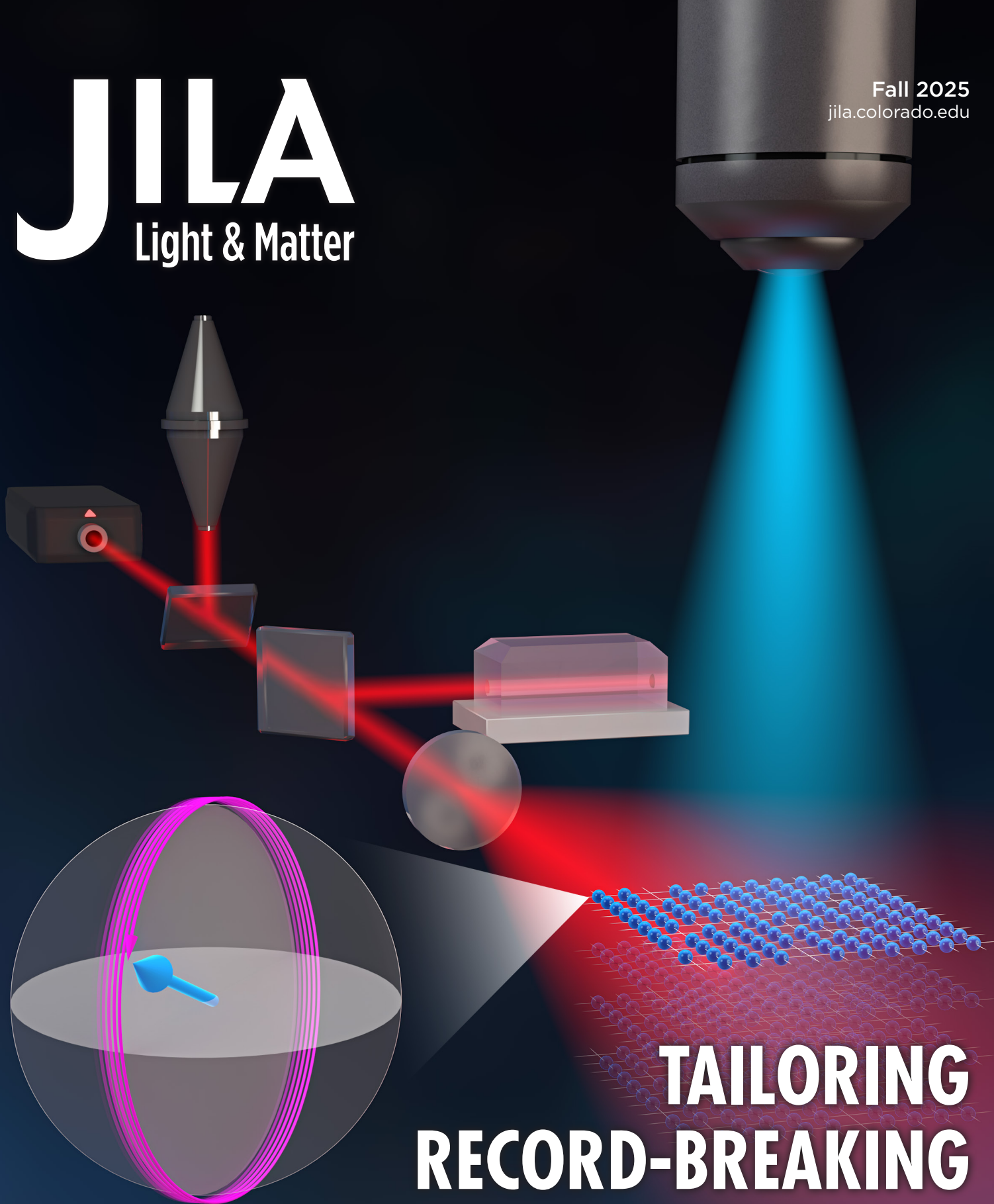




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JILA Light & Matter is published quarterly by the Scientific Communications Office at **JILA**, a joint institute of the **University of Colorado** and the **National Institute of Standards and Technology**.

Steven Burrows | Design, Production & Artwork



Second JAGS Industry Spotlight Seminar shines light on neutral atom computing

On Wednesday, May 14th, over 115 students, postdoctoral researchers, staff, research scientists, and principal investigators attended the second Industry Spotlight Seminar, surpassing the record-breaking attendance from the inaugural event in this series the month prior. This seminar, hosted by JAGS, featured two current employees (and former JILAns) from Atom Computing, a Colorado quantum computing company founded in 2018 by JILA alumni and former Ye group member, Dr. Benjamin Bloom. Like the first Industry Spotlight Seminar, attendees came from JILA, NIST, the University of Colorado Boulder's Physics and Engineering departments, and other departments at the university.

Two former JILAns, Dr. Matthew Norcia, the Director of Quantum Engineering, and Dr. William Cairncross, the Quantum Engineering Manager, both now at Atom Computing, spoke with students and postdoctoral researchers at the event. Dr. Norcia presented the seminar, which included both an overview of the company and a technical presentation about neutral atom quantum computing. Atom Computing uses the nuclear spin of 171-Ytterbium atoms as qubits in their quantum computer, holding the record for the largest neutral atom computer at 1,225 qubits.

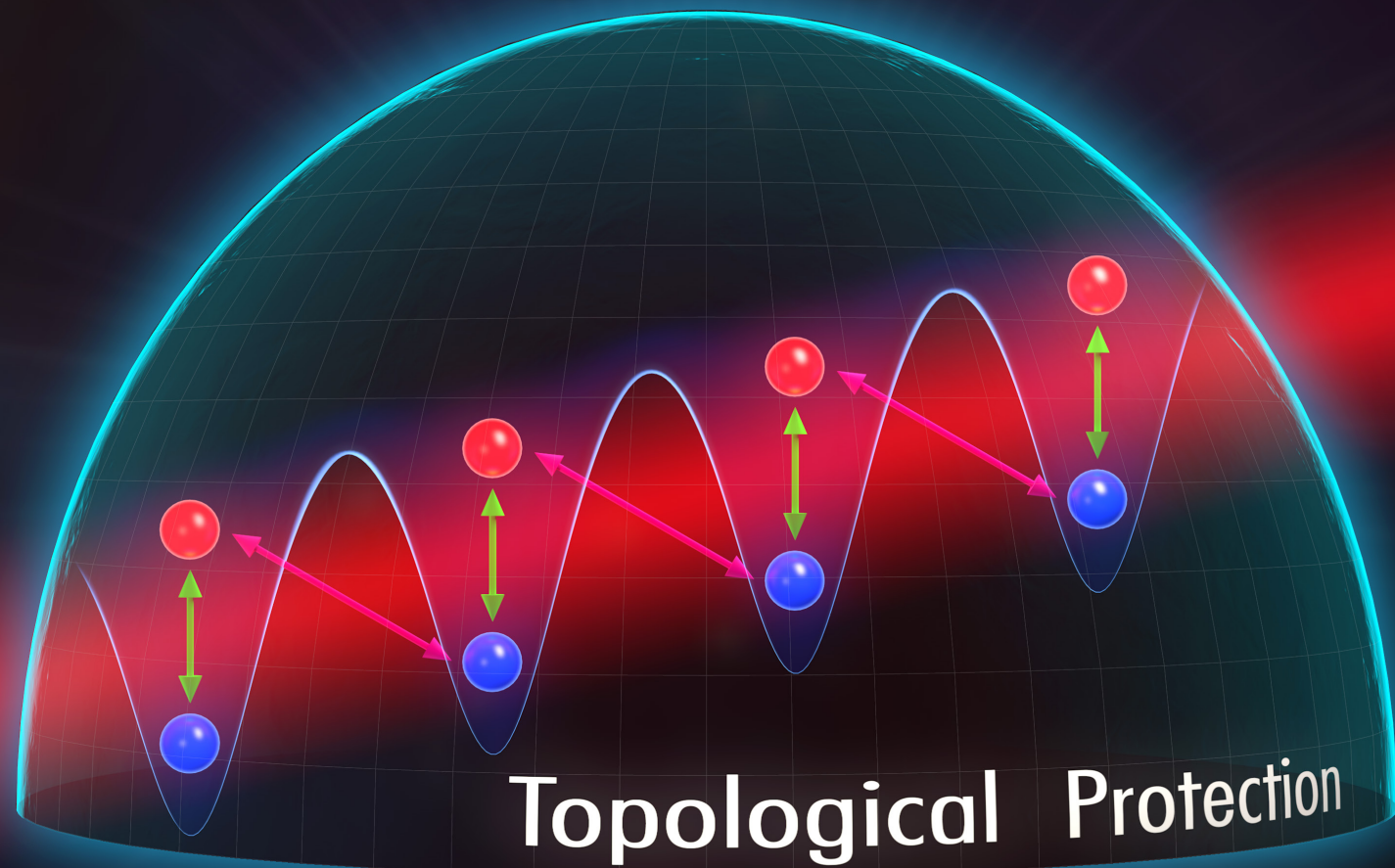
The goal of the JAGS Industry Spotlight Seminar series is to connect graduate students and postdoctoral researchers with Colorado industries, so they can learn about cutting-edge industry research and local job opportunities. Along with their participation in this seminar, Atom Computing donated funds to support a JAGS Graduate Student Seminar, a seminar series enabling graduate students to hone their presentation skills and foster collaboration across various research areas.

When asked about the seminar, Dr. Norcia said, "It was great to be back at JILA, and very valuable for Atom Computing to have a chance to engage with the research community at JILA."

Written by Emma Nelson, JILA graduate student



Smoother Ticking Through Topology



Imagine walking a tightrope in a windstorm. Every gust threatens to knock you off balance. Now imagine that the rope itself is designed in such a way that it naturally resists the wind, keeping you steady even when conditions are less than ideal. That's the kind of protection topological physics offers to quantum systems.

In the world of atomic clocks, the "tightrope" is the delicate quantum state of atoms trapped in a lattice of laser light. These states are exquisitely sensitive to time and frequency, which is what makes optical lattice clocks so precise. But they're also vulnerable to noise—tiny fluctuations in laser in-

tensity, temperature, or magnetic fields can nudge the atoms off their ideal path, degrading the clock's performance.

The new study, led by JILA postdoctoral researchers Tianrui Xu and Anjun Chu of Ana Maria Rey's group, together with postdoc Kyungtae Kim of Jun Ye's group, and in collaboration with James Thompson and JILA visiting Fellow Tillman Esslinger, proposes a way to stabilize these quantum states using the principles of topological phases of matter, a branch of physics that deals with properties that remain unchanged under continuous deformations. In these systems, the quantum states are 'knotted' in its quasimomentum space. Such

'knotting', quantified by the 'topological invariants' of the wavefunctions, remains constant even when the system is perturbed in ways that it does not change the global symmetry of the system.

Rey explains, "While discovering topological phases has been a big deal in condensed matter and atomic physics, what could be even more exciting is figuring out how these systems can help us build better sensors. For example, the quantum Hall effect, a topological state, has already been super useful—it has helped us measure the Hall resistance with incredible precision, which in turn lets us pin down constants like the fine-structure constant and even the elementary electron charge with great accuracy. Right now, atomic clocks are limited by laser noise. Even when we do clever tricks like comparing two clocks at once, we are still not hitting the theoretical limit of how precise they should be. So, the question is, can we use topology to improve state-of-the art clocks? This was the main question we tried to answer, and we found out that indeed it is possible."

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From Quantum Simulation to Quantum Sensing

Over the past decade, JILA has been at the forefront of both quantum simulation and quantum sensing. In one line of research, scientists use ultracold atoms to simulate exotic phases of matter, such as those found in high-temperature superconductors or topological insulators. In another, they build some of the world's most accurate clocks and sensors, capable of detecting tiny changes in gravity or time dilation across millimeters.

Until now, these two fields have largely developed in parallel. But the new study brings them together, showing that the same topological phases explored in quantum simulators can also enhance the performance of quantum sensors.

At the heart of the proposal is the Su-Schrieffer-Heeger (SSH) model, a simple yet powerful model that provides the essential intuitions of topological phases and phase transitions. Originally developed to describe electrons in polyacetylene,

a type of polymer, the SSH model describes a chain of sites with alternating strong and weak connections, leading to topological edge states and the corresponding topological bulk properties, both protected by symmetry.

JILA researchers propose implementing this model in a one-dimensional optical lattice clock (OLC) tilted by gravity or by an applied force. In this setup, known as Wannier-Stark OLC, atomic tunneling between lattice sites can be controlled by laser drives, as demonstrated by the collaboration of the Rey group and Jun Ye's lab in recent years. In this study, the Rey group proposes to use two laser tones to create a hybrid synthetic lattice

combining atomic internal states and the position of the atoms, leading to a natural realization of the SSH model.

One of the key innovations in the study is a new spectroscopic protocol that leverages the topological properties of the SSH model. In conventional Rabi spectroscopy, atoms are driven between two states using a single laser tone, and the resulting oscillations are used to measure the transition frequency between the two states. However, this method is sensitive to noise in the laser amplitude, which can distort the signal.

In the SSH-based protocol, the resulting dynamics of the atomic wavefunctions under two laser tones depends on the 1D topological invariant of the SSH model known as the winding number—a quantity that is robust against many types of noise.

JILA researchers have shown that the winding number can be measured by tracking the displacement of the atomic wavefunction over time. This protocol can thus in-turn be used as a spectroscopic probe for atomic transition frequencies. Numerical simulations show that this "SSH spectroscopy" is less sensitive to both global and local amplitude noise than the traditional Rabi spectroscopy. In particular, the statistical noise scales more favorably with the number of atoms, suggesting that the protocol could be especially useful in future clocks that interrogate millions of atoms simultaneously.

Measuring Gravity with Quantum Pumps

The study also explores how topological physics can enhance matter-wave interferometry, a technique used to measure forces like gravity by splitting and recombining atomic wave packets. In a typical matter-wave interferometer, atoms are pushed apart using a sequence of laser pulses, allowed to evolve in different gravitational potentials, and then brought back together to measure the accumulated phase difference.

However, imperfections in the laser pulses can introduce errors, limiting the sensitivity of the device. To address this, the Rey group proposes using a technique known as Thouless pumping—an adiabatic process in which particles are transported across a lattice by slowly varying the system’s parameters.

In their proposed “topological pumping protocol,” atoms are adiabatically moved apart and then recombined using a sequence of laser-driven transitions that trace out a topologically-nontrivial path in parameter space. Here, a topological non-trivial path means a trajectory that is robust to changes in system parameters. This method is inherently robust to many types of experimentally-relevant noise and can achieve larger separations with lower uncertainty than conventional pulse sequences.

Simulations show that the topological protocol outperforms traditional methods in terms of both signal strength and noise resilience, especially when the number of atoms is large. This could pave the way for new types of interferometers capable of measuring gravitational gradients or testing fundamental physics with reduced sensitivity to experimental noise.

Topologically Enhanced Clocks

The proposed protocols are designed to be compatible with existing optical lattice clock platforms, such as those developed in Jun Ye’s lab at JILA. These clocks already operate with extraordinary precision—recent experiments have

achieved fractional uncertainties below 10^{-18} —but further improvements are needed to reach the standard quantum limit (SQL), the ultimate sensitivity allowed by quantum mechanics for uncorrelated atoms.

By reducing classical noise, the topological approach offers a practical path toward SQL-limited performance. It also opens the door to new applications, such as measuring gravitational redshifts over even shorter distances or detecting tiny variations in fundamental constants.

Moreover, the study suggests that the same principles could be extended

to more complex systems, including higher-dimensional lattices or atoms with multiple internal states. This could enable the exploration of richer topological phases and their potential benefits for quantum sensing and metrology.

In the quantum world, precision often comes at the cost of fragility. But topology offers a way to have both precision and protection. By embedding topological structures into the architecture of optical lattice clocks, the Rey group has outlined a strategy for making these devices more resilient to noise, more sensitive to signals, and more versatile in their applications.

As JILA researchers continue to refine these protocols and bring them into the lab, we may soon see a new generation of quantum sensors that are not only more accurate, but also more robust, thanks to the hidden geometry of quantum states.

This research was supported by the U.S. Air Force Office of Scientific Research, the U.S. Department of Energy Office of Science, National Quantum Information Science Research Centers, Quantum Systems Accelerator, NIST, NSF, Swiss National Science Foundation, Heising-Simons Foundation, Simons Foundation, and Sloan Foundation.

Written by Steven Burrows, JILA Science Communications Manager

New Quantum Navigation Device uses atoms to measure acceleration in 3D

In a new study, physicists at JILA and the University of Colorado Boulder have used a cloud of atoms chilled down to incredibly cold temperatures to simultaneously measure acceleration in three dimensions—a feat that many scientists didn’t think was possible.

The device, a new type of atom “interferometer,” could one day help people navigate submarines, spacecraft, cars and other vehicles more precisely.

“Traditional atom interferometers can only measure acceleration in a single dimension, but we live within a three-dimensional world,” said Kendall Mehling, a co-author of the new study and a graduate student in the Department of Physics at CU Boulder. “To know where I’m going, and to know where I’ve been, I need to track my acceleration in all three dimensions.”

The researchers published their paper, titled “Vector atom accelerometry in an optical lattice,” this month in the journal *Science Advances*. The team included Mehling; Catie LeDesma, a postdoctoral researcher in physics; and Murray Holland, professor of physics and fellow of JILA, a joint research institute between CU Boulder and the National Institute of Standards and Technology (NIST).

In 2023, NASA awarded the CU Boulder researchers a \$5.5 million grant through the agency’s Quantum Pathways Institute to continue developing the sensor technology.

The new device is a marvel of engineering: Holland and his colleagues employ six lasers as thin as a human hair to pin a cloud of tens of thousands of rubidium atoms in place. Then, with help from artificial intelligence, they manipulate those lasers in complex patterns—allowing the team to measure the behavior of the atoms as they react to small accelerations, like pressing the gas pedal down in your car.

Today, most vehicles track acceleration using GPS and traditional, or “classical,” electronic devices known as accelerometers. The team’s quantum device has a long way to go before it can compete with these tools. But the researchers see a lot of promise for navigation technology based on atoms.

“If you leave a classical sensor out in different environments for years, it will age and decay,” Mehling said. “The springs in your clock will change and warp. Atoms don’t age.”

Fingerprints of Motion

Interferometers, in some form or another, have been around for centuries—and they’ve been used to do everything from transporting information over optical fibers to searching for gravitational waves, or ripples in the fabric of the universe.

The general idea involves splitting things apart and bringing them back together, not unlike unzipping, then zipping back up a jacket.

In laser interferometry, for example, scientists first shine a

laser light, then split it into two, identical beams that travel over two separate paths. Eventually, they bring the beams back together. If the lasers have experienced diverging effects along their journeys, such as gravity acting in different ways, they may not mesh perfectly when they recombine. Put differently, the zipper might get stuck. Researchers can make measurements based on how the two beams, once identical, now interfere with each other—hence the name.

In the current study, the team achieved the same feat, but with atoms instead of light.

Here's how it works: The device currently fits on a bench about the size of an air hockey table. First, the researchers cool a collection of rubidium atoms down to temperatures just a few billionths of a degree above absolute zero.

In that frigid realm, the atoms form a mysterious quantum state of matter known as a Bose-Einstein Condensate (BEC). Carl Wieman, then a physicist at CU Boulder, and Eric Cornell of JILA won a Nobel Prize in 2001 for creating the first BEC.

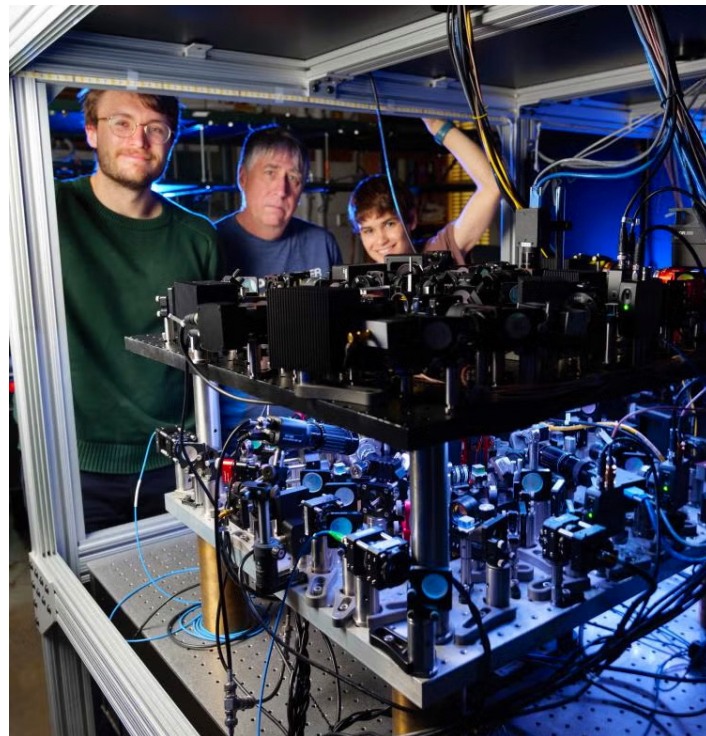
Next, the team uses laser light to jiggle the atoms, splitting them apart. In this case, that doesn't mean that groups of atoms are separating. Instead, each individual atom exists in a ghostly quantum state called a superposition, in which it can be simultaneously in two places at the same time.

When the atoms split and separate, those ghosts travel away from each other following two different paths. (In the current experiment, the researchers didn't actually move the device itself but used lasers to push on the atoms, causing acceleration).

"Our Bose-Einstein Condensate is a matter-wave pond made of atoms, and we throw stones made of little packets of light into the pond, sending ripples both left and right," Holland said. "Once the ripples have spread out, we reflect them and bring them back together where they interfere."

When the atoms snap back together, they form a unique pattern, just like the two beams of laser light zipping together but more complex. The result resembles a thumb print on a glass.

"We can decode that fingerprint and extract the acceleration that the atoms experienced," Holland said.



Planning with computers

The group spent almost three years building the device to achieve this feat.

"For what it is, the current experimental device is incredibly compact. Even though we have 18 laser beams passing through the vacuum system that contains our atom cloud, the entire experiment is small enough that we could deploy in the field one day," LeDesma said.

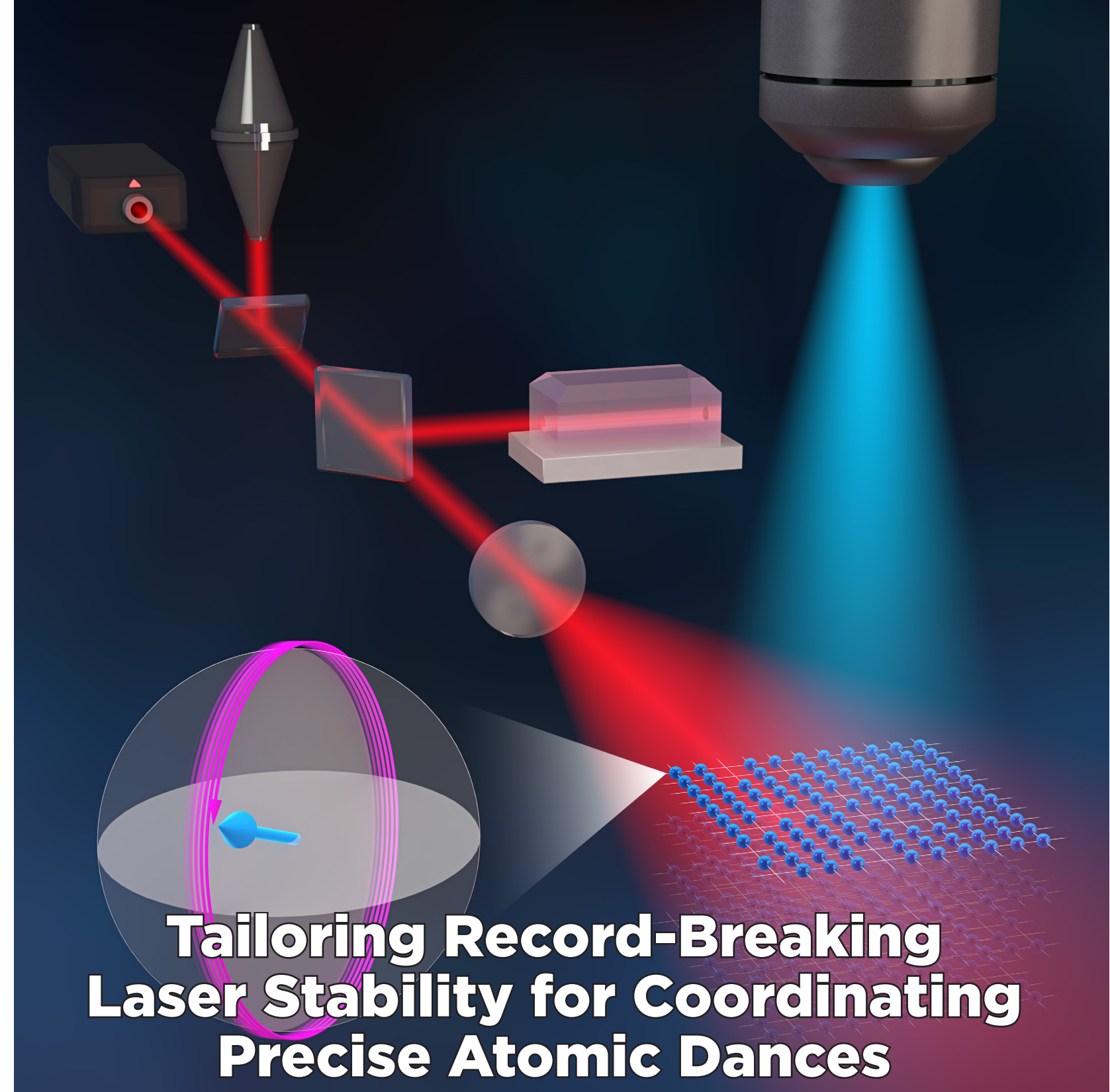
One of the secrets to that success comes down to an artificial intelligence technique called machine learning. Holland explained that splitting and recombining the rubidium atoms requires adjusting the lasers through a complex, multi-step process. To streamline the process, the group trained a computer program that can plan out those moves in advance.

So far, the device can only measure accelerations several thousand times smaller than the force of Earth's gravity. Currently available technologies can do a lot better.

But the group is continuing to improve its engineering and hopes to increase the performance of its quantum device many times over in the coming years. Still, the technology is a testament to just how useful atoms can be.

"We're not exactly sure of all the possible ramifications of this research, because it opens up a door," Holland said.

Written by Daniel Strain, CU Boulder



Light is incredibly useful in daily life. We use light to see objects and determine details about them. Light is similarly valuable in probing the quantum world. It is often critical for both observing quantum objects and interacting with them.

When scientists need to precisely control atoms or molecules, light is often the only tool for the job. Selecting the correct frequency—color—of laser light and projecting it in

the right configuration allows scientists to detect, trap, and even manipulate individual quantum particles.

However, keeping a laser stable at the right frequency is challenging. Even the most stable lasers randomly shift to slightly different frequencies and experience noise—random spurts of different frequencies similar to static on a radio signal. This frequency noise is currently one of the main limitations

of lasers in many experiments. As researchers improve lasers, the improvements reliably produce better experiments and technologies, including more precise atomic clocks and quantum computers that experience fewer errors.

“Every quantum scientist dreams of having a laser that can keep driving quantum systems without introducing errors,” says Lingfeng Yan, a graduate student at JILA.

A team of researchers, led by JILA and National Institute of Standards and Technology Fellow and University of Colorado Boulder Physics professor Jun Ye, took on the challenge of tailoring a laser system to an unprecedented level of stability and showing the improvements it could deliver for practical applications. Achieving this new level of stability required them to make multiple lasers work together.

In an article published in the journal *Physical Review X* on August 26, 2025, they described their laser setup and showing the improvements it could deliver for practical applications. They showed that the laser delivered practical advantages by putting many neutral atoms through their paces working as a qubit—the basic building block of a quantum computer—and achieving an unprecedented low error rate for the particular design of qubit used.

The bespoke laser was needed because lasers aren’t all equal. Even with the best available designs, lasers of some colors are more stable than others in particular situations, and it’s impossible for any particular laser to do every job.

Fortunately, researchers can impart the stability of one laser onto another. It is like a dance teacher who has one student who is perfect at keeping their timing no matter how long the dance and another who is great at performing the necessary steps but frequently speeds up or

slows down randomly. The teacher pairs them up, and whenever they notice the student messing up, they remind them to follow the lead of their partner. Properly directed, the group exceeds the performance of the individuals.

The group has access to a laser that can stay stable for extended periods—a prima ballerina. The researchers decided to test how well they could do at transferring its stability to a less stable dancer—specifically a laser compatible with altering the quantum states of strontium atoms. Such lasers

are used to manipulate strontium in certain atomic clocks and quantum computers.

The lab’s stable dancer was a laser cavity made from a silicon crystal. The crystal’s rigidity makes it very stable over extended

periods of time, but it must be kept at frigid temperatures to not be negatively impacted by temperature fluctuations.

“It is one of the best lasers in the world,” says Yan, who is the first author of the paper. “It provides an excellent long-term stability, but it’s a specialized cavity.”

The specialized design means it is expensive and works for just a specific set frequency. So, to get similar performance at other frequencies, the team needed to become dance instructors and get other lasers to follow the silicon cavity’s lead over the long term.

Unfortunately, you can’t just yell dance instructions to a laser. The researchers had to use a specialized tool, called a

frequency comb, to coordinate their lasers. A frequency comb is a device that, instead of producing a single laser beam, produces many precise, evenly spaced frequencies of light.

The regular spacing makes frequency combs ruler-like tools for comparing different lasers and maintaining the frequency spacing between them.

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“It is one of the best lasers in the world,” says Yan. “It provides an excellent long-term stability, but it’s a specialized cavity.”

However, even with the silicon cavity and frequency comb in the loop, the final beam would still experience high-frequency noise that would impair its use. This is largely because even the silicon cavity contributes a little noise, including some introduced by vibrations from the necessary cooling equipment.

To tamp down this residual noise, the researchers added another cavity to the dance: a simpler cavity that operated at the same laser frequency used to manipulate the strontium atoms. The second cavity is less stable over long times but doesn’t need to be cooled and therefore doesn’t experience the remaining troublesome noise over shorter periods. This second cavity handled suppressing their high-frequency noise issues while letting the silicon cavity steer the frequency over the long term.

The team carefully coordinated the appropriate set of correction procedures and technological connections between the two cavities, the optical frequency comb and the final laser, but that was just the beginning. The group still needed to confirm if their laser setup worked as intended. Was the meticulously tailored custom laser actually stable and could it deliver improved results?

The team created a test for themselves: Shining the laser at strontium atoms. The atoms’ sensitivity to specific light frequencies made them a precision tool for checking exactly how the laser was behaving. The researchers essentially turned the atoms into a tool for measuring the laser-frequency noise of the laser.

In the test, the strontium atoms reacted to subtle fluctuations in the light and could catch details that are otherwise easily missed. For example, during one test, they discovered an unexpected spike in the noise despite the laser seeming to run correctly. They discovered the noise was because a device designed to prevent the silicon cavity from vibrating had accidentally been turned off.

“What we trust most are measurements of the atomic re-

sponse,” says Max Frankel, a graduate student at JILA and a co-author of the paper. “Atomic measurement should have the final word on our laser frequency noise model.”

Their test confirmed that their new setup delivered the improved performance they had predicted. Then, they moved on to demonstrating the practical advantage of all their effort by using the laser to make the atoms perform as qubits in a standardized test.

Using the stabilized laser, they performed strings of many gates—the basic operations of quantum computers—on each of 3000 qubits. They used gates that essentially signal an atom’s quantum state to spin around to various positions, which physicists call performing state rotations. Then, the researchers performed the gate that should reverse the whole string of operations. As long as noise didn’t interfere, the la-

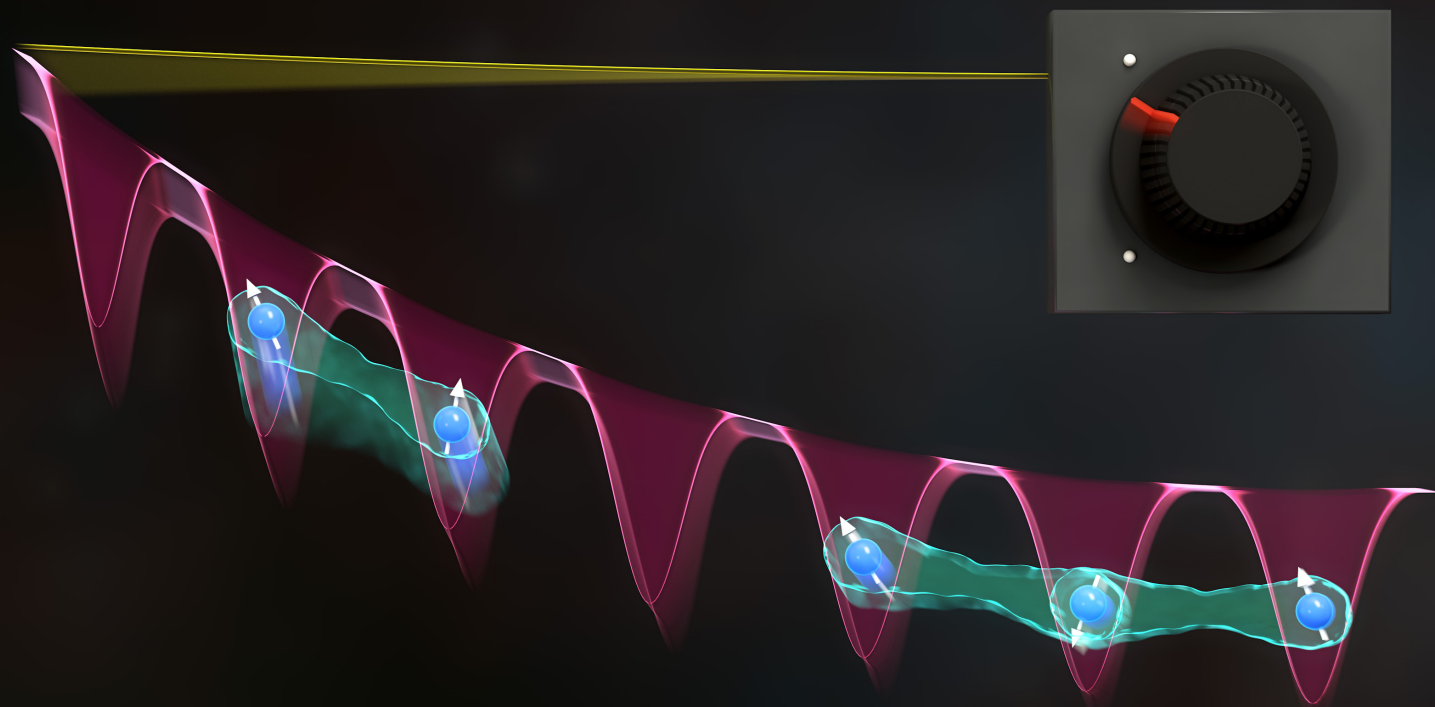
ser guided all the qubits through the set of steps to the same final position. By analyzing how well the qubits returned to their initial state over many runs, the researchers determined how reliably the laser executed the gates on average. They established a new record for the

fidelity achieved using a laser to optically manipulate neutral atoms to perform state rotations.

The results of their test also match well with their model of the laser noise, which they say suggest that further laser improvements will likely deliver even better results. The team says that other researchers should be able to use the same techniques to tailor lasers with different frequencies to have similar refined stability.

“Lasers are central to manipulating quantum systems, which are very sensitive to imperfections, so improving lasers benefits scientists and engineers all over the world.” says Stefan Lannig, a JILA postdoctoral researcher and co-author of the paper. “To benefit from many ideas put forward by modern science, we need to enhance our control over intricate quantum systems, which requires first improving our tools.”

Written by Bailey Bedford, Freelance Science Communicator



The Pursuit of Perfect Timekeeping

Understanding Superexchange Interactions in Atomic Clocks

The challenge of creating the world’s most precise clock is that even the slightest deviations limit the precision. Atomic clocks, which rely on the coherent evolution of atomic states, are the most accurate timekeeping devices known to humanity. However, achieving this level of precision requires a deep understanding of the interactions between atoms, especially as many atoms are packed in a dense ensemble to increase the signal strength.

In a recent study published in *Science*, by JILA and NIST Fellows and University of Colorado Boulder physics professors Jun Ye and Ana Maria Rey, interactions between atoms are explored in depth, focusing on superexchange processes that occur in a three-dimensional optical lattice.

The Role of Superexchange Interactions

Superexchange interactions are second-order tunneling processes between nearest neighbor atomic spins. These interactions are central to understanding magnetic phenomena such as antiferromagnetism and superconductivity. In the context of atomic clocks, superexchange interactions can influence the coherence time and precision of the clock.

To grasp the concept of superexchange, consider a relay race where the baton is passed through several intermediaries before reaching the final runner. Similarly, in superexchange interactions, atoms exchange spins through virtual tunneling processes, leading to coherent spin dynamics. This interaction is ordinarily quite weak, and would have been ignored had the researchers not been pursuing the best possible clock precision.

In the study, researchers used a degenerate Fermi gas of nuclear spin-polarized ^{87}Sr atoms loaded into a three-dimensional optical lattice. By tuning the lattice confinement and applying imaging spectroscopy, they mapped out favorable atomic coherence regimes. The clock laser prepared each atom in a coherent superposition of the two electronic states, which can be considered as a pseudo-half spin. The propagation effect of the clock laser introduced a spin-orbit coupling phase, transforming the Heisenberg spin model into one with XXZ-type spin anisotropy.

William Milner, first author on the paper, explains, “You want to use as many atoms as possible and get the best precision.

As you pack them into this 3D lattice, they can start to interact. These atoms can talk to each other, so you can no longer think of them as isolated atoms.”

The experimental setup involved a highly filled Sr 3D lattice, where atoms were confined in the ground band of the lattice. The researchers employed Ramsey spectroscopy to measure atomic coherence and observe superexchange interactions. This technique allowed them to directly probe the coherent nature of superexchange interactions over timescales of multiple seconds.

Balancing Interactions

One of the key findings was the identification of regimes where atomic coherence is maximized. By varying the lattice confinement, researchers observed how both s- and p-wave interactions contribute to decoherence and atom loss. These interactions can be balanced to achieve optimal coherence times, which are crucial for the precision of optical lattice clocks. Imagine balancing a seesaw with two children of different weights. To achieve equilibrium, you need to adjust their positions carefully. Similarly, in the optical lattice, researchers balanced s- and p-wave interactions to minimize decoherence.

However, at deep transverse confinement, coherent superexchange interactions were directly observed, tunable via on-site interaction and site-to-site energy shift. Milner elaborates, “In this regime is where you get these superexchange interactions. These higher order interactions occur because the atoms can’t move around, but they can virtually jump onto a site and then jump back, with spin exchanged.”

The study provided direct observations of superexchange dynamics, which were manifested in oscillations of the Ramsey fringe contrast persisting over a timescale of several seconds. These observations were well captured by an anisotropic lattice spin model, breaking the Heisenberg $\text{SU}(2)$ symmetry due to the spin-orbital coupling phase. Additionally, the experiments showed the direct tunability of the interactions via lattice strength and potential gradients.

Enhancing Clock Performance

Optical lattice clocks are advancing the fields of fundamental physics, metrology, and quantum simulation. By controlling superexchange interactions, researchers can enhance the performance of these clocks, leading to more precise time-

keeping and new insights into quantum magnetism and spin entanglement.

Just as a finely tuned orchestra produces a flawless performance, a well-controlled optical lattice clock can achieve unprecedented precision. The experiment demonstrated that by tuning the lattice confinement and controlling superexchange interactions, researchers can optimize the coherence time of the clock. This has the potential to further advance timekeeping and enable new applications in quantum technologies.

Milner notes, “By changing the confinement, you can make it so these superexchange interactions are very small and pretty much negligible. On the other hand, there’s promise that you can use these interactions to create entangled states, which should give you even better precision.”

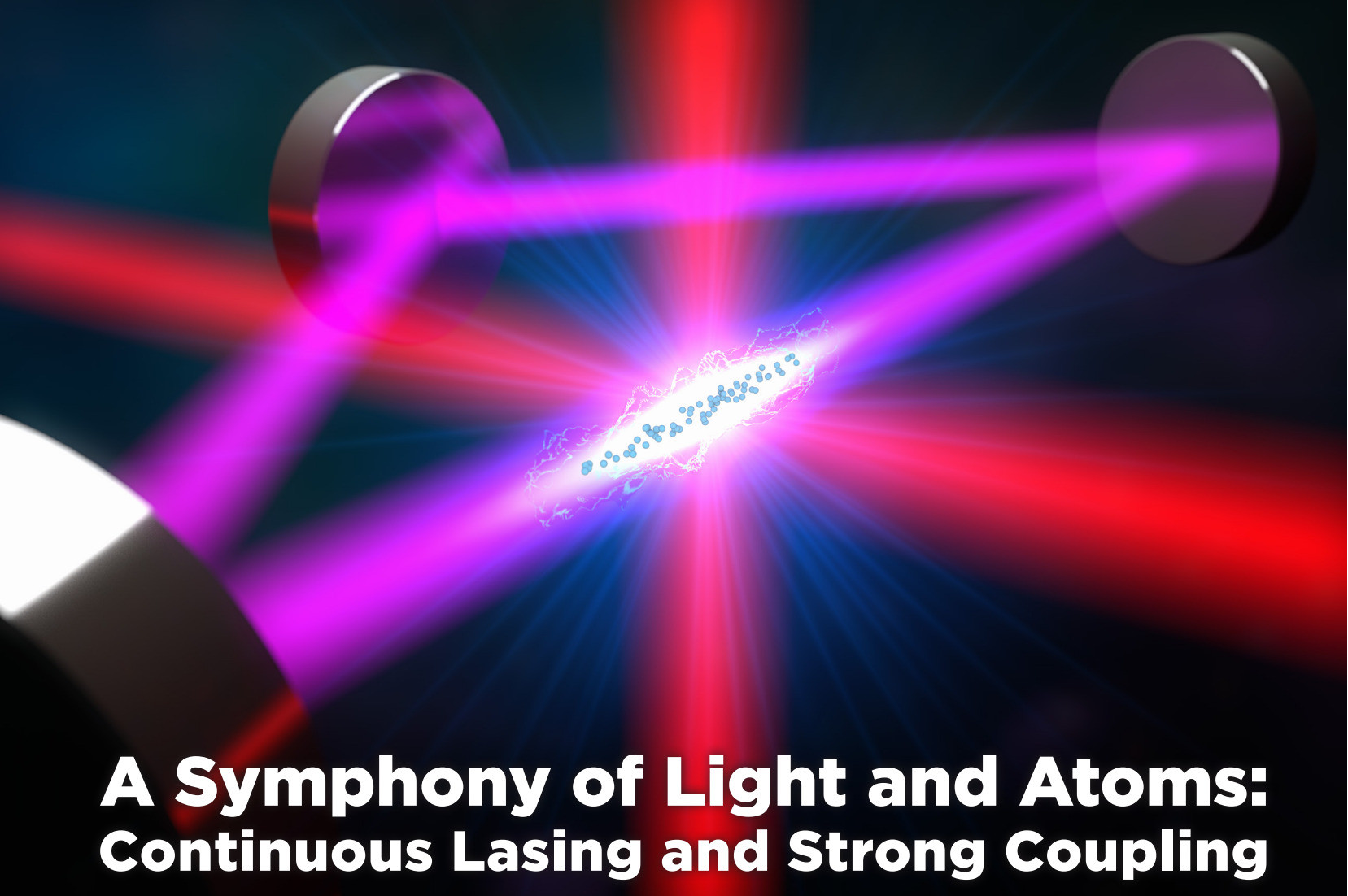
Stefan Lannig, a postdoc in the Ye group, adds, “We want to trap the atoms in the 3D lattice to get the highest atom number for the best precision, but in a sample as small as possible. This helps us get rid of background effects and achieve optimal performance.”

Looking ahead, the research opens new avenues for exploring quantum magnetism and spin entanglement using optical lattice clocks. By leveraging the coherent nature of superexchange interactions, scientists can probe deeper into the quantum dynamics of many-body systems. This could lead to breakthroughs in understanding fundamental physics and developing advanced quantum technologies.

This study by the Ye group represents a significant step forward in the field of atomic clocks and quantum metrology. By unraveling the complexities of superexchange interactions, researchers have laid the groundwork for enhancing the precision and performance of optical lattice clocks. Researchers at JILA are orchestrating the interactions of atoms to unlock the secrets of time itself, pushing the boundaries of what is possible in the quest for perfect timekeeping.

This research is supported by U.S. Department of Energy Center of Quantum System Accelerator, National Science Foundation QLCI, JILA Physics Frontier Center, V. Bush Fellowship, and NIST.

Written by Steven Burrows, JILA Science Communications Manager



A Symphony of Light and Atoms: Continuous Lasing and Strong Coupling

Imagine a symphony that never stops. The musicians are atoms, the concert hall that lets their sound build is an optical cavity, and the skilled conductor is a new continuous loading with strong coupling technique—keeping perfect time, seating new players quietly mid-performance, and blending everyone into one steady, pure tone. The ‘music’ you hear is the single, coherent laser beam emerging from the cavity.

In this experiment, supporting laser beams cool and move the atoms—think of them as the metronome and stage crew, not the performance itself. The performance is the new light the atoms collectively create inside the ring cavity, which then exits as a continuous laser. With this conductor-like control, Professor James K. Thompson, a Fellow of JILA, NIST and the Department of Physics at the University of Colorado, Boulder, and his team, maintain both continuous operation and strong collective coupling between the atoms and the cavity, a key step toward ultra-stable light sources and precision measurement tools.

In a set of papers, published in *Nature Physics* and *Physical*

Review Letters, the Thompson group demonstrated continuous loading and strong coupling of strontium atoms to a high-finesse optical ring cavity, and continuous recoil-driven lasing with an unexpected pinning of the cavity frequency.

Vera Schäfer, one of the lead researchers, explained, “The original goal of our experiment was to build a continuous superradiant laser, a tool which allows us to make high precision frequency measurements at short timescales. This could help us to explore different regimes to search for dark matter and other new physics.”

Zhijiang Niu, the graduate student noted, “We managed to realize continuous laser cooling of strontium atoms into an optical ring cavity and to transport them within the cavity. This allowed us to keep a steady stream of extremely cold atoms, which is essential for building a continuous superradiant laser.”

Thompson added, “But along the way we found something very curious and unexpected that reflects the fact that nature has a way of self-organizing when you pump energy into a

system. We saw laser light coming out of our system when we were just trying to load a very cold gas of atoms between the highly reflective mirrors that form our laser cavity.”

Continuous Lasing: Quantum Light Sources

Lasing, or light amplification by stimulated emission of radiation, is a process familiar to many through everyday devices like laser pointers and barcode scanners. Past lasing realized with laser-cooled atoms often involve pulsed operation, where the light source is intermittently active. In contrast, continuous lasing provides a steady stream of coherent light, which is crucial for applications requiring high stability and precision.

The researchers utilized laser-cooled strontium atoms, which were continuously loaded into a high-finesse ring cavity. This setup allowed for the atoms to be trapped and cooled using a series of laser cooling stages, including a three-dimensional red molasses and a vertical slowing beam. The continuous nature of this process ensures that atoms continuously replenished, crucial for sustained lasing.

Niu explained, “We have figured out how to laser cool and load our atoms continuously rather than staggered in time like almost all other experiments in our field do (i.e., cool and load some atoms, briefly do some science, throw them away, repeat).” Thompson added, “However, even before getting a chance to use the very narrow atomic transition, we saw laser light coming out of the cavity, and it would keep going all day long until we went home for the day!”

Recoil-Driven Lasing: The Heartbeat of Quantum Light

To understand recoil-driven lasing, think of a game of pool. When the cue ball strikes another ball, it transfers its momentum, causing the second ball to move. Similarly, in recoil-driven lasing, photons (light particles) transfer their momentum to atoms, causing them to move more quickly. This movement creates a population inversion, a key requirement for lasing.

In traditional lasers, achieving population inversion often involves complex setups and intermittent operation. However, the researchers at JILA have developed a method to maintain this inversion continuously. By using laser-cooled strontium atoms and a high-finesse ring cavity, they have created a system where the atoms are constantly replenished and kept in a low-energy state. This continuous replenishment ensures

that the lasing process never stops.

Thompson noted, “We realized that the lasing involved absorbing a photon and then undergoing stimulated emission (the s and e of LASER) to a different momentum state since the atom recoils when it catches a photon of light and then throws it into the cavity.” Niu added, “This appears to be the gain mechanism provided by nature when we put energy into the system via our laser-cooling beams.”

Strong Collective Coupling: Enhancing Atom-Cavity Interactions

In addition to continuous lasing, the study also achieved strong collective coupling of strontium atoms to the optical cavity. This phenomenon occurs when the collective interaction between the atoms and the cavity field is strong enough to significantly alter the properties of the system. The researchers demonstrated this by observing continuous atom-cavity vacuum Rabi splitting, a clear indication of strong coupling. This effect is akin to a dance where the atoms and the cavity photons are in perfect sync, leading to new and exciting quantum behaviors.

Schäfer highlighted, “A lot of the physics we saw only happens because this is a continuous rather than a cyclic experiment. The most interesting lasing regime only appears when starting in a noisier state, and then slowly changing the cavity parameters to a less stable regime that is only upheld by the continuous lasing.”

Cavity Frequency Pinning: Stabilizing the Quantum Orchestra

One of the challenges in maintaining continuous lasing and strong coupling is the sensitivity of the system to external disturbances. Any fluctuation in the cavity frequency can disrupt the delicate balance, much like a sudden noise can throw an orchestra off-key. To address this, the researchers discovered a new mechanism that pins or stabilizes the resonance frequency of the cavity. Schäfer notes, “[we] found out that without us even trying, this lasing mechanism stabilized the effective frequency of our cavity.”

Cavity frequency pinning involves stabilizing the frequency of the dressed cavity mode to match the frequency at which there is gain for light inside the cavity. This is achieved through an atomic loss mechanism that adjusts the number of atoms in the cavity based on the lasing intensity. When the cavity

frequency drifts, the system automatically compensates by altering the atom number, keeping the cavity frequency and hence the lasing frequency stable.

“This gain mechanism also causes atom-heating which then causes a funny feedback loop that keeps the effective optical cavity frequency to a fixed value, even when we tried our darndest to change the cavity frequency,” Thompson explained.

The Future is in Narrow Linewidths

The continuous lasing and strong collective coupling achieved in this study represent an important milestone in laser and quantum science. These advancements not only enhance our understanding of fundamental quantum interactions but also open the door to a wide range of practical applications.

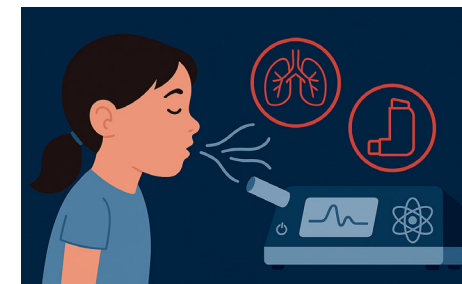
Thompson shared their next steps, “Many different groups in atomic and laser physics are moving towards continuous rather than cyclical operation, whether it be for quantum computing or for ultranarrow linewidth lasers. We plan to re-

ally use the narrow linewidth transition in strontium to build incredibly single-color lasers to explore the world.”

Soon, this technology could lead to the development of ultra-stable superradiant lasers with millihertz linewidths, which are crucial for high-precision measurements and tests of fundamental physics. Additionally, the techniques developed in this study could be applied to create new quantum sensors and devices that leverage the unique properties of continuous atom-cavity interactions. By orchestrating a tightly synchronized ensemble of atoms and light under conductor-like control, researchers are not only pushing the boundaries of what’s possible but also laying the groundwork for the next generation of quantum technologies.

This research is supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Systems Accelerator, the National Science Foundation JILA Physics Frontier Center and Q-SEnSE QLCI, and the Humboldt Foundation.

Written by Steven Burrows, JILA Science Communications Manager



Jun Ye Awarded 2025 AB Nexus Grant for Quantum-Focused Research Collaborations

JILA and NIST Fellow and University of Colorado Boulder physics professor Jun Ye has been awarded a prestigious 2025 AB Nexus seed grant for his pioneering work in quantum sensing technologies. The grant, part of a \$750,000 funding initiative supporting interdisciplinary research between CU Boulder and the CU Anschutz Medical Campus, will help Ye and his collaborators develop a revolutionary breath test to diagnose respiratory illnesses in children.

Partnering with Dr. Lilliam Ambroggio of CU Anschutz, Ye’s team is harnessing the precision of quantum optics and advanced laser systems to analyze molecular signatures in exhaled breath. The goal: to rapidly and non-invasively distinguish between bacterial pneumonia, viral infections, and asthma—conditions that often present similarly but require vastly different treatments.

The project exemplifies the mission of AB Nexus, which was launched in 2020 to foster cross-campus collaborations that tackle complex health challenges. This year’s grant cycle emphasized quantum-enabled health research and support for early-career investigators. Ye’s project was one of two quantum-focused initiatives selected for \$300,000 in seed funding.

Ye’s work continues JILA’s tradition of

applying fundamental physics to real-world challenges. If successful, the breath test could eventually be adapted into portable devices for clinical use, offering a powerful new tool for pediatric care.



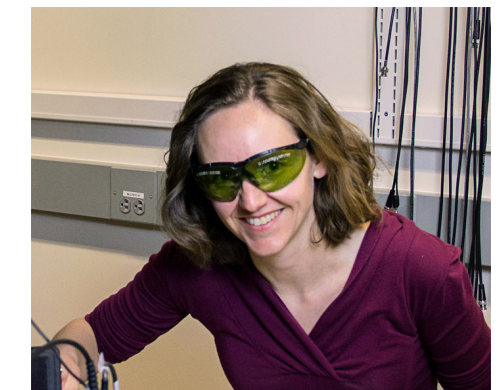
Dr. Surya Pratap Deopa Wins 2025 BioFrontiers Outstanding Contribution Award

JILA is proud to announce that Dr. Surya Pratap Deopa, Postdoctoral Fellow in the lab of JILA Fellow and MCDB Professor Tom Perkins, has been honored with the 2025 BioFrontiers Outstanding Contribution Award. This prestigious recognition celebrates Dr. Deopa’s impactful research contributions within the BioFrontiers community.

Dr. Deopa was recognized for his innovative technical advances that revitalized a previously stalled research project, significantly enhancing both the data quality and throughput of cutting-edge atomic force microscopy (AFM) experiments. His work has not only pushed the boundaries of experimental precision but also established molecular dynamics simulations as a powerful computational companion to AFM measurement interpretation.

Beyond his technical achievements, Dr. Deopa has distinguished himself as a generous and collaborative colleague, contributing meaningfully through both formal partnerships and informal scientific exchanges. His dedication to fostering a supportive and productive research environment exemplifies the values of the BioFrontiers Institute.

As part of the award, Dr. Deopa receives a certificate of appreciation and a \$1,000 prize in recognition of his outstanding contributions.



Cindy Regal Named 2025 Brown Investigator for Pioneering Quantum Research

Cindy Regal, University of Colorado Boulder Physics Professor and Baur-SPIE Chair at JILA, has been named a 2025 Brown Investigator by the Brown Institute for Basic Sciences at Caltech.

The Brown Institute for Basic Sciences was established in 2023 through a transformative \$400 million gift from Caltech alumnus Ross M. Brown. The institute supports fundamental research with the potential to seed long-term breakthroughs in chemistry and physics.

“Mid-career faculty are at a time in their careers when they are poised and prepared to make profound contributions to their fields,” Brown says, “My continuing hope is that the resources provided

JILA NEWS & AWARDS



JILA Welcomes Dr. Taeho Ryu as New Associate Fellow

JILA is delighted to welcome Dr. Taeho Ryu as an Associate Fellow and Assistant Professor in the Department of Astrophysical and Planetary Sciences at

the University of Colorado Boulder.

Dr. Ryu brings an interdisciplinary approach to theoretical astrophysics, with a research portfolio that spans the complex interactions between stars and black holes, the formation and evolution of dense stellar clusters, and the observational signatures of transient astrophysical phenomena. His work is deeply rooted in multi-messenger astronomy, exploring phenomena such as tidal disruption events, stellar collisions, and gravitational wave sources.

His recent efforts have focused on advancing our understanding of transient formation mechanisms beyond conventional models, particularly in environments shaped by complex gravitational

interactions.

Before joining CU Boulder and JILA, Dr. Ryu held a fellowship at the Max Planck Institute for Astrophysics in Garching, Germany. He earned his undergraduate degrees in Chemistry and Physics from Seoul National University, received a PhD from Stony Brook University, and completed his postdoc at Johns Hopkins University.

Outside of academia, Dr. Ryu is a passionate musician, tennis player, and snowboarder.

We are thrilled to have Dr. Ryu join the JILA community and look forward to the exciting contributions he will make to our understanding of the transient universe.

by the Brown Investigator Awards will allow them to pursue riskier innovative ideas that extend beyond their existing research efforts and align with new or developing passions, especially during this time of funding uncertainty.”

Regal is one of eight recipients selected this year, and she will receive up to \$2 million over five years to support her groundbreaking work in quantum physics.

Regal said the Brown Investigator Award is a thrilling opportunity for her research group. “The Brown Institute’s focus on fundamental and risky studies will allow us to explore quantum mechanical phenomena in a regime that is enticing to physicists and for future impact, yet also exceedingly difficult to achieve in the laboratory,” she said, adding:

“We are keen to try a new concept in precision optical measurement and control that we hypothesize will generate quantum states in ever-larger and more tangible mechanical excitations. These explorations would not be possible to embark on without the unique resources provided to Brown Investigators.”

Her research focuses on the fundamental nature of quantum entanglement—a phenomenon where particles become interconnected such that the state of one instantly influences the state of another, regardless of distance. Her Brown Investigator project aims to push the boundaries of this phenomenon by demonstrating entanglement in objects with greater mass than ever before.

Regal joins a distinguished cohort of scientists from institutions including Princeton, Cornell, and the University

of Chicago. Her selection underscores JILA’s continued leadership in quantum science and its commitment to advancing knowledge at the frontiers of physics.



Thi Hoang emerges victorious at the inaugural Quantum Science Slam at CLEO 2025

In a thrilling display of scientific communication and creativity, Thi Hoang, a graduate student at JILA, emerged victorious at the inaugural Quantum Science Slam held during the Conference on Lasers and Electro-Optics (CLEO) 2025. This new event, celebrating 100 Years of Quantum, designed to bring cutting-edge science to life for a broader audience, saw participants deliver engaging and entertaining 10-minute presentations on their research.

Hoang captivated the audience with her presentation One, Two, Three Photons—shedding light onto the quantum world and quantum technology, one photon at a time. She discussed the development of our understanding of light, from rays of light to light as coherent waves that can be created through laser, along with all the technologies that this knowledge has rewarded us with.

“Now in our research, we are looking at the next big understanding of light as discrete particles called photons. To study and learn more about how we can leverage this quantum nature of light,

we are working to build a bright and reliable single photon source. The fact that we are now able to create, count, and manipulate photons one by one (out of trillions in a room at a turn of a switch!) is an amazing feat that, I sure hope, will unlock new understandings and even more technologies we have yet to discover,” Hoang summarized.

The Quantum Science Slam, a highlight of this year’s CLEO, aimed to make the audience think, laugh, and learn simultaneously. Hoang’s ability to explain her complex quantum research in an accessible and humorous manner won over the crowd, who ultimately decided the winner through audience voting. Her victory earned her a \$1,000 cash prize and the prestigious title of Science Slam Champion.

Thi Hoang’s achievement is a testament to the importance of making science accessible and engaging. Her success at the Quantum Science Slam highlights the growing recognition of the need for scientists to communicate their work effectively to a broader audience.



Sun Group becomes 2025 JILA Cup Champions

Exciting news for those following the JILA Cup! After a hard-fought and thrilling match, The Sun group emerged victorious and claimed the title of JILA Cup Champions!



Humans of JILA: Lane Terry

Though many within JILA’s community approach our understanding of the universe through a physics lens, graduate student Lane Terry applies a chemist’s perspective. In the laboratory of JILA fellow Mathias Weber, Terry uses cryogenic ion vibrational spectroscopy to isolate and probe molecular ions, revealing unique characteristics.

Already well on her way to earning her doctorate in the fall of 2025, Terry has been thinking about a PhD for as long as she can remember. Growing up, interest in science wasn’t just encouraged for Terry, but a foundation of her childhood. Having a nuclear physicist father, family vacations didn’t take her to beaches, but to laboratory tours and museums.

“I have a picture of myself, when I was maybe 7 years, old posing with Fat Man and Little Boy,” Terry elaborates, referring to the atomic bombs developed in the Manhattan Project. “My sister was looking into Little Boy and I was striking a dance pose in the background with Fat Man. It’s so silly.”

For Terry, self-expression, in the form of dance, and science have always been complimentary. Dancing since she could walk, Terry danced with a collegiate

dance company while working on her double major in Chemistry and French Language and Culture at Purdue University. “I feel better when I’m dancing. It’s nice to have a break outside of work. I also think dance teaches you a lot, especially when you do it from a young age with ballet,” Terry said. “You learn a lot of discipline, you learn creativity.”

Terry maintained her dancing career after choosing the University of Colorado Boulder for graduate school, a recommendation made by her undergraduate advisor, Jon Hood. “My undergrad PI came through Boulder and recommended the university. Additionally, a post-doctoral researcher that I worked with had seen Mathias speak at conferences and thought that he was a kind human being, would be a good person to work with, and had interesting research,” Terry explains.

Despite being trained as a chemist in an institute comprised largely of physicists, Terry has found JILA to be a place where community transcends disciplines.

“I’ve really enjoyed my time in JILA. I think that it has a great community,” Terry says. “Even though I am technically a chemist—and I’ve been called by my friends (jokingly) ‘almost a physicist’—I’ve never felt left out.”

Instead, Terry’s taken every opportunity to learn from the community of JILAns around her, attending events and colloquia focusing on different research areas. “Even though I don’t work with phonons, I go to the Phonon Club meetings. I just think it’s interesting to learn about different fields,” she adds. “It’s all these events that provide channels for meeting people that make us human. It gives us something to talk about in the

hallway other than our work. So, people like Ari, our safety person, or James from the electronics shop have come up to me and asked me about dance,” Terry said. “JILA does really make sure we know that we’re humans too, outside of being scientists.”

Terry is passionate about building communities, especially for her fellow chemistry students. Having encountered institutional inertia and wanting to pursue change, Terry joined the Chemistry Graduate Student Committee. After realizing that this structure didn’t give her the community she hoped for, she took matters into her own hands, forming a graduate student group for women and gender minorities within the chemistry department. “So, I formed an RSO. But it’s not just me—I had the support of a group of amazing women. We have a lot of first- and second-year grad students in the group. That makes me excited for the future. I think it will continue once I’m gone.”

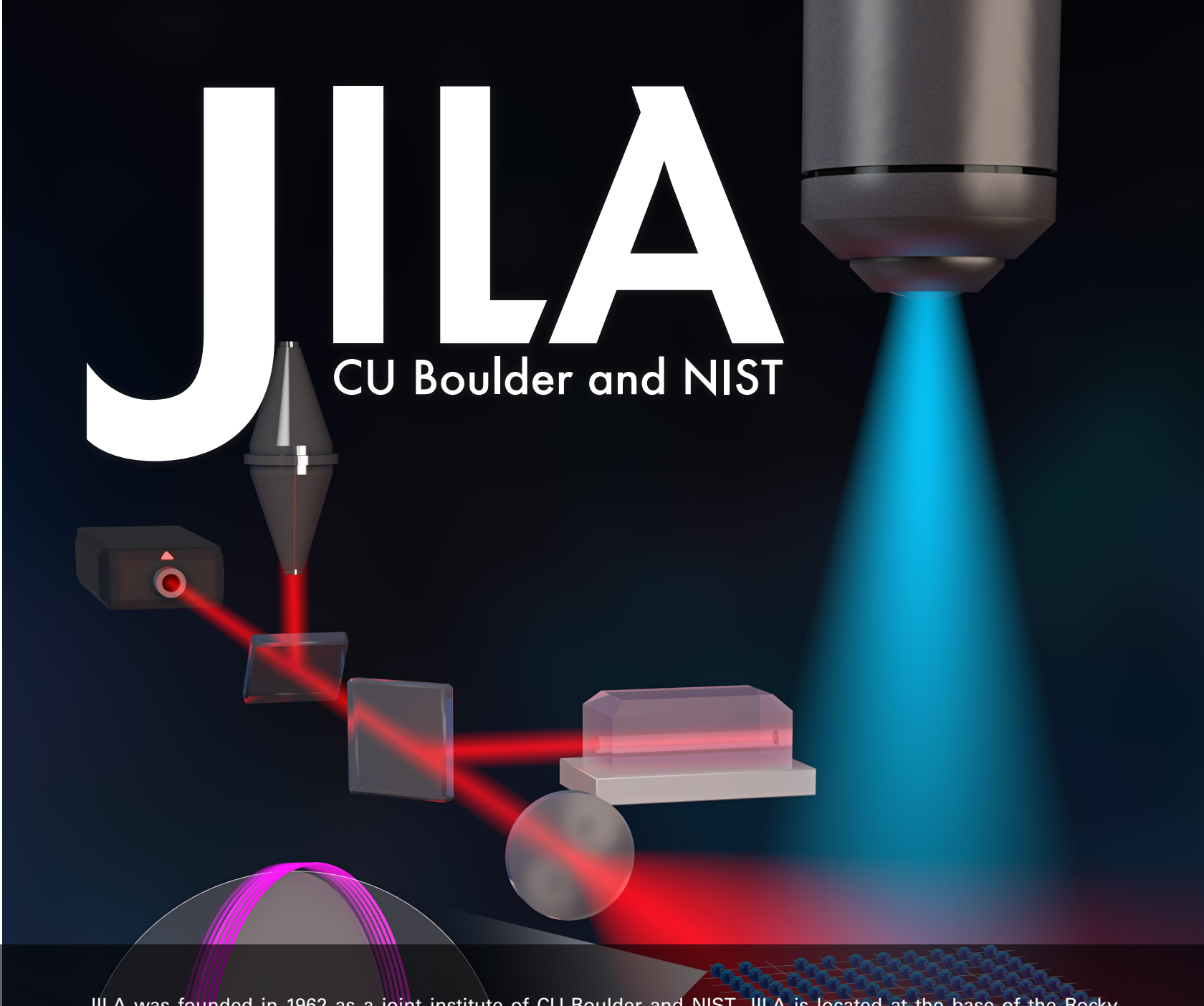
Though Terry’s path to JILA and beyond seems clear, it hasn’t always been smooth. For all the positive examples of leadership she has benefitted from along the way, Terry has also persisted through difficult experiences. Her ultimate goal is to become a professor and help shape the experiences of future students in chemistry.

“I have seen the changes that we can make as graduate students,” Terry explains. “I think that being a professor, I can make more changes and help support students who do belong in graduate school, though they may struggle a bit more than others.”

Written by Willa Arthur-Dworschack, University of Colorado Boulder Graduate Student.

JILA

CU Boulder and NIST



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.

To learn more visit jila.colorado.edu

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



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