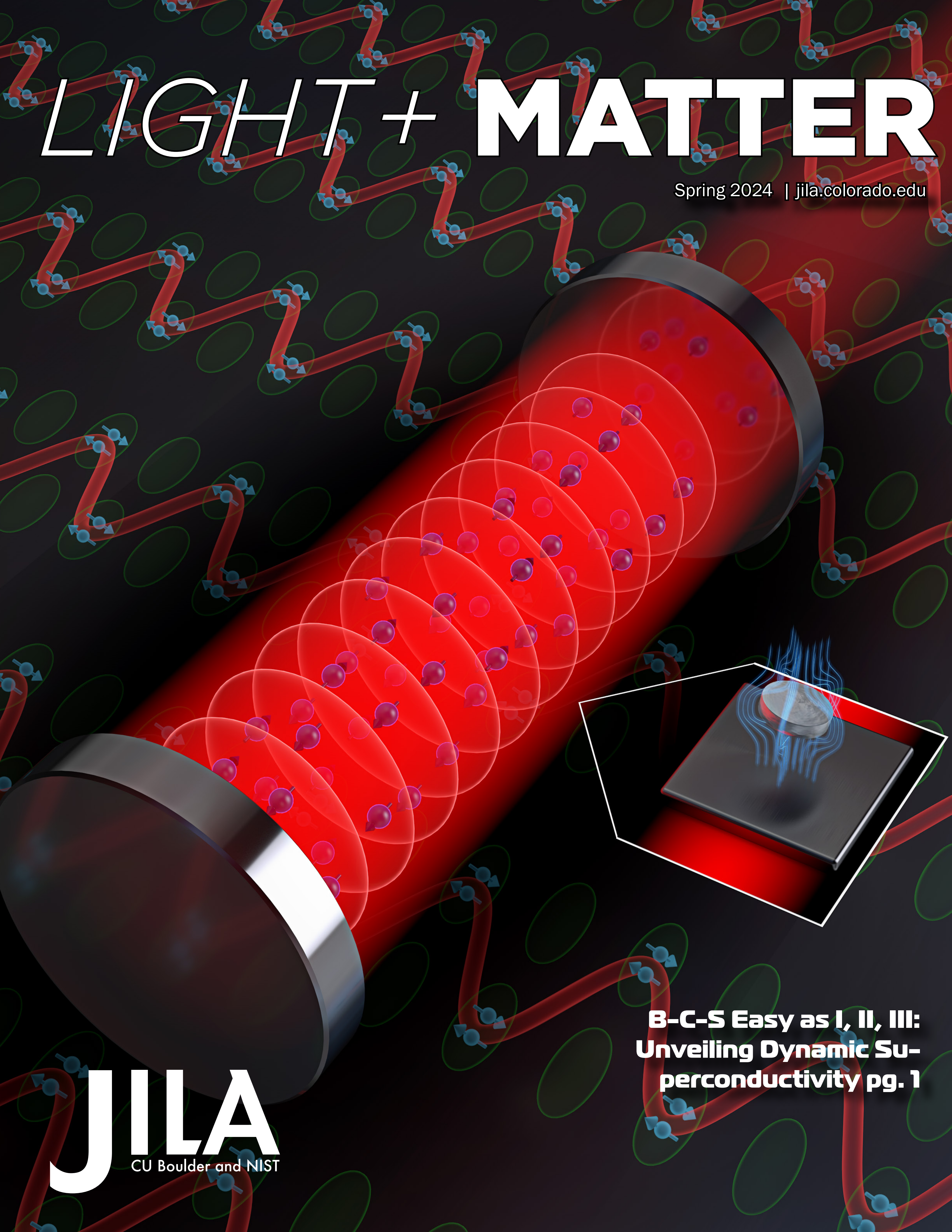
LIGHT+ MATTER

Spring 2024 | jila.colorado.edu



B-C-S Easy as I, II, III: Unveiling Dynamic Superconductivity pg. 1

JILA
CU Boulder and NIST

Women of JILA, from first-year undergraduates to third-year postdocs, celebrate International Day of Women and Girls in Science with cookies and lemonade.
Credit: Kenna Hughes-Castleberry/JILA

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.

The science communicators do their best to track down recently published journal articles and illuminating research photos and graphics. If you have an image or a recent paper you'd like to see featured, contact us at: sco@jila.colorado.edu

Please check out this issue of JILA Light & Matter online at
https://jila.colorado.edu/publications/jila-light-matter-quarterly

Kenna Castleberry, Science Writing, Project Manager
Steven Burrows, Project Manager, Artwork
Kristin Conrad, Design & Production
Gwen Dickinson, Copy Editor

Research Highlights

Feature Articles

B-C-S—Easy as I, II, III: Unveiling Dynamic Superconductivity

In physics, scientists have been fascinated by the mysterious behavior of superconductors—materials that can conduct electricity with zero resistance when cooled to extremely low temperatures. Within these superconducting systems, electrons team up in "Cooper pairs" because they're attracted to each other due to vibrations in the material called phonons.

As a thermodynamic phase of matter, superconductors typically exist in an equilibrium state. But recently, researchers at JILA became interested in kicking these materials into excited states and exploring the ensuing dynamics. As reported in a new *Nature* paper, the theory and experiment teams of JILA and NIST Fellows Ana Maria Rey and James K. Thompson, in collaboration with Prof. Robert Lewis-Swan at the University of Oklahoma, simulated superconductivity under such excited conditions using an atom-cavity system.

Instead of dealing with actual superconducting materials, the scientists harnessed the behavior of strontium atoms, laser-cooled to 10 millionths of a degree above absolute zero and levitated within an optical cavity built out of mirrors. In this simulator, the presence or absence of a Cooper pair was encoded in a two-level system or qubit. In this unique setup, photon-mediated interactions between electrons were realized between the atoms within the cavity.

Thanks to their simulation, the researchers observed three distinct phases of superconducting dynamics, including a rare "Phase III" featuring persistent oscillatory behavior predicted by condensed matter physics theorists but never before observed.

These findings could pave the way for a deeper understanding of superconductivity and its controllability, offering new avenues for engineering unique superconductors. Moreover, it holds promise for enhancing the coherence time for quantum sensing applications, such as improving the sensitivity of optical clocks.

The team focused on simulating the Barden-Cooper-Schrieffer (BCS) model, which describes the Cooper pair behavior. As co-first author and JILA graduate student Dylan Young elaborated: "The BCS model has been around since the 1950s and is central to our understanding of how superconductors work. When condensed matter theorists began studying the out-of-equilibrium dynamics of superconductors, they naturally started with this model."

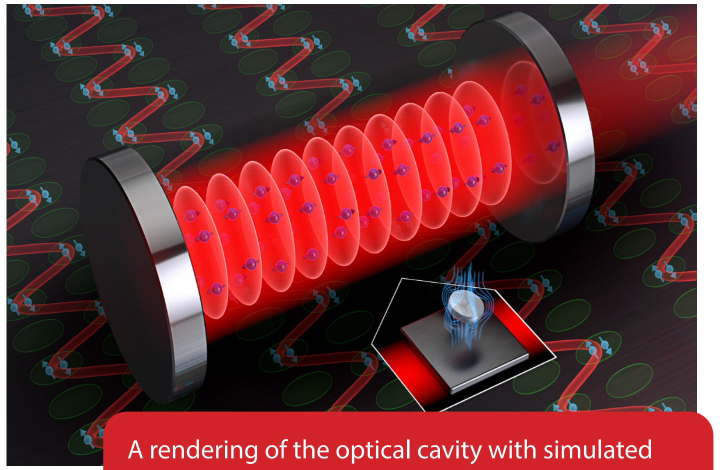
In the past few decades, condensed matter theorists have predicted three distinct dynamical phases for a superconductor to experience when it evolves. In Phase I, the strength of superconductivity decays rapidly to zero. In contrast, Phase II represents a steady state in which superconductivity is preserved. However, the previously unobserved Phase III is the most intriguing. "The idea of phase III is that the strength of superconductivity has persistent oscillations with no damping," explained JILA graduate student and co-first author Anjun Chu. "In the phase III regime, instead of suppressing the oscillations, many-body interactions can lead to a self-generated periodic drive to the system and stabilize the oscillations. Observing this exotic behavior requires precise control of experimental conditions."

To observe this elusive phase, the team leveraged the collaboration of theory from Rey's group and experiment from Thompson's group to create a precisely controlled experimental setup, hoping to fine-tune the experimental parameters to achieve Phase III.

While researchers previously tried to observe Phase III in real superconducting systems, measuring this phase has remained elusive due to technical difficulties. "They didn't have the right 'knobs' or readout mechanisms," explained Young. "On the other hand, our implementation in an atom-cavity system gives us access to both tunable controls and useful observables to characterize the dynamics."

Building on previous work, the researchers trapped a cloud of strontium atoms within an optical cavity. In this "quantum simulator'', the atoms emulated Cooper pairs and experienced a collective interaction that parallels the attraction experienced by electrons in BCS superconductors. "We think of each atom as representing a Cooper pair," Young explained. "An atom in the excited state simulates the presence of a Cooper pair, and the ground state represents the absence of one. This mapping is powerful because, as atomic physicists, we know how to manipulate atoms in ways you just can't with Cooper pairs."

The researchers applied this knowledge to induce different phases of dynamics in their simulation by a process known as "quenching." As Young elaborated: "Quenching is when we suddenly change or 'kick' our system to see how it responds. In this case, we prepare our atoms in this highly collective superposition state between ground and excited states. Then, we induce a quench by turning on a laser beam that gives all the atoms different energies."



A rendering of the optical cavity with simulated Cooper pairs undergoing quenching.
Credit: Steven Burrows/Rey and Thompson Groups

By changing the nature of this quench, the researchers could see different dynamical phases. They even devised a trick to observe the elusive Phase III, which involved splitting the cloud of atoms in half. "Using two clouds of atoms with separate control over energy shifts is the key idea to achieve Phase III," Chu remarked.

In superconductors, energy levels of electrons can be split into two sectors, largely occupied or barely occupied, separated by the Fermi level. "Our setup in spin systems does not have a Fermi level intrinsically, so we take account of this using two atomic clouds: one cloud simulates the states below the Fermi level, while another cloud simulates the other [quantum] states," Chu added.

To measure the dynamics of the superconductor within the cavity, the researchers tracked the light leaking from the optical cavity in real time. Their data found distinct points where the simulated superconductor transitioned between phases, eventually reaching Phase III.

Seeing the first measurements of Phase III surprised many of the team. As Thompson stated: "Actually seeing the wiggles was extremely satisfying." For her part in the collaboration, Rey was just as excited to see the theory and experiment align. "On the theory side, BCS superfluids [and] superconductors could, in principle, be observed in actual degenerate fermionic gases, such as the ones Debbie Jin at JILA taught us how to create. However, it has been hard to observe the dynamical phases in these systems. We predicted back in 2021 that all BCS dynamical phases could instead manifest in an atom-cavity experiment. It was so nice to see our theory predictions become a reality and actually observe the dynamical phases in a real experiment!"

Dylan J. Young, Anjun Chu, Eric Yilun Song, Diego Barberena, David Wellnitz, Zhijing Niu, Vera M. Schäfer, Robert J. Lewis-Swan, Ana Maria Rey & James K. Thompson. " Observing dynamical phases of BCS superconductors in a cavity QED simulator." Nature, 625(1), 679–684, 2023.

Written by Kenna Hughes-Castleberry

The Tale of Two Clocks: Advancing the Precision of Timekeeping

Historically, JILA has been a world leader in precision timekeeping using optical atomic clocks. These clocks harness the intrinsic properties of atoms to measure time with unparalleled precision and accuracy, representing a significant leap in our quest to quantify the most elusive of dimensions: time.

However, the precision of these clocks has fundamental limits, including the "noise floor," which is affected by the "quantum projection noise" (QPN). "This comes from the spin-statistics of the individual qubits, the truly quantum nature of the atoms being probed," elaborated JILA graduate student Maya Miklos. State-of-the-art clock comparisons, like those directed by JILA and NIST Fellow and University of Colorado Boulder Physics professor Jun Ye, are pushing ever closer to this fundamental noise floor limit. However, this limit can be circumvented by generating quantum entanglement in the atomic samples, boosting their stability.

Now, Ye's team, in collaboration with JILA and NIST Fellow James K. Thompson, has used a specific process known as spin squeezing to generate quantum entanglement, resulting in an enhancement in clock performance operating at the 10^{-17} stability level. Their novel experimental setup, published in *Nature Physics*, also allowed the researchers to directly compare two independent spin-squeezed ensembles to understand this level of precision in time measurement, a level never before reached with a spin-squeezed optical lattice clock.

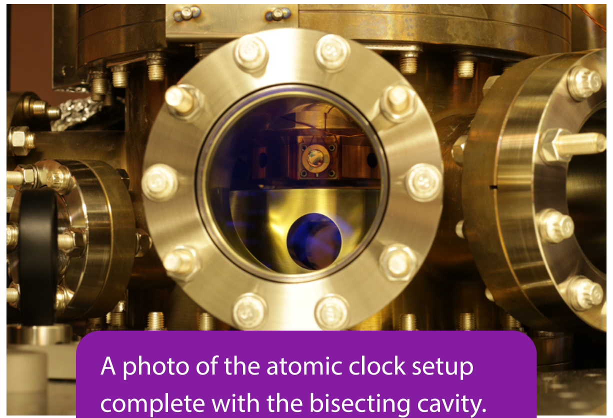
Beyond the realm of timekeeping, enhanced clocks hold potential advantages for use in various scientific explorations, including testing fundamental physics principles, improving navigation technologies, and possibly contributing to the detection of gravitational waves. "Advancing optical clock performance up to, and beyond, the fundamental limits imposed by nature is already an interesting scientific pursuit, explained JILA graduate student John Robinson, the paper's first author. "When one considers what physics you can uncover with the improved sensitivity, it paints a very exciting picture for the future."

Optical atomic clocks function not through gears and pendulums but through the orchestrated rhythms between atoms and excitation lasers.

QPN poses a fundamental obstacle to the precision of these clocks. This phenomenon arises from the inherent uncertainty present in quantum systems. In the context of optical atomic clocks, QPN manifests as a subtle but pervasive disturbance akin to a background noise that can obscure the clarity of time measurement.

"Because each time you measure a quantum state, it gets projected into a discrete energy level, the noise associated with these measurements looks like flipping a bunch of coins and counting if they show up as heads or tails," said Miklos. "So, you get this law-of-large-number scaling where the precision of your measurement increases with the square root of *N*, your atom number. The more atoms you add, the better the stability of your clock is. However, there are limits to that because, past certain densities, you can have density-dependent interaction shifts, which degrade your clock stability."

There are also practical limits on the achievable number of atoms in a clock. However, entanglement can be utilized as a quantum resource to circumvent this projection noise. Miklos added, "That square root of *N* scaling holds if those particles are uncorrelated. If you can generate entanglement in your sample, you can reach an optimal scaling that increases with *N* instead."



A photo of the atomic clock setup complete with the bisecting cavity. Credit: JILA/Ye Group

To address the challenge posed by QPN, the researchers employed a technique known as spin squeezing. In this process, the quantum states of atoms are delicately adjusted. While the uncertainties of a quantum measurement always obey the Heisenberg uncertainty principle, these spins are "squeezed" through precise interventions, reducing uncertainty in one direction while increasing it in another.

Creating a Quantum "Elevator"

To achieve the spin-squeezing, the team created a novel laboratory setup comprising a vertical, 1D moving lattice intersecting with an optical cavity (a resonator composed of two mirrors) along the horizontal direction. The researchers used the laser beams of the lattice to move the atomic ensembles up and down the entire lattice like an elevator, with some groups of atoms, or sub-ensembles, entering the cavity.

This project was inspired by a recent collaboration between the Ye research group and JILA Fellow Adam Kaufman, who had also explored spin-squeezing in other laboratory setups.

Using the optical cavity, the researchers manipulated the atoms to form spin-squeezed, entangled states. This was achieved by measuring the collective properties of the atoms in a so-called "quantum non-demolition" (QND) fashion. QND takes a measure of a quantum system's property so that the measurement doesn't disturb that property. Two repeated QND measurements exhibit the same type of quantum noise, and by taking the difference, one can enjoy the cancellation of the quantum noise.

In an atom-cavity coupled system, the interaction between the light probing the optical cavity and the atoms located in the cavity allowed the researchers to project the atoms into a spin-squeezed state with reduced impact of QPN uncertainty. The researchers then used the elevator-like lattice to shuffle an independent group of atoms into the cavity, forming a second spin-squeezed ensemble within the same experimental apparatus.

A key innovation in this study was directly comparing the two atomic sub-ensembles. Thanks to the vertical lattice, the researchers could switch which atomic sub-ensembles were in the cavity, directly comparing their performances by alternately measuring the time as indicated by each spin-squeezed sub-ensemble.

"At first, we performed a classical clock comparison of two atomic sub-ensembles without spin squeezing," Tso explained. "Then we spin-squeezed both sub-ensembles and compared the performance of the two spin-squeezed clocks. In the end, we concluded that the pair of spin-squeezed clocks performed better than the pair of classical clocks in terms of stability by an improvement of about 1.9 dB [~25% improvement]. This is pretty decent as the first result of our experimental setup."

This stability enhancement persisted even as the clocks' performance averaged down to the level of 10^{-17} fractional frequency stability, a new benchmark for spin-squeezed optical lattice clock performance. "In one generation of this experiment, we've roughly halfway closed the gap between the stability of the best spin-squeezed clocks and the best classical clocks for precision measurement," elaborated Miklos, who, with the rest of the team, hopes to improve this value even further.

John M. Robinson, Maya Miklos, Yee Ming Tso, Colin J. Kennedy, Tobias Bothwell, Dhruv Kedar, James K. Thompson & Jun Ye "Direct comparison of two spin-squeezed optical clock ensembles at the 10^{-17} level." Nature Physics, 20(2), 208–213, 2024.

Written by Kenna Hughes-Castleberry,

New Findings from the JWST: How Black Holes Switched from Creating to Quenching Stars

Astronomers have long sought to understand the early universe, and thanks to the James Webb Space Telescope (JWST), a critical piece of the puzzle has emerged. The telescope's infrared detecting “eyes” have spotted an array of small, red dots, identified as some of the earliest galaxies formed in the universe.

This surprising discovery is not just a visual marvel, it's a clue that could unlock the secrets of how galaxies and their enigmatic black holes began their cosmic journey.

“The astonishing discovery from James Webb is that not only does the universe have these very compact and infrared bright objects, but they're probably regions where huge black holes already exist,” explains JILA Fellow and University of Colorado Boulder astrophysics professor Mitch Begelman. “That was thought to be impossible.”

Begelman and a team of other astronomers, including Joe Silk, a professor of astronomy at Johns Hopkins University, published their findings in *The Astrophysical Journal Letters,* suggesting that new theories of galactic creation are needed to explain the existence of these huge black holes.

“Something new is needed to reconcile the theory of galaxy formation with the new data,” elaborates Silk, the lead author of the potentially groundbreaking study.

Astronomers had previously posited a somewhat orderly evolution when thinking about how galaxies formed. Conventional theories held that galaxies form gradually, assembling over billions of years. In this slow cosmic evolution, stars were thought to emerge first, lighting up the primordial darkness.

“The idea was that you went from this early generation of stars to the galaxies really becoming mainly dominated by stars,” adds Begelman. “Then, towards the end of this process, you start building these black holes.” Supermassive black holes, those enigmatic and powerful entities, were believed to appear after the first stars, growing quietly in the galactic core. They were seen as regulators, occasionally bursting into action to temper the formation of new stars, thereby maintaining a galactic balance.

Thanks to the observations of the “little red dots” by the JWST, the researchers found that the first galaxies in the universe were brighter than expected, as many showed stars coexisting with central black holes known as quasars.

“Quasars are the most luminous objects in the universe,” explains Silk. “They are the products of gas accretion onto massive black holes in galaxy nuclei that generate immense luminosities, outshining their host galaxies. They are like monsters in the cuckoo’s nest.”

Seeing the coexistence of stars with black holes, the researchers quickly realized that the conventional theories of galaxy formation had to be flawed. “[This new data] looks like [the process is] reversed, that these black holes formed along with the first stars, and then the rest of the galaxy followed,” says Begelman. “We're saying that the growth of the black hole, at first, promotes the stars. And only later, when conditions change, does it flip into a mode of turning off the stars.”

From this proposed new process, the researchers found that the relationship between star formation and black hole formation seemed closer than expected, as each initially amplified the growth of the other via a process known as positive feedback.

“Star formation accelerates massive black hole formation, and vice versa, in an inextricably connected interplay of violence, birth, and death that is the new beacon of galaxy formation,” says Silk.

Then, after almost a billion years, the nurturing giants became suppressive, depleting the gas reservoirs in their galaxies and quenching star formation. This “negative feedback” was due to energy-conserving outflows—powerful winds that drove gas out of the galaxies, starving them of the material needed to create new stars.

Armed with the revelation of the black holes’ nurturing behavior, the researchers proposed a new timeline for the shift from positive to negative feedback in early galaxy formation. By looking at the different light spectra and chemical signatures emitted from these “little red dots,” the researchers suggested that this shift occurred around 13 billion years ago, one billion years after the Big Bang, a period astronomers classify as “$z \approx 6$.”

Identifying this transition epoch helps astronomers target specific periods in the universe's history for observation. It can guide future observational strategies using telescopes like JWST, and others, to study the early universe more effectively. Additionally, by understanding when this shift occurred, astronomers can better contextualize the characteristics of modern galaxies, including size, shape, star composition, and activity level.

To validate this new theory of collaborative galactic formation between the stars and black holes, and provide further insight into the processes involved, computer simulations are needed.

“This will take some time,” Begelman says. “The current computer simulations are rather primitive, and you need high resolution to understand everything. It takes a lot of computing power and is expensive.”

Until then, there are other steps the astronomy community can take to review and validate this new theory.

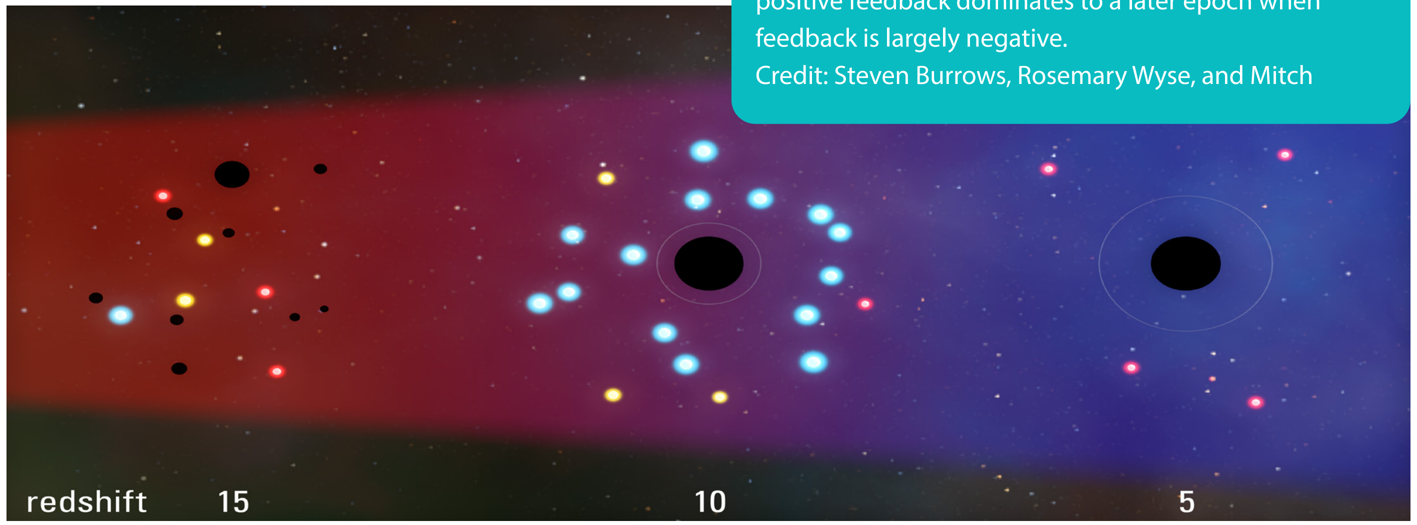
“The next steps will come from improved observations,” Silk adds. “The full power of JWST to study the spectra of the most distant galaxies will be unleashed over the next years.”

Both Begelman and Silk are optimistic about the rest of their field adopting their proposed idea.

“As far as I know, we're the first to go in quite this extreme direction,” adds Begelman. “I was kind of pushing the envelope over the years with my collaborators working on this black hole formation problem. But JWST shows us that we didn't think outside the box enough.”

Joseph Silk, Mitchell C. Begelman, Colin Norman, Adi Nusser, and Rosemary F. G. Wyse. " Which Came First: Supermassive Black Holes or Galaxies? Insights from JWST." The Astrophysical Journal Letters, 961(2), L39, 2024.

Written by Kenna Hughes-Castleberry,



The transition in star formation rates and black hole growth as redshift decreases from regimes where positive feedback dominates to a later epoch when feedback is largely negative.
Credit: Steven Burrows, Rosemary Wyse, and Mitch

Dipole-Dipole Interactions: Observing a New Clock Systematic Shift

In a new study published in *Science*, JILA and NIST (National Institute of Standards and Technology) Fellow and University of Colorado Boulder physics professor Jun Ye and his research team have taken a significant step in understanding the intricate and collective light-atom interactions within atomic clocks, the most precise clocks in the universe.

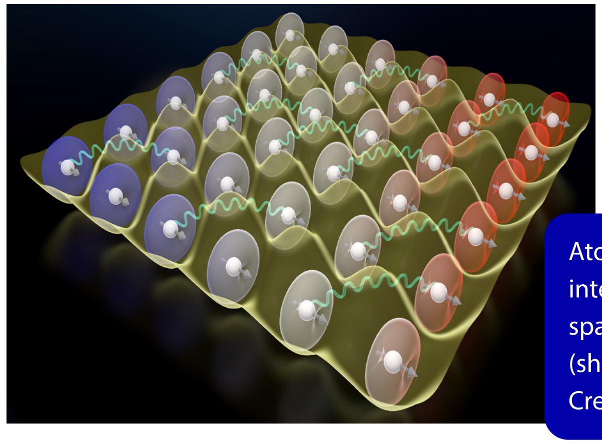
Using a cubic lattice, the researchers measured specific energy shifts within the array of strontium-87 atoms due to dipole-dipole interactions. With a high density of atoms, these mHz-level frequency shifts—known as cooperative Lamb shifts—were spectroscopically studied. These shifts were studied spatially and compared with calculated values using imaging spectroscopy techniques developed in this experiment.

These cooperative Lamb shifts, named because the presence of many identical atoms in a tightly confining space modifies the electromagnetic mode structure around them, are an important factor as the numbers of atoms in clocks continue to grow.

"If you can understand and control these interactions at high density in this grid, you can always make the grid bigger and bigger," explains JILA graduate student William Milner, the paper's second author. "It's an inherently scalable technology, important for improving clock performance."

Time in a Cube

Atomic clocks, long regarded as the pinnacle of precision, operate on the principle of measuring the frequency of light absorbed or emitted by atoms. Each tick of these clocks is governed by the oscillations of the quantum superposition of electrons within these atoms, stimulated by the corresponding energy from a probing laser. The laser excites the atoms into a quantum state known as the clock state.



Atomic dipoles on a lattice interact to produce an observable spatially varying frequency shift (shown as blue to red).
Credit: Steven Burrows/Ye Group

While more traditional optical lattice clocks use a one-dimensional optical lattice, suppressing the atoms' movements only along one strongly confining direction, the strontium quantum gas clock used in this study confined the atoms in all directions by placing them in a cubic arrangement. While using a 3D lattice is an attractive clock geometry, it also requires preparing an ultracold quantum gas of atoms and carefully loading them into the lattice.

"It's more complicated, but it has some unique benefits as the system features more quantum properties," Milner elaborates.

In quantum physics, the spatial arrangement of particles critically influences their behavior. With its uniformity and equilibrium, the cubic lattice created a controlled environment where atomic interactions were observable and manipulable with unprecedented precision.

Watching Dipole-Dipole Interactions

Using the cubic lattice, Ross Hutson (a recent JILA Ph.D.graduate), Milner, and the other researchers in the Ye lab, were able to facilitate and measure the dipole-dipole interactions between the strontium atoms. These shifts, normally so small they are neglected, arise from collective interference between the atoms behaving as dipoles when they are prepared in a superposition of the two clock states.

Because the spatial ordering of the atoms within the cubic lattice influences the dipolar coupling, researchers could amplify or diminish the dipole interactions by manipulating the angle of the clock laser relative to the lattice. Operating at a special angle—the Bragg angle—the researchers expected strong constructive interference and observed a correspondingly larger frequency shift.

Looking at Cooperative Lamb Shifts

With stronger dipole-dipole interactions occurring within the lattice, the researchers found that these interactions created local energy shifts throughout the clock system. These energy shifts, or cooperative Lamb shifts, are very small effects that are normally hard to detect. When many atoms are grouped, such as in a cubic clock lattice, these shifts become a collective affair and are revealed by the newly achieved clock measurement precision. Left uncontrolled, they can affect the accuracy of atomic clocks.

"These [shifts were] initially proposed back in 2004 as a futuristic thing to worry about [for clock accuracy]," adds Milner. "Now, they're suddenly more relevant [as you add more atoms to the lattice]."

As if measuring these shifts wasn't interesting enough, even more interesting was that the researchers saw that the cooperative Lamb shifts weren't uniform across the lattice, but varied depending on each atom's specific location.

This local variation is significant for clock measurement: it implies that the frequency at which atoms oscillate, and hence the clock's 'ticking,' could slightly differ from one part of the lattice to another. Such spatial dependence of the cooperative Lamb shifts is an important systematic shift to understand as researchers strive to improve timekeeping precision.

"By measuring these shifts and seeing them align with our predicted values, we can calibrate the clock to be more accurate," Milner says.

From their measurements, the team realized there was a close connection between the cooperative Lamb shifts and the propagation direction of the clock probe laser within the lattice. This relationship allowed them to find a specific angle where a "zero crossing" was observed and the sign of the frequency shift transitioned from positive to negative.

"It's a particular quantum state that experiences zero collective Lamb shift (equal superposition of ground state and excited state)," explains JILA graduate student Lingfeng Yan. Playing around with the connection between the laser propagation angle with respect to the cubic lattice and the cooperative Lamb shifts has allowed the researchers to fine-tune the clock further to be more robust against these energy shifts.

Beyond controlling and minimizing these dipole-dipole interactions in the cubic lattice, the JILA researchers hope to use these interactions to explore many-body physics in their clock system.

"There's some really interesting physics going on because you have these interacting dipoles," Milner elaborates, "So people, such as Ross Hutson, have ideas for even potentially using these dipole-dipole interactions for spin squeezing [a type of quantum entanglement] to make even better clocks."

Ross B Hutson, William R. Milner, Lingfeng Yan, Jun Ye, and Christian Sanner. "Observation of millihertz-level cooperative Lamb shifts in an optical atomic clock" Science, 383(6681), 384–387, 2024.

Written by Kenna Hughes-Castleberry

Probing Proton Pumping: New Findings on Protein Folding in Bacteriorhodopsin (bR)

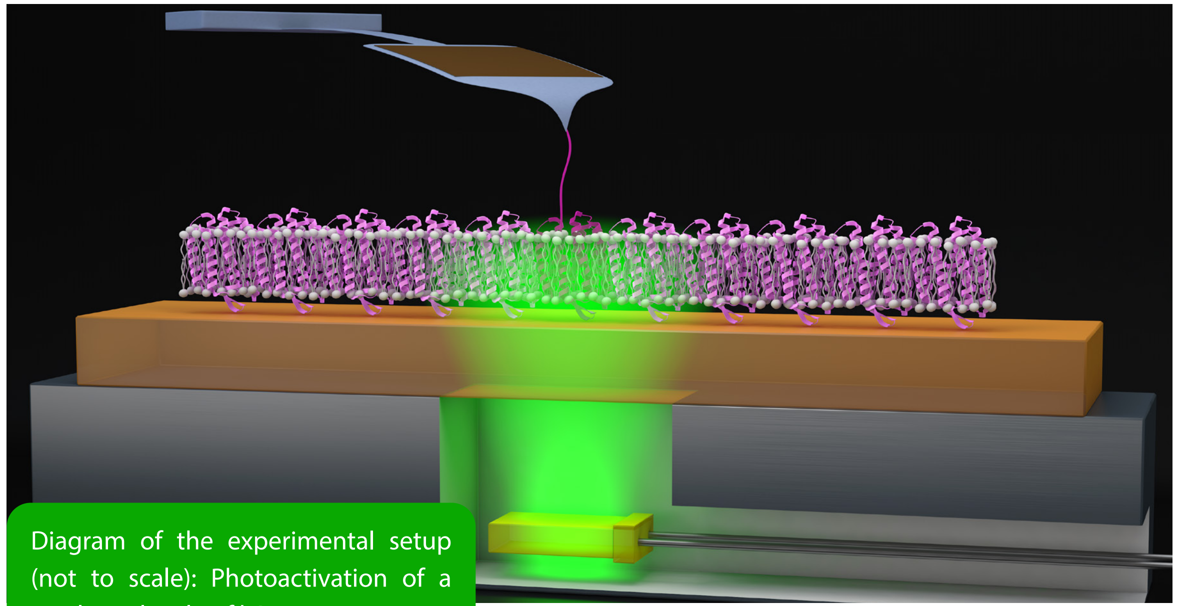


Diagram of the experimental setup (not to scale): Photoactivation of a single molecule of bR.
Credit: Steven Burrows/Perkins Group

When it comes to drug development, membrane proteins play a crucial role, with about 50% of drugs targeting these molecules. Understanding the function of these membrane proteins, which connect to the membranes of cells, is important for designing the next line of powerful drugs. To do this, scientists study model proteins, such as bacteriorhodopsin (bR), which, when triggered by light, pump protons across the membrane of cells.

While bR has been studied for half a century, physicists have recently developed techniques to observe its folding mechanisms and energetics in the native environment of the cell's lipid bilayer membrane. In a new study published in *Proceedings of the National Academy of Sciences (PNAS),* JILA and NIST Fellow Thomas Perkins and his team advanced these methods by combining atomic force microscopy (AFM), a conventional nanoscience measurement tool, with precisely timed light triggers to study the functionality of the protein function in real time.

"The energetics of membrane proteins hast been challenging to study and therefore not well understood," explained Perkins. "Using AFM and other methods, we can create ways to look into this further." Armed with a better understanding of the energetics of these proteins, chemists can design drugs that are more potent toward specific symptoms and illnesses caused by protein misfunction

Measuring Millisecond Protein Dynamics

While bR is a microscopic protein, it can be seen by the naked eye, and even in satellite images, when blooms of archaeon microorganisms leave vast amounts of it as residue in salt-water ponds. "The ponds become filled with what's called Halobacterium salinarum, the parent organism of bacteriorhodopsin," Perkins elaborated. "These ponds are used to harvest salt, and because they're warm and salty, the bacteria love to grow there."

At the microscopic level, bR works with other membrane proteins to produce energy for the cell by creating a proton gradient on one side of the cell membrane, which ushers the proton through to the other side of the membrane. Bacteriorhodopsin does this by folding and unfolding its helices into specific shapes to control how many protons pass through the membrane. During this process, the proton migration produces chemical energy in the form of adenosine-tri-phosphate (ATP).

For Perkins and his co-author David Jacobson (a former JILA postdoctoral researcher and now an assistant professor at Clemson University), bR presented an opportunity to design a new experimental method for looking at real-time functional energetics. To study proteins like bR, Jacobson and Perkins utilize AFM, which acts like a tiny finger to pull on the protein gently, which helps the AFM to feel the protein's surface, mapping out its structure and giving a better understanding of how the protein folds.

Because bR's folding processes are triggered by light, Perkins and Jacobson added a lighting element to the AFM procedure. "We had this clever idea to glue super thin green LEDs—which trigger the bacteriorhodopsin—to a metal puck, which we can attach to the AFM," Perkins elaborated. "These green LEDs are also cheap, like a $1.00 apiece or a $1.50 apiece. Compared to our AFM cantilever, which costs about $80.00 apiece, throwing away a $1.50 LED is hardly something we worry about."

With this inexpensive add-on to their AFM, Perkins and Jacobson could induce the bR to fold and unfold with millisecond precision. After collecting their data, the researchers found that the protein correctly folded 60% of the time, allowing the protons to pass through the membrane.

To verify the energetics and real-time function of the protein folding, the scientists mutated the bR protein to remain always in the "open" or unfolded state. Using their new experimental setup, they could reproduce findings similar to what they observed before in the "open" phase of the bR photocycle.

"In biology, you might see something, but you need to ask, am I seeing what I think I'm seeing?" Perkins said. "So, by making a mutation and seeing the effect that we expected, we have increased confidence that we're really studying the process we think we are studying."

The Mystery of the Misfolded Protein

While Perkins and Jacobson observed proper folding 60% of the time, the other 40% of cases surprised them, as the protein misfolded but could still pump a proton through the membrane. "The misfolding is actually stabilizing," added Perkins. "And that was really surprising." In many cases, protein misfolding does not result in stabilization.

Due to the energetic stabilization, Perkins and Jacobson theorized that the bR's structural helices weren't separating properly to provide a completely open tunnel for the proton, though it still wiggled through, a process difficult to detect with AFM imaging.

Trying to understand the underlying mechanisms for the misfolding better, Perkins and Jacobson lowered the force on the AFM pulling assay to zero to see if this would coax the protein to fold correctly. However, the results remained the same: 40% of cases resulted in misfolding.

These results, with the same amount of misfolding, puzzled the researchers. While Perkins and Jacobson couldn't identify the cause of these misfolding cases, they hope to investigate further. Now, they are interested in seeing what the rest of the biophysics community makes of these results.

"There could be more subtle effects, or maybe some new science there," Perkins added. "It could be that there's a pathway that perhaps people haven't been able to see before."

David R. Jacobson and Thomas T. Perkins. " Quantifying a light-induced energetic change in bacteriorhodopsin by force spectroscopy" the Proceedings of the National Academy of Sciences, 121(7), e2313818121, 2024.

Written by Kenna Hughes-Castleberry

Humans of JILA: Luca Giuseppe Talamo

In the bustling realm of scientific exploration, there are individuals whose dedication allows them to stand out as a leader within their research group. Such is the case for JILA graduate student Luca Giuseppe Talamo, a researcher within JILA Fellow Cindy Regal's group.

For Talamo, the journey to JILA was far from linear. "Originally, when I went to undergrad, I thought I wanted to attend med school and be a doctor," Talamo elaborated. "I had friends in my math and physics classes who saw that I was getting more enjoyment out of those types of courses than my life science courses." From this observation, Talamo's friends encouraged him to participate in more upper-level physics classes during his undergraduate career at the University of Toronto.

Once he switched from life sciences to physics, Talamo quickly found himself welcomed into a close community. According to Talamo: "We spent countless hours in the physics lounge, working on problem sets with each other and trying to go over lectures. There was a lot of discussion and a lot of learning outside of the classroom. I think that community really encouraged me to stay in physics and math."

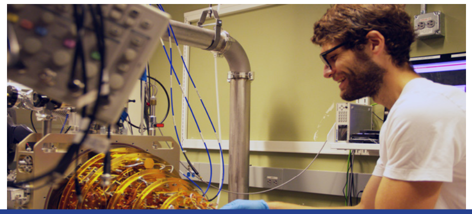
Along with his newfound interest in physics, Talamo participated in an electronics course and discovered that he enjoyed building his own instruments, starting with a blueprint and finishing with a working model. "I think that exposed me to the joys of designing something, troubleshooting it, and seeing the initial design come to fruition (or more often than not realizing why it won't work)," he added. Working in an atomic physics laboratory as an undergraduate prepared Talamo to transition to JILA, as he received hands-on training with laser arrays and vacuum chambers.

It took Talamo's undergraduate professor Amar Vutha to encourage his class to "be bold" for Talamo to ask for a position in Vutha's laboratory. Talamo elaborated: "While there, I performed optical spectroscopy on atoms in a cryogenically cooled crystal, which introduced me to the world of AMO physics. Amar also informed me of the strong AMO research culture at JILA and encouraged me to apply."

Now, as a graduate student at JILA, Talamo finds himself at the forefront of cutting-edge science. "I am working on a joint project between Konrad Lehnert [another JILA Fellow] and Cindy," he elaborated. "This project aims to utilize mechanical objects to link up two disparate parts of the electromagnetic spectrum—microwaves and optics. While both propagate through free space in the form of photons the later have energies that are roughly forty thousand times higher than the former. By sticking these mechanical objects in specialized fridges known as dilution refrigerators and using laser-cooling techniques, we can cool these mechanical objects to almost-absolute-zero temperatures. This lets us take information from the microwave domain and transfer it to the optical domain. We're trying to do this in a way that's as efficient and low-noise as possible so that we can transfer sensitive quantum information between these two domains in reasonable amounts of time. Because of the energy disparity, this is actually a very difficult task."

Despite starting his work with lasers during his undergraduate research, Talamo hasn't stopped being amazed by the things they can do. "Every day I'm remind how versatile lasers can be. We routinely use them as precision instruments to stabilize a path of a hundred meters it to within the width of a human hair. We also use them to laser cool our mechanical objects to tempeatures 1000 times colder than our ultra-cold refrigerators."

Beyond this, Talamo also highlights that JILA's funding helps make it a key place for physics research. As he explained: "It really is a great place to do research."



Luca Giuseppe Talamo works on an experiment.
Credit: JILA/Kenna Hughes-Castleberry

News and Awards

News

JILA Celebrates International Day of Women and Girls in Science 2024. In a vibrant celebration of International Day of Women and Girls in Science, women of JILA's scientific community gathered in the Debbie Jin Rooms (S209) for a unique networking event designed to foster connections and celebrate the achievements of women in the field of science.

Press Clipping: JILA and NIST Fellow Judah Levine Explains Leap Seconds and Leap Day for "The New York Times" and "Denver 7 News." Levine, the head of the Network Synchronization Project at the National Institute of Standards and Technology (NIST) in Boulder, Colorado and a JILA Fellow, delved into the origins of leap year, tracing it back to Julius Caesar's era.

Press Clipping: JILA and NIST Fellow Jun Ye and his Team are Featured in "MIT Technology Review" Magazine. As detailed in a recent *MIT Technology Review* article, JILA and NIST Fellow Jun Ye's and his team's innovative approach of using quantum squeezing is set to enhance the detection of gravitational waves and improve the precision of atomic clocks, promising new insights into cosmic phenomena and the fundamental laws of physics.

New "Humans of JILA" Podcast Episode. To make some of the most precise measurements in the world, JILA scientists need customized electronic components. This is where the JILA instrument shop staff comes in, as they design, improve, and implement these unique electronic devices throughout the institute's laboratories. In the next episode of the "Humans of JILA" podcast, listeners meet three of the electronic staff members: Terry Brown, James Fung-A-Fat, and Ivan Ryger, and hear about their favorite moments of working in the electronics shop.

Awards

JILA and the University of Colorado Boulder Lead Pioneering Quantum Gravity Research with a new Heising-Simons Foundation Grant. The Heising-Simons Foundation's Science program has announced a generous grant of $3 million over three years, aimed at bolstering theoretical and experimental research efforts to bridge the realms of Atomic, Molecular, and Optical (AMO) physics with quantum gravity theories. Among the recipients, a notable grant was awarded to a multi-investigator collaboration spearheaded by JILA with collaborators from the Univerity of Colorado Boulder and NIST. This distinguished team comprises leading experts including JILA and NIST Fellows Ana Maria Rey and James Thompson, and JILA Fellow and NIST Physicist Adam Kaufman Kaufman and Thompson are both recognized for their pioneering experimental work using tweezer arrays and optical cavities, respectively. Additionally, Dr. Andrew Lucas, Assistant Professor at CU Boulder, and Dr. Chris Akers, Fellow at the Institute for Advanced Study, experts in holography and quantum gravity, are also included in this team of researchers.

JILA Fellow Murray Holland is awarded a Translational Quantum Research Seed Grant Administered by CU Boulder. Holland's work at CU Boulder's Department of Physics is among the three university-led projects to be honored, alongside four commercial enterprise-led initiatives. These grants, each amounting to $50,000 and spanning an 18-month period, are designed to bridge the gap between laboratory research and commercial viability, emphasizing the importance of translating academic discoveries into real-world applications.

The podcast cover art of JILA's "Humans of JILA" podcast. The latest episode features interviews with JILA's Electronics Shop staff members about their experiences working at JILA.
Credit: kenna Hughe-Castleberry/JILA

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

University of Colorado **Boulder**

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

About JILA

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

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Astrophysical & Planetary Science; Chemistry; Biochemistry; and Molecular, Cellular, and Developmental Biology, as well as in the School of Engineering.

The wide-ranging interests of our scientists have made JILA one of the nation's leading research institutes in the physical sciences. They explore some of today's most challenging and fundamental scientific questions about quantum physics, the design of precision optical and x-ray lasers, the fundamental principles underlying the interaction of light and matter, and processes that have governed the evolution of the Universe for nearly 14 billion years. Research topics range from the small, frigid world governed by the laws of quantum mechanics through the physics of biological and chemical systems to the processes that shape the stars and galaxies. JILA science encompasses eight broad categories: Astrophysics, Atomic & Molecular Physics, Biophysics, Chemical Physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information Science & Technology.

To learn more visit:
jila.colorado.edu