Horizon Telescope group combined data collected from telescopes spread across our own planet. That information allowed the team to measure the polarization of light from M87's accretion disk, which, in turn, holds clues to the churning dynamics below.

The group's results suggest that the black hole's magnetic fields are anything but weak.

"They're not being dragged around passively with the gas," Dexter said. "They're strong, and that can change the entire structure of how gas is falling into the black hole, and even how this black hole is growing over time."

Bright jets

Just what that means for the black hole isn't clear yet.

Dexter, however, believes that strong magnetic fields could be the key to understanding M87's explosive nature. Scientists have previously observed a humungous "jet" of gas that seems to blast off from around the black hole and stretch for potentially tens-to-hundreds of thousands of light-years. According to theory, the rotation of a black hole itself may twist up the magnetic fields in an accretion disk, generating built up energy that can occasionally burst out to form jets.

"The Event Horizon Telescope gives us the ability to study these processes where they're really important—where energy is being released and where jets are being launched," Dexter said.

For now, he's excited that the data coming from the study has, at least so far, matched the theory. Put differently, the images of M87 to date look a lot like what researchers expected them to—something Dexter finds comforting.

"To me, that's evidence that we're on the right track," he said. "We seem to understand the basic physics of accretion disks and how these black holes grow, which to me is amazing."

Written by Daniel Strain

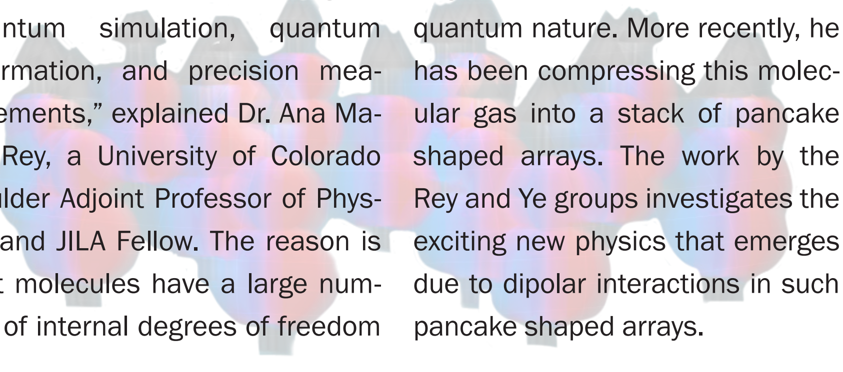
The Event Horizon Telescope Collaboration et al. M87 Event Horizon Telescope Results. VII. Polarization of the Ring, Astrophysical Journal Letters, 910, L12 (2021).

Molecules in Flat Lands: An Entanglement Paradise

Within the realm of quantum mechanics, the generation of quantum entanglement remains one of the most challenging goals. Entanglement, simply put, is when the quantum state of each particle or a group of particles is not independent of the quantum states of other particles or groups, even over long distances. Entangled particles have always fascinated physicists, as measuring one entangled particle can result in a change in another entangled particle, famously dismissed as "spooky action at a distance" by Einstein. By now, physicists understand this strange effect and how to make use of it, for example, to increase the sensitivity of measurements. However, entangled states are very fragile, as they can be easily disrupted by decoherence. Researchers have already created entangled states in atoms, photons, electrons, and ions, but only recently have studies begun to explore entanglement in gases of polar molecules.

"Molecules are very appealing for quantum simulation, quantum information, and precision measurements," explained Dr. Ana Maria Rey, a University of Colorado Boulder Adjoint Professor of Physics and JILA Fellow. The reason is that molecules have a large number of internal degrees of freedom that can be a useful resource for quantum sensing and fundamental physics tests. Another benefit of using molecules in quantum experiments is that molecules also have long-range dipolar interactions: in contrast to atoms which have to bump into each other to interact, molecules can interact at a distance. "Molecules offer really great advantages compared to atoms, but at the same time, they are really hard to cool down. In fact, cooling molecules to quantum degeneracy (condition reached when they are cold enough to make quantum effects dominate) has been one of the most sought-after outstanding goals for many years. The progress has been very slow, but it's happening now," said Rey.

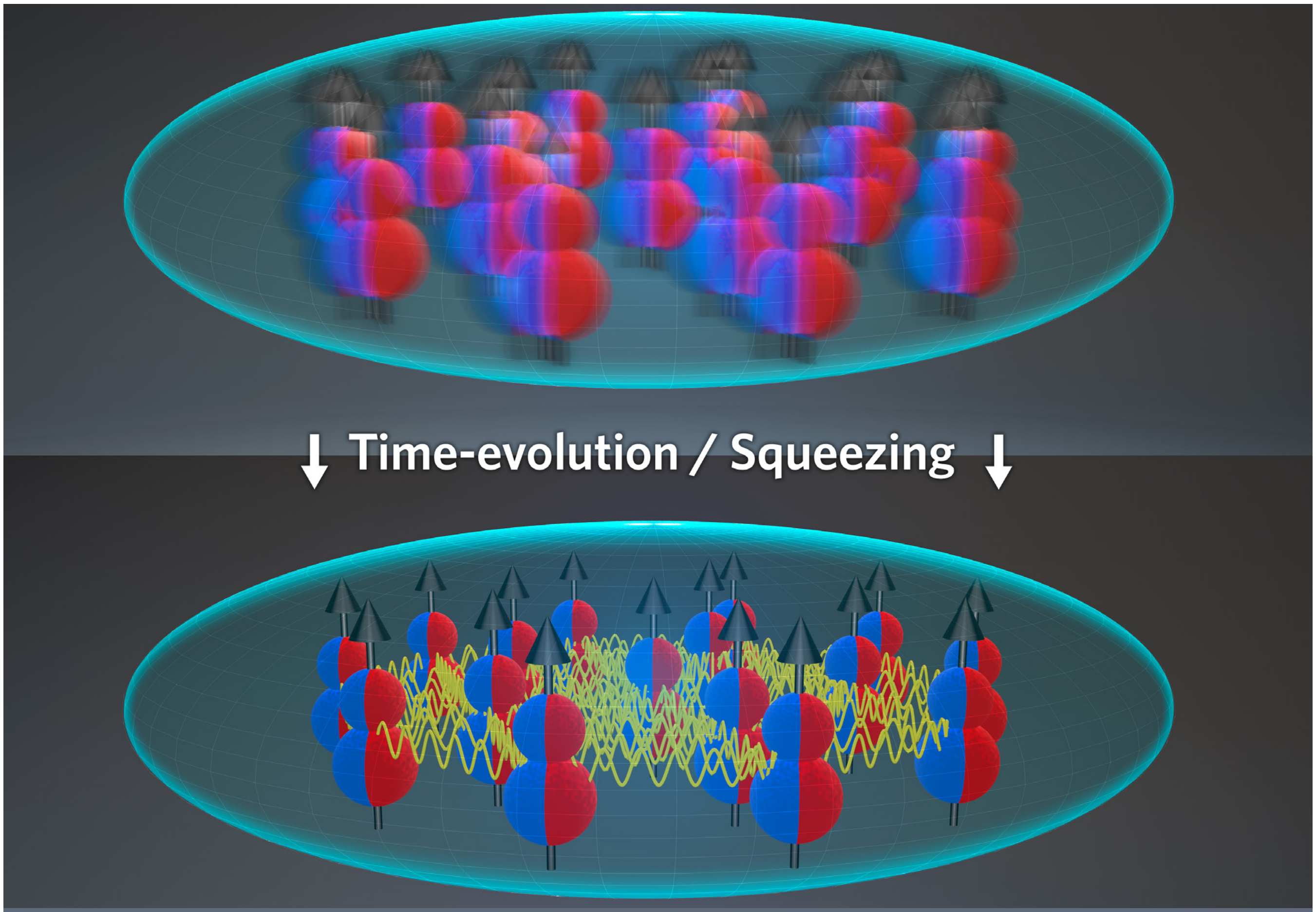
In 2019, JILA Fellow and Adjoint professor for University of Colorado Boulder, Jun Ye, finally achieved this important milestone. Ye's lab managed to cool down molecules consisting of one rubidium and one potassium atom down to quantum degeneracy and observe their quantum nature. More recently, he has been compressing this molecular gas into a stack of pancake shaped arrays. The work by the Rey and Ye groups investigates the exciting new physics that emerges due to dipolar interactions in such pancake shaped arrays.



The Importance of Pancake Geometry

Chemical reactions are one of the most detrimental enemies to cooling molecules. A few years ago, the Ye lab was able to avoid chemical reactions while allowing molecules to interact with each other via dipolar interactions by loading the molecules in a 3D lattice. A 3D lattice can be imagined as a perfect crystal of light. In a 3D lattice, molecules are pinned at individual lattice sites without moving. The molecules then interact via dipolar interactions in the same way that magnets interact: when they are placed side by side they repel and when they are placed head to tail they attract. In a 3D lattice, molecules experience both attractive and repulsive interactions, and, as a consequence, on average the interactions between molecules cancel each other out. Moreover, in this experiment the molecular filling fraction was very low, which is to say that the molecules were mostly quite far apart and interacted only very weakly

In a recent experiment, however, the Ye group was able to increase the density by compressing a 3D quantum degenerate gas into a few pancakes, each one with a flat 2D shape. Within a pancake the Ye group found it is possible to suppress undesirable chemical reactions and, in addition, make dipole interactions stronger. This is because in a 2D configuration all molecules repel and the interactions do not average out. The exciting observation made by the investigators is that the strong dipolar interactions in the pancake can also make the gas robust to undesirable dephasing effects and chemical reactions. As Rey Group postdoc Bilitewski stated: In studying this shape, "conceptually, and this is at the heart of this work, the interactions between the molecules depend on the quantum states they are in, and thus on this confinement. So, you first have to figure out the interactions in this new geometry. It turns out these actually have very beneficial properties for generating the collective dynamics we are after." But the even better news is that interactions not only protect the state by forcing the molecular dipoles to be all aligned, but also naturally create entanglement. In Bilitewski's words, "The benefit to this collective synchronization is that the entanglement we generate becomes robust to certain effects that would usually destroy it." Such entangled arrays of molecules could have applications for future measurements of various quantities, such as electric fields, with sensitivity enhanced by the entanglement.



Model of the quantum gas pancake with quantum interactions
Image Credit: The Rey Lab, Steven Burrows, JILA

The work done by the Rey group illustrates the importance of geometrical effects in dipolar gases and the exciting many-body phenomena yet to be explored once molecules are brought to quantum degeneracy. In theorizing about the importance of this 2D shape, Rey said: “Thanks to the amazing work done by Thomas Bilitewski, we have been able to model their quantum dynamics and show it should be possible to entangle them. He computed all the integrals needed to write an effective model, solved the equations of motion and showed everything can be made to work out to generate entanglement through flip-flop processes induced by dipolar interactions.”

The production of ultracold molecular gases in controllable geometries hints at new discoveries and predictions within the field of quantum mechanics. “This observation was a demonstration that molecules can explore quantum magnetism,” Rey added, “In other words, the molecules can behave as quantum magnets and emulate the behavior of electrons in solids, for example. In our recent work, we have made a step forward toward this direction.” The proposal put forth by the Rey and Ye groups is only the beginning of all the great science yet to be studied with entanglement arrays of molecules. According to Bilitewski, “This is all really exciting in the sense that we are exploring a novel regime that has only now become available in the lab.”

Thomas Bilitewski, Luigi De Marco, Jun-Ru Li, Kyle Matsuda, William G. Tobias, Giacomo Valtolina, Jun Ye, and Ana Maria Rey. Dynamical Generation of Spin Squeezing in Ultracold Dipolar Molecules. *Physical Review Letters* **126**, 113401 (2021).

Highlighting the Research Centers within JILA

JILA is the host of multiple centers within its campus. Some are National Science Foundation (NSF) funded and others funded by more private centers. Each center focuses on specific topics to advance the knowledge, education, and research on some of the biggest ideas within physics.

STROBE

STROBE NSF Science and Technology Center on Real-Time Functional Imaging is one of the 12 nationwide NSF funded Science and Technology centers. According to Ellen Keister, the STROBE Director of Education: “STROBE research groups have common challenges associated with big data, detectors, as well as pushing the limits of x-ray, electron, and visible nano-imaging. STROBE enables research groups to address common challenges, enhance tabletop and national facilities, and use new capabilities to address current nano and bio materials challenges.”

While STROBE works on collaboration between investigators within its center, it also encourages collaboration from a younger generation. “STROBE encompasses K–12 outreach, undergraduate education, graduate education programming, essentially focusing on how to build and maintain a top STEM workforce,” Keister comments, “and do it in a way that is inclusive, and that provides students and trainees with the technical and soft skills and tools they need to be prepared and successful when they go out into the 21st century workforce.”

Lauren Mason, STROBE Director of Communications and Operations, echoes this importance of collaboration, but specifically with the undergraduate population: “Undergraduate students from across the nation who apply to the STROBE Summer Undergraduate Research Scholars (SURS) Program have the opportunity to participate in research experiences at multiple STROBE nodes over consecutive summers. Our program is unique in that STROBE offers multiple summer research experiences in different labs to develop community and deep technical expertise.” STROBE not only shows the value of collaboration, but also the value of educating a younger generation of researchers.

PEAQS:

Like STROBE, The Partnership for Education and the Advancement of Quantum and nanoSystems (PEAQS) works heavily to provide STEM opportunities for underrepresented undergraduate students. As Sarah Schreiner, the PEAQS Co-PI and STROBE Director of Outreach and Broadening Participation explains, “PEAQS is an NSF Partnerships for Research and Education in Materials Research (PREM) program. The lead institution is Fort Lewis College, a non-tribal, Native American-Serving Institution, down in Durango. PEAQS is also partners with Norfolk State University, which is a member of the Historically Black Colleges and Universities, and STROBE. The research provides students with access to the whole cycle of material science, all the way from the synthesis and fabrication of the materials to the characterization and integration of materials.” PEAQS is an excellent program for undergraduates wanting to learn the research process, as well as find resources for internships and future job positions.

MID-IR MURI:

One center within JILA that is funded by the Department of Defense (DOD) is a multidisciplinary university research initiative (MURI). This center is awarded funding to work on laser technology at JILA and other universities. According to Eric Cornell: “MURIs have a smaller number of people, usually. They’re very collaborative, right in the name ‘MU’ stands for multidisciplinary universities. The MURIs are getting individual professors to work on a collective idea.” This year is the last year for the current MURI, and it will be renewed soon.

The Physics Frontier Center (PFC):

“I’ve been the admin in the PFC for 20 years, before it was the Physics Frontier Center (PFC). Back then, it was called the Group Grant until we won NSF funding to create the PFC center. The PFC then replaced the Group Grant.” Krista Beck, an administrator, describes her early work at the PFC. The PFC is one of the three NSF centers located on JILA’s campus and hosts around 22 JILA investigators. PI Jun Ye explains that the center “is broader subject-wise as it touches on chemistry, biology, and other topics.” The PFC encourages active collaboration between investigators to solve some of the biggest mysteries within science.

In fact, this teamwork within the PFC is quite contagious. “The PFC has this nice spirit of collaboration and I, myself, have collaborated with quite a few PFC investigators in JILA over the past two decades, writing many papers together.” Ye states. “And this JILA culture has been extremely powerful. When we were building up Q-SEnSE, the PFC culture was one we borrowed from, emphasizing on collaboration within Q-SEnSE.” In echoing the power of teamwork, PFC director Eric Cornell adds, “Some of our projects are explicitly multi-investigator projects.” With these multi-investigator projects, PIs use their skills to complement each other’s knowledge in order to successfully answer research questions. “It’s been pretty amazing,” Beck comments. “There have been lots of papers put out that have more than one PFC PI, which is really cool. Some theorists and experimentalists will work together across projects. Acknowledgements will include also several centers. They all work together really well.”

Quantum Systems through Entangled Science and Engineering (Q-SEnSE):

The research centers within JILA also include Quantum Systems through Entangled Science and Engineering (Q-SEnSE). According to Director of Operations, Steve ONeil: “The Q-SEnSE focus on Quantum Sensors commands a unique status in relation to the related fields of quantum simulation, quantum computing, and quantum networking, because Quantum Sensing and Measurement both underlies the ultimate success of those other fields and uses them to achieve its own full technological potential.” With that in mind, Q-SEnSE derives enormous benefits from collaborations among 37 investigators at 11 organizations in the U,S, and one in Europe. Director Jun Ye states: “It connects with other academic institutions such as Stanford, MIT, Harvard, University of New Mexico, and national laboratories. They are all connected and collaborating together to solve challenging problems in quantum information science and technology.”

Q-SEnSE’s collaboration and teamwork extends beyond its own members, as the center also shares some common research interests with the Quantum Systems Accelerator (QSA), a DOE research center with a goal of building a scalable quantum computer in five years. The QSA is led by the Lawrence Berkley National Laboratory, and partners with CU Boulder and 14 other institutions. Upon thinking of the benefits of having so many collaborative centers at CU, ONeil comments, “in addition to significant research synergies, there is a reputational advantage that plays out in attracting talent. Whether it’s at the level of recruiting a junior professor, the level of a postdoc looking for a place to work, or the level of a graduate student looking for a place to study with a professor to do a Ph.D.”

While Q-SEnSE engages prominent researchers from around the world, it also emphasizes a community of collaboration and teamwork within the center and with its many partners. Q-SEnSE illustrates the importance of working together to advance the boundaries of modern physics. As Ye states: “As a scientist, you are always curious whether you can advance the knowledge or technology to the next level.”

CUbit:

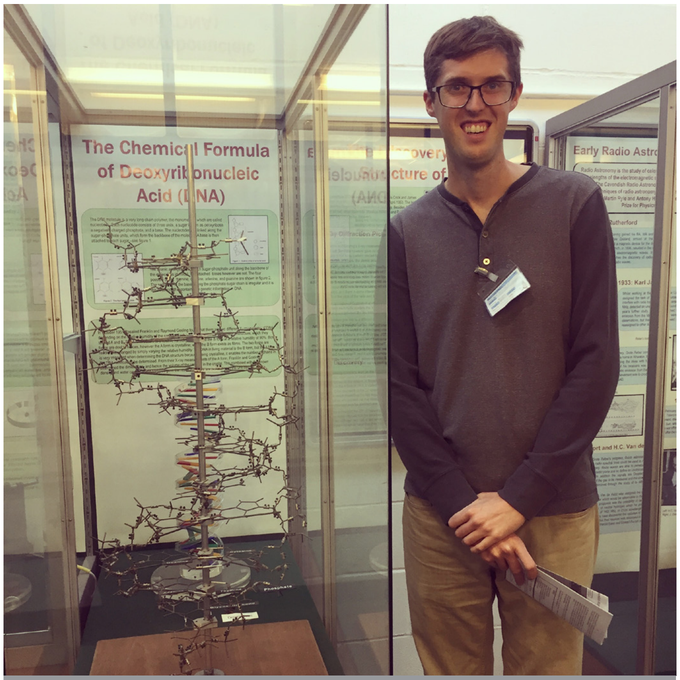
The CUbit center is also part of the quantum initiative, and is the parent organization for Q-SEnSE. Its goal is to advance fundamental science and build a strong foundation for novel quantum technologies and their rapid dissemination, application, and commercialization. Using collaboration within its sub-centers, CUbit has been able to publish some ground-breaking work.

CTQM:

The Center for Theory of Quantum Matter (CTQM) is a sub-center of CUbit, and is focused solely on theory. Director Ana Maria Rey states that: “we have this synergy between research in condensed matter, high energy physics, and quantum information. This center allows funding for external speakers and sharing information and new ideas.” Allowing a place for theorists specifically to discuss their work gives way to new types of collaboration. “This is a unique way to be in touch with a different type of community and know what they’re doing.” Rey adds. “That’s the heart of the center.”

DAVID JACOBSON IS AWARDED THE 2021 NIH PATHWAY TO INDEPENDENCE AWARD

Post-doc David Jacobson in JILA Fellow Tom Perkins' laboratory was ecstatic to discover he had won the competitive NIH K99/R00 Pathway to Independence Award. "The process of applying for this award is very involved," Jacobson said. "I had been in Tom Perkins' group for three years when I applied. And you write this big proposal describing the two phases, one you do as a postdoc and one you do as an independent investigator. So, you prepare this big document and send it in. It feels like you've done a lot of work. Then you wait a long time. And so, when I finally got it, I was kind of relieved that this process was over and, of course, very excited."


Postdoc David Jacobson
Image Credit: The Perkins Lab

When asked about this type of award, Jacobson explained that: "this is a career transition award, so there are scientific goals, but one of the main goals is my career. So, it's very humbling to think that the National Institute of Health (NIH) has set aside a fairly large amount of money to promote my career." This grant program from the NIH strives to support postdoc and clinician-scientists who currently work in mentored research positions in transitioning to independent investigator positions in academia. "In the short term," Jacobson added, "it allows me to continue to work on what I've been doing with Tom Perkins, which is single molecule biophysics experiments on membrane proteins. When I get to the point where I am a professor somewhere, hopefully, it'll give me a lot more initial support to start building a lab and really dive into research."

In anticipating his next career moves, Jacobson commented: "I want to take the techniques I've learned from working with Tom at JILA, and start to apply them to other biological systems that are more directly biomedically relevant than what we're working with now. And this award, getting $250,000 a year in research support, is enough, for example, to hire two people. Your lab can start bigger sooner, and hopefully you get better results faster." Through this program, Jacobson will get the financial support he needs, along with a network of fellow cohorts, to transition successfully into the next phase of his career.

Jacobson's goal is to become a professor. As a postdoc, he is currently researching the biophysics of membrane protein folding, as well as improvements on AFM-based force spectroscopy techniques within the Perkins Laboratory. In transitioning forward, Jacobson hopes to continue researching protein folding physics. "I plan to work on the arginine vasopressin receptor 2 protein system. I chose that because it has interesting biomedical implications, in particular for the urinary condition diabetes insipidus, which can be caused by mutations in this protein. There is great interest, from a biomedical point of view, in doing detailed physical studies of the energetics of how this protein assembles and folds. And it is also a protein I think I will be able to work with...."

Looking back on his work to achieve this prestigious award, Jacobson thanks his mentor, Tom Perkins.

"The thing that has always impressed me with Tom is that over his time as a professor in JILA, obviously he's worked on many projects, but there's always in the background this overarching project of advancing the underlying measurement technology that we're using."

Jacobson hopes to mimic Perkins' goals of advancing technology in his own future work. He is grateful to be receiving this award, and can't wait to get started in reaching his career goals.

LIFE AFTER JILA

This is our first article in the "Life After JILA" series, where we highlight the journeys of JILA alumni, and illustrate the impact that JILA has had on their careers. This article's focus is on Jason Ensher, EVP and CTO at Insight Photonic Solutions. Like many of us, Ensher's career path has been affected by the environment of industry, the economy as a whole, and new opportunities within different fields of physics. In getting to the position that he is in today, Ensher is grateful for the skills he learned, and experiences he had, at JILA. According to Ensher, "The people you work with at JILA—they're your first professional network."


JILA alumnus Jason Ensher
Image Credit: Jason Ensher

Ensher started at JILA the summer before his graduate studies began. "I had a really good first impression of JILA, because I interviewed with Eric Cornell and Carl Wieman on my visit to the university." Ensher joined Cornell's team and contributed to the discovery of Bose-Einstein condensate (BEC) of ^{87}RB. Ensher learned many skills under both Cornell and Wieman, skills which he still uses today.

Speaking of his old supervisor, Ensher remarked that Cornell "was very supportive and encouraging in both intangible and structured ways. I always felt smarter after talking with him, and more motivated to get smarter and become more skilled."

The value of a good supervisor was not wasted on Ensher's learning.

After graduating from JILA, Ensher moved onto studying at the University of Connecticut. His work there taught him quite a bit about the difference in career paths between academia and industry. "Statistically speaking, unless the numbers have changed, I think there are a lot more of us studying physics than there are positions as full-time faculty." In observing this, Jason felt motivated to pursue a career in industry.

He began with a small start-up company, Precision Photonics, then moved to working at Ball Aerospace. From Ball Aerospace, he moved through other smaller companies until he came to his current position at Insight Photonic Solutions. Many of his moves between companies was due to downsizing and the 2008 recession.

In looking back, Ensher observed, “I learned one of the most important lessons about working in industry and that is: through no fault of your own, you could be laid off.”

This lesson Ensher carried with him when pursuing other positions. He believed it to be an important lesson for anyone working in industry. “It’s people in our background I think, that are not accustomed to that idea of failing, or being told ‘your services are not required here anymore.’ What I would say from that is: you can’t control when these bad things are going to happen to you, but you can definitely control how you respond to them.” Reminiscing,

Ensher was grateful of the skills he learned at JILA that set him apart from other applications when trying to find his next job. He noticed that thanks to his training, he was able to find his next position rather quickly compared with colleagues or friends.

Ensher’s current work still calls on his training learned at JILA, as he is working on making tunable lasers into products. He’s focusing on many applications for these tunable lasers, including imaging Optical Coherence Tomography (OCT) for patients with eye ailments, but also applying this product into self-driving cars’ radar technology. He is excited by the challenges his current job presents, and knows his work is making an impact in industry as a whole.

In sharing life lessons and wanting to inspire current JILAns, Ensher says: “I would encourage people coming out of graduate school and JILA, in particular, to keep in mind that you are armed with an incredible experience and set of skills that not many people have the benefit of.” Ensher continues to use the skills he learned at JILA, and is extremely grateful for having the opportunity to work there.

If you’re interested in learning more about Life after JILA, or want to join, contact Chris Natynski at Chris.Natynski@colorado.edu

Heather Lewandowski Wins the 2021 Boulder Faculty Excellence Award

JILA Fellow Heather Lewandowski has been awarded the 2021 Boulder Faculty Excellence Award. This award was given specifically for Lewandowski's excellence in teaching and pedagogy.

The Boulder Faculty Excellence Awards strive to recognize advances within the university. Candidates are nominated based on innovative practices and classroom teaching. Letters from students and colleagues testify to a candidate's success and allow the selection committee to assess a candidate fairly and accurately.

Heather Lewandowski's group focuses on experimental cold molecular physics and physics education research. Lewandowski is not only dedicated in her laboratory, but also studies how students learn experimental physics. With both research topics having interdisciplinary approaches, it's no wonder Lewandowski was selected for this award. Congratulations!

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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