LIGHT + MATTER

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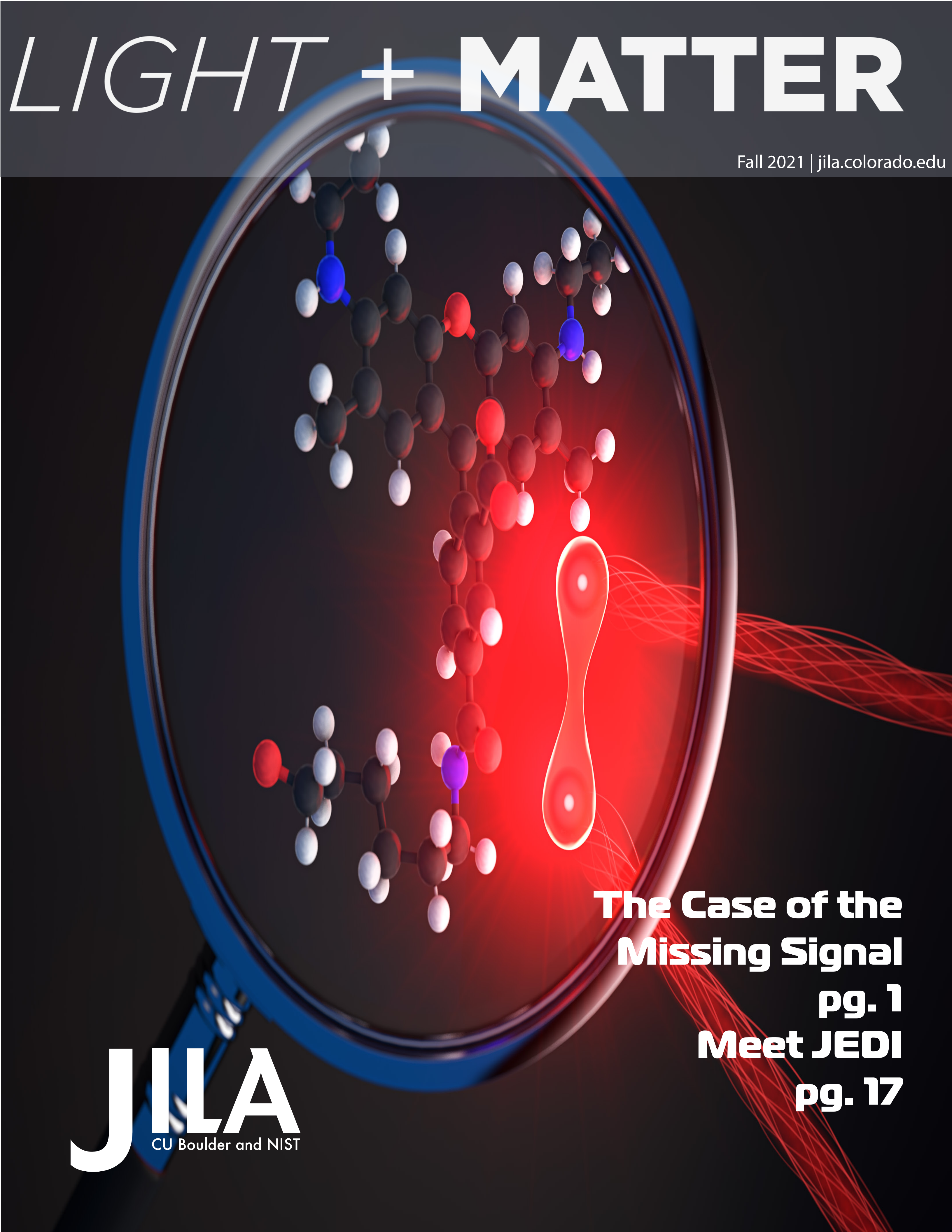

The Case of the Missing Signal

Meet JEDI

JILA
CU Boulder and NIST

Image caption: 2021 Group Photo of JILA from the August barbeque
Image Credit: Kenna Castleberry/JILA

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The Case of the Missing Signal

Most researchers would agree that it is much easier to write a paper having an observed effect to report on than a missing signal. NIST JILA Fellow Ralph Jimenez found this to be the case in contributing to a recent paper published in *Physical Review Applied.* The authors of this paper were originally hoping to observe the increased efficiency in two-photon absorption, a special type of process used in microscopy of living tissue, that had been reported by other research labs. This increased efficiency would be determined by an absorption signal in addition to the one being produced from classical light. This additional signal came from using entangled photons. Instead, Jimenez and his team of collaborators from NIST found no additional signal in their measurements, indicating a lack of absorption entirely from the entangled photons. When speaking to other researchers around the world performing similar experiments, Jimenez found that sometimes the signal was seen and sometimes it wasn't. This randomness in signal appearance began a mystery for Jimenez to solve when it came to the process of using entangled photons in two-photon absorption.

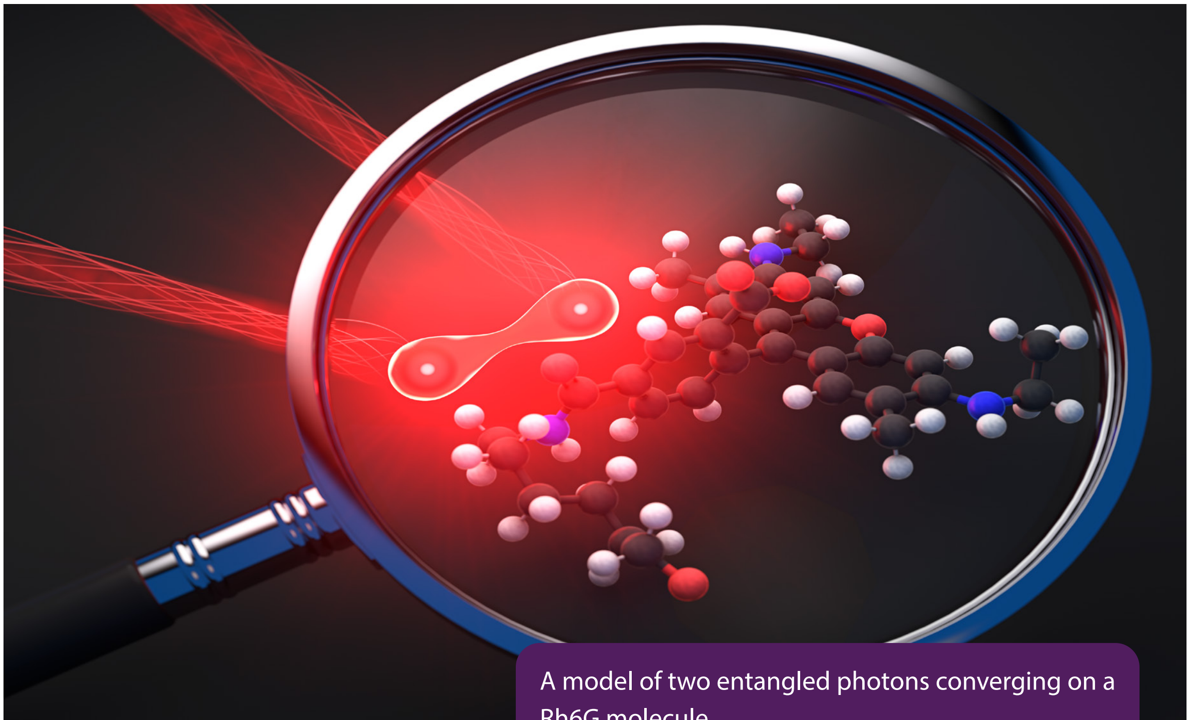
A Brief History of Two-Photon Absorption

According to NIST scientist Martin Stevens: "Two-photon absorption is a very inefficient process. If two photons happen to be in the same place at the same time, and hit the molecule that you're trying to excite, there's a chance you'll get absorption." However, the chances of this absorption happening are very slim. That is why teams like Jimenez's and Stevens' use high-powered lasers with short light pulses. This increases the probability of two photons being next to each other and being absorbed. Previous studies suggested that the efficiency of two-photon absorption could be enhanced up to 10 orders of magnitude by using entangled photons. Quantum entanglement of light occurs when quantum states of two photons are not independent of each other. As Stevens explained: "The hope is that by generating entangled photon pairs, we can make photons that are highly correlated in energy and time, so they arrive at the same place at the same time with exactly the right energy, making the absorption process very efficient." If an entangled photon pair is absorbed, the instruments would be able to detect a signature of this absorption.

The Clues of Fluoresence

In order to test this theory, graduate students and postdocs from both the Jimenez and Stevens labs joined forces to build a state-of-the-art quantum optics laboratory starting with an empty room. This laboratory was specifically built by co-first authors Kristen Parzuchowski and Alexander Mikhaylov of the Jimenez laboratory. Stevens commented: "That's been a really rewarding part of this work with myself, Thomas Gerrits, and Mike Mazurek--who have quantum optics backgrounds--interacting with Ralph his postdocs, and students--who did not have this background--and merging these different streams of talent together with these different areas of expertise." The team did several tests on this proposed efficiency by looking for the absorption of entangled photon pairs by molecules in liquids, without seeing any signals that corroborated previous studies.

After this initial testing with a transmission-based experiment didn’t turn up any clues, "we then realized that the more sensitive experiment would detect fluorescence," Jimenez stated. This would allow for more thorough testing. "In that case, if the molecules absorb a pair of photons, then a fluorescence photon will come out. If there's no two-photon absorption, you shouldn't see any signal, unless it's something else. So, we built this new experiment to detect two-photon absorption with fluorescence, and again, we didn't see a signal." Frustrated about their lack of signal, Jimenez and Stevens began informal discussions with other teams around the world to determine if other researchers were getting the same result that they were. These discussions, which includes a group in Geneva that has detected entangled two-photon absorption, evolved into a biweekly global seminar series, where different labs presented their findings. The results puzzled Jimenez and Stevens, as some labs have found a signal showing entangled photons being absorbed in two-photon absorption, while others haven't. Jimenez commented: "We thought there's something going on around the world as different people are seeing different things, such as a group in South America saw this process, and there's a group in Mexico that sees the same thing we do, with no signal. There's a group at the University of Oregon that also saw no signal. And we've been trying to understand what's going on here."



A model of two entangled photons converging on a Rh6G molecule.

Image Credit: Steven Burrows/Jimenez Group

The Mystery Deepens

In their fluorescence experiments, graduate student Kristen Parzuchowski and postdoc Alex Mikhaylov worked together with the NIST-campus team to show that even in the absence of a signal from entangled photon absorption, they could precisely calibrate their experiment and estimate upper bounds for the enhancement which are up to 10,000 times smaller than what was reported by others. The next steps are clear for both Jimenez and Stevens, who have a number of experiments lined up as they try to find the reason for why some labs are seeing a signal and others aren't. "I think what's come out of this is that we've been able to largely come to a consensus as a community about what measurements need to be done to verify this process." Stevens explained. With global established protocols, both Jimenez and Stevens are excited to try to solve the answer to the case of the missing entangled photon absorption signal.

Parzuchowski, Kristen M., Alexander Mikhaylov, Michael D. Mazurek, Ryan N. Wilson, Daniel J. Lum, Thomas Gerrits, Charles H. Camp Jr., Martin J. Stevens, and Ralph Jimenez. "Setting Bounds on Entangled Two-Photon Absorption Cross Sections in Common Fluorophores." Physical Review Applied 15(4): 044012 (2021).

Written by Kenna Castleberry

Building a Cavity Superconductor

The idea of quantum simulation has only become more widely researched in the past few decades. Quantum simulators allow for the study of a quantum system that would be difficult to study easily and quickly in a laboratory or model with a supercomputer. A new paper published in *Physical Review Letters,* by a collaboration between theorists in the Rey group and experimentalists in the Thompson laboratory, proposes a way to engineer a quantum simulator of superconductivity that can-measure phenomena that, so far, are inaccessible in real materials.

JILA Fellow, NIST Physicist, and Adjoint Physics Professor James Thompson explained: “We are trying to simulate this much more complicated system. If we have all the ingredients that we want and have the probes we want, because it’s an artificial system we have the favorability that we are not constrained by problems such as femtosecond timescales. We have the timescale set by our ingredients, which are more favorable. We see the same physics but with different components building it up.” The published paper highlights the importance of using quantum simulators to access difficult areas of research.

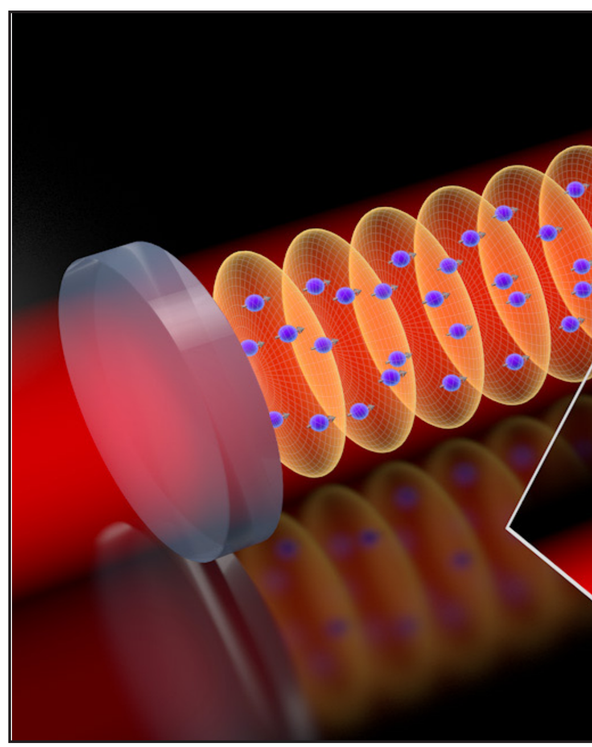
A New Way of Exploring Superconductivity:

Conventional superconductors, also known as the Bardeen-Cooper-Schrieffer (BCS) superconductors in honor of John Bardeen, Leon Cooper, and John Robert Schrieffer, who first developed a theory that explained auperconductors' microscopic origin, have been studied by physicists for decades. Besides their fundamental interest, what makes superconductors important is their ability to sustain a persistent current without the need of a power source due to their zero electrical resistance and their capability to expel magnetic fields from their interior.

In a BCS superconductor, under specific conditions and below a critical temperature, electrons can overcome their electrostatic repulsion and manage to attract each other, forming Cooper pairs. When Cooper pairs are created, the material becomes a superconductor. In real materials, superconductivity is induced by slowly changing the system parameters such as temperature or pressure in a way that the material remains always at thermal equilibrium.

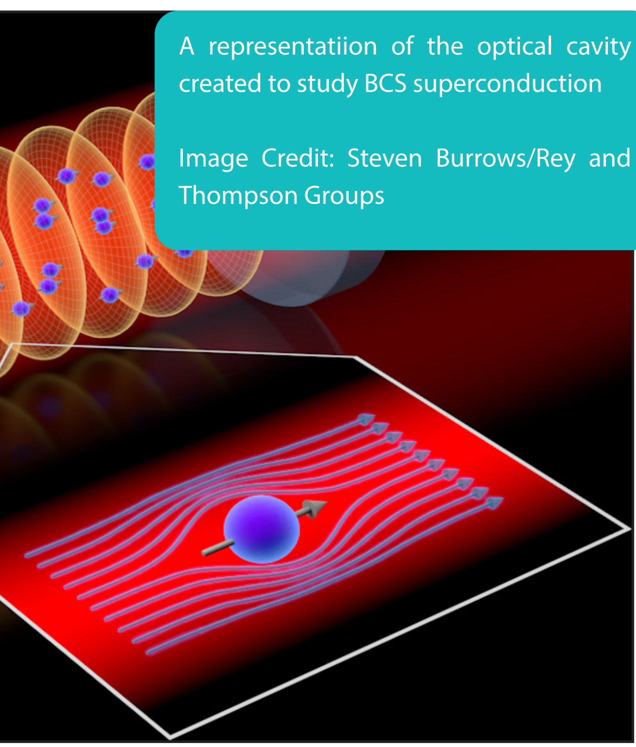
The Rey group and Thompson laboratory were looking at superconductors differently. The team focused instead on abrupt, or dynamical, changes in parameters where the transition between a normal and a superconducting system happens suddenly. However, to avoid cooling the system down to a low critical temperature, the Rey group proposed a different method of studying dynamical changes in superconductivity: Instead of using Cooper pairs made of electrons in solids, they proposed to use atoms with two internal levels interacting via the exchange of photons in an optical cavity. The two internal states served as a spin degree of freedom. In that way, atoms in the optical cavity would act as a quantum simulator of a BCS superconductor.

As Ana Maria Rey, JILA Fellow, NIST Fellow, and Adjoint Physics Professor, described: “An optical cavity is formed by two mirrors which



allow light to bounce back and forth between them many times. Only a small part leaks outside the mirrors. An atom inside an optical cavity can emit a cavity photon and flip its spin from up to down." The spin flip-floping process mediated by the photons can emulate the attractive interactions experienced by electrons in a superconductor that lead to the formation of Cooper pairs.

First author Robert Lewis-Swan clarified that the team encoded the presence or absence of a Cooper pair into the atomic spin degree of freedom. "We have this spin-half degree of freedom, and we can translate that to: do we have a Cooper pair or don't we have a Cooper pair?" Not only could the proposed cavity scheme allow for the researchers to learn more about dynamical processes in superconductors, but could also allow them to easily manipulate parameters within the simulator to access regimes not possible in solid state systems. Lewis-Swan added: "We have the control to shift the kinetic energies of the individual Cooper pairs by applying additional optical fields or magnetic fields to the atoms in the cavity, or by using different internal levels of strontium atoms." These extra controls would let the team tune the system with the quantum simulation, something difficult to achieve in a superconductor.



A representatiion of the optical cavity created to study BCS superconduction

Image Credit: Steven Burrows/Rey and Thompson Groups

Light Leaking out of the Cavity: An Excellent Probe?

In addition to atoms inside the optical cavity letting both the Rey and Thompson team emulate the behavior of Cooper pairs in a superconductor, the light emitted out of the cavity would allow them to dynamically extract information on the behavior of the atoms without perturbing them. According to Lewis-Swan: "Because we have a cavity, and because our Cooper pairs kind of talk through the cavity, the light that bounces between the mirrors can eventually leak out. Essentially, information about the effective Cooper pairs inside the cavity is mapped onto that light field. So, in principle, if we put a detector outside and watch the light coming out, we can actually learn about what is going on inside the cavity in real time." Thompson added: "We actually can think about our atoms as described by some kind of arrow that points in space. Basically, the arrow tells us information about what the Cooper pairs are doing. That's really building on these techniques called quantum non-demolition measurements that often happen in my lab in both the rubidium and strontium experiments. But, it's being done in a really weird limit. It's a particularly strange limit you have to work in because the dynamics are still kind of fast compared to how fast the cavity itself likes to respond."

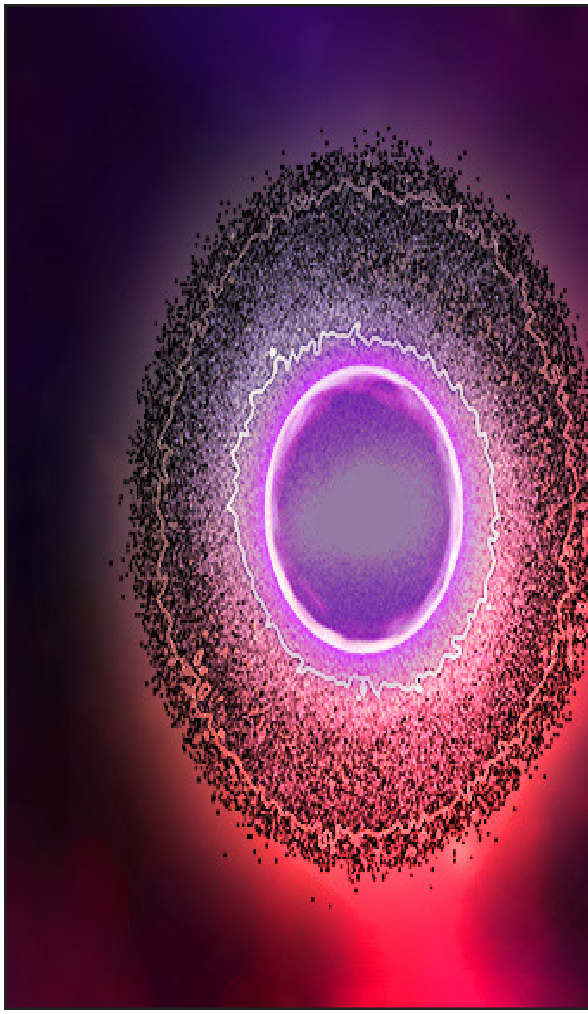
Although the current paper summarizes the theoretical proposal and explains the types of control the experiment needs to achieve to observe dynamical phases of superconductors in JILA's cavity simulator, the Thompson group expects to be able to actually observe the phases and the predicted emergent dynamical behaviors for the first time in an experiment soon.

The building of this cavity setup illustrates the importance of quantum simulators within research, as they allow the researcher to push the limits of science further in search of new knowledge.

Lewis-Swan, Robert J., Diego Barberena, Julia R.K. Cline, Dylan J. Young, James K. Thompson, and Ana Maria Rey. "Cavity-QED Quantum Simulator of Dynamical Phases of a Bardeen-Cooper-Schrieffer Superconductor." Physical Review Letters 126(17): 173601 (2021).

Written by Kenna Castleberry

Galaxy Quest: Stellar Bars and Dark Halos



When it comes to galaxies in our universe, there is still much work to do. Part of this work is being done by JILA Fellow and Assistant Professor of Astrophysics, Ann-Marie Madigan, and postdoc Dr. Angela Collier. In a recent paper published in *The Astrophysical Journal,* Collier and Madigan postulate that the evolution of a galaxy can be affected by dark matter interacting with the stars within the galaxy. Like everything else, Galaxies evolve over billions of years, changing shape, speed of rotation, and other factors. Studying what effects galaxy evolution is important in answering questions about the foundation of our universe, of how stars and planets are formed, and the origins of dark matter.

The Importance of Dark Matter Halos

The type of dark matter being studied by Collier and Madigan is in the form of a dark matter halo. All galaxies live within these massive, invisible dark matter halos. While these halos have never been observed directly, their presence has been inferred from their gravitational effects on a spiral galaxy's rotation curve. These dark matter halos are important as they provide clues to the origins of dark matter, and how it interacts with other matter.

According to Collier: "We are looking at how dark matter affects the material we can observe. By studying the interaction between the dark halo and the stars, we can look at other galaxies and see how the stars are moving and, hopefully, make inferences about what the dark matter is doing in those systems." Dark matter halos can also hint at galaxy formation. Madigan explained that "what Angela's work is showing is that dark matter evolves in response to baryonic material (this is the material we can observe---stars and gas for example). It sometimes forms really interesting and unexpected structures that are not at the center of the galaxy. So, it gives us new places to look for evidence of dark matter." In studying the effects of these dark matter halos, Collier and Madigan found that a fraction of this dark matter spun in an opposite rotation to the stellar bar. Stellar bars are clusters of stars that travel in a group, as if they're rigidly connected. These opposite rotations would make it easier to see and study the dark matter, answering many important questions.

Stellar Bars and Galaxy Evolution

In their paper, Collier and Madigan postulated that dark matter halos must be coupled with stellar bars. Collier explained how a stellar bar functions: "Stellar bars are the drivers of galaxy evolution; they funnel angular momentum throughout the galaxy. The stellar bar rotates as a solid object and

A model of isodensity contours for the surface density of the stellar disks for three galaxy models.

Image Credit: Steven Burrows/Madigan Group

as it does that, it kind of hits the dark matter halo and slows down. In this way it can move angular momentum to the dark matter halo. But also, the stellar bar is this deep gravitational well that can trap dark matter which forms the dark matter bar. The strength of your dark bar can affect how much the [stellar] bar slows down over time." Using numerical simulations, Collier and Madigan theorized that the dark matter halos and stellar bars interacted over billions of years to affect the formation of a galaxy's structure and shape. This shift in shape could affect how the galaxy evolved over these billions of years. This galaxy evolution is what Collier plans to focus on in the next phase of her work as she studies galaxies that are closer to home. "The next steps will be trying to simulate a more representative model of our galaxy. One that looks more like the Milky Way and then makes a prediction of what we think the dark matter bar at our galactic center looks like and what the observables of that would be."

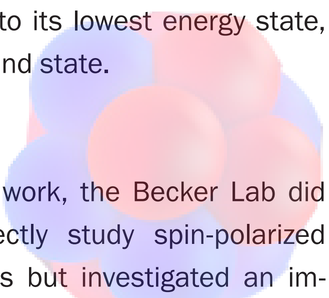
Collier's and Madigan's work will be tested when new galactic surveys are completed using the soon-to-be-launched James Webb Space Telescope. The team also postulates that using their theory of coupling dark halos and stellar bars could help explain the exotic structures that make up observed galaxies. Collier is looking forward to continuing to study these dark halos and stellar bars. She has received a prestigious NSF postdoctoral fellowship to fund this research.

Collier, Angela, and Ann-Marie Madigan. "The Coupling of Galactic Dark Matter Halos with Stellar Bars." The Astrophysical Journal 915 (1): 23. (2021)

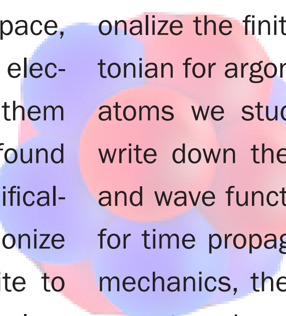
Written by Kenna Castleberry

The Atomic Trampoline

The process of creating spin-polarized electrons has been studied for some time, but continues to surprise physicists. These types of electrons have their spin aligned in a specific direction. The probability of creating a spin polarized electron from an atom tends to be rather small except in some very specific situations. Yet, in a new paper published in *Physical Review A*, JILA graduate student Spencer Walker, former graduate student Joel Venzke, and former undergraduate student Lucas Kolanz in the Becker Lab theorized a new way towards enhancing this probability through the use of ultrashort laser pulses and an electron's doorway states. These doorway states are excited states of an electron in an atom that are closest to its lowest energy state, the ground state.



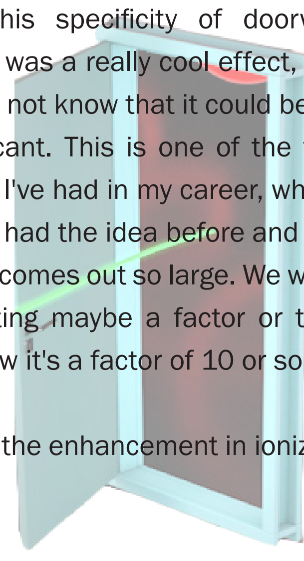
In their work, the Becker Lab did not directly study spin-polarized electrons but investigated an important step towards producing such electrons via these doorway states. Atoms have a set of electrons that rotate in one direction around the atom, while another set of electrons rotate in the opposite direction: the co-rotating and counter-rotating electrons. The Becker Lab used a circularly polarized laser pulse, in which the electric field rotates in space, to initiate ionization in these electrons, a process that causes them to leave the atom. And, they found that doorway states can specifically enhance the probability to ionize electrons that rotate opposite to the rotation direction of the electric field of the laser.



The ionization process is different for the counter-rotating electrons as compared with the co-rotating electrons. According to JILA fellow Andreas Becker: "The counter-rotating electrons can use excited states as a trampoline and can jump out with a higher probability. For certain wavelengths of the laser these doorway states can only be accessed by the counter-rotating electrons, but not by the co-rotating electrons. So, the trampoline, can only be used by the counter-rotating electrons."

Jumping with Computer Codes

To study this further, the team used computer codes to determine what was happening. In describing the process, Spencer Walker explained: "We used two codes we wrote: a grid code and a basis code. For the basis code we diagonalize the finite-difference Hamiltonian for argon and neon, the two atoms we studied, and then we write down the dipole interaction and wave function in energy basis for time propagation." In quantum mechanics, the Hamiltonian is an operator describing the interactions of the electrons in the atom and with the laser field, here being the counter- and the co-rotating electrons. From their work, the Becker Lab could show that since counter-rotating electrons are the only ones able to access the doorway states, their ionization probability can be 10 times greater than that of their co-rotating electron counterparts. This large difference was surprising to the whole team. "You come in with a theoretical prediction, so you have a picture in your mind," Becker said, "And all four of us working on this thought that this specificity of doorway states was a really cool effect, but we did not know that it could be so significant. This is one of the few times, I've had in my career, where you've had the idea before and the effect comes out so large. We were expecting maybe a factor or two, but now it's a factor of 10 or so."



Since the enhancement in ionizing

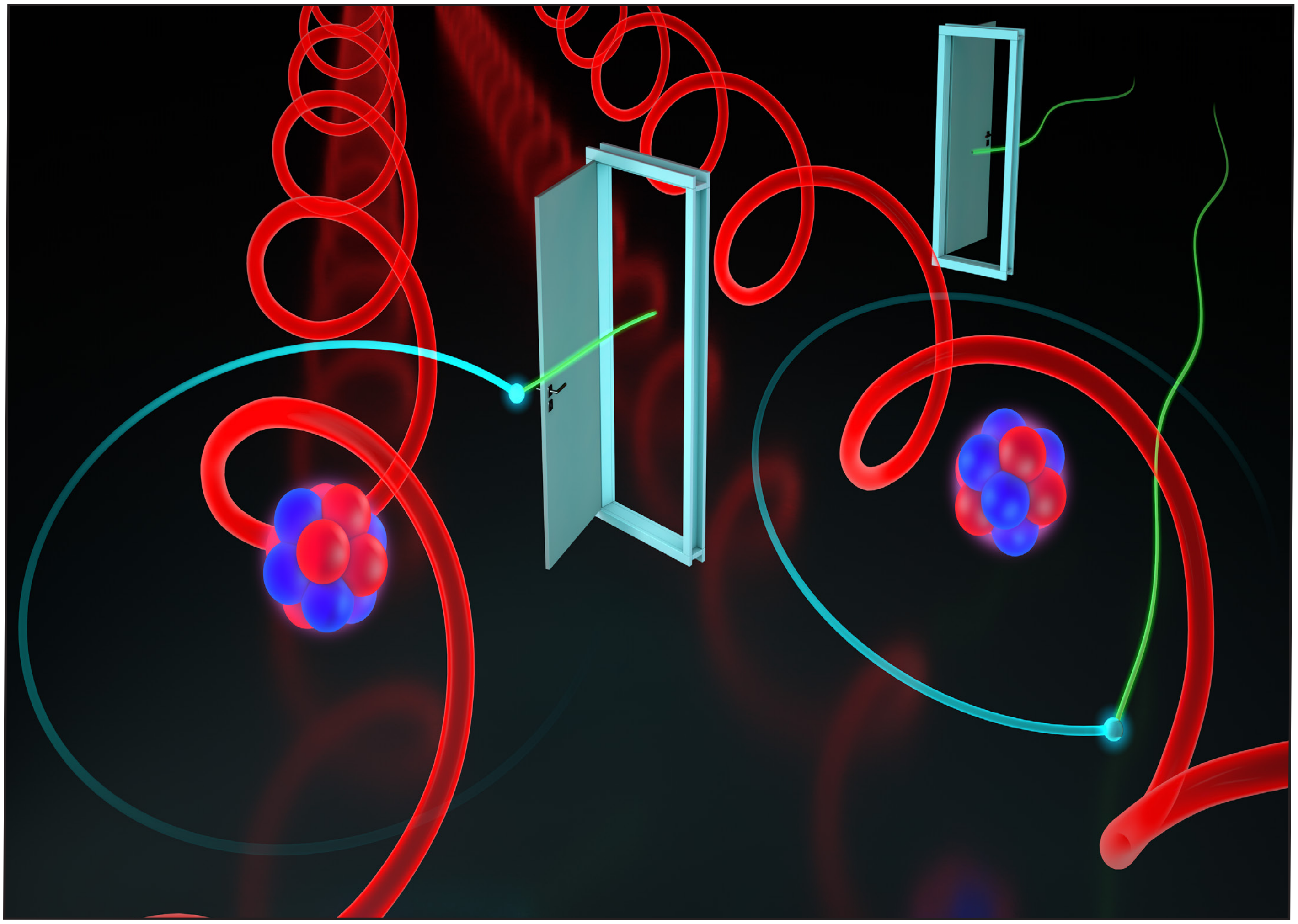
a specific set of electrons---here those counter-rotating with respect to the laser field---is an important step towards generating spin-polarized electrons, both Walker and Becker believe that their proposed method would make this process more efficient. "In these laser pulses that we are studying theoretically, you create electrons in very short pulses," Becker clarified. “These short pulses can allow you to do pump-probe experiments. And this may be opening an alternative pathway toward probing magnetic materials on ultrafast timescales." Becker and Walker both look forward to other physicists expanding on their work to produce spin-polarized electrons.

Walker, Spencer, Lucas Kolanz, Joel Venzke, and Andreas Becker. "Enhanced Ionization of Counter-rotating Electrons via Doorway States in Ultrashort Circularly Polarized Laser Pulses." Physical Review A 103(6): L061101 (2021).

Written by Kenna Castleberry

A model of the dorway states taken by counter-rotating electrons

Image Credit: Steven Burrows/Becker Group



Wiggles in Time: The Search for Dark Matter Continues

In a new paper published in *Physical Review Letters,* JILA and NIST Fellows Eric Cornell, Jun Ye, and Konrad Lehnert developed a method for measuring a potential dark matter candidate, known as an axion-like particle. Axion-like particles are a potential class of dark matter particle which could explain some aspects of galactic structure. This work is also a result of collaboration with Victor Flambaum who is a leading theorist studying possible violations of fundamental symmetries.

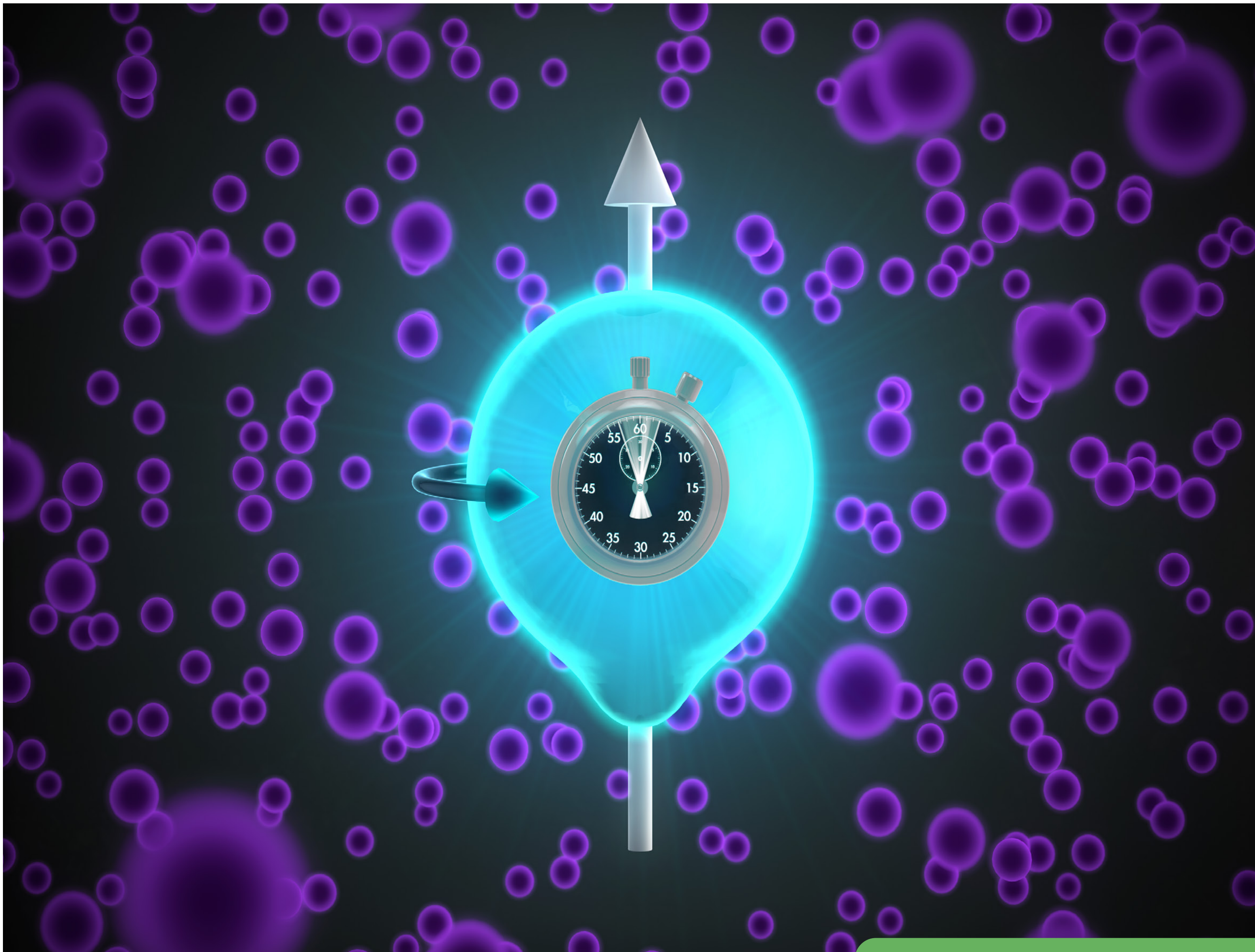
The microscopic nature of dark matter has been a looming question within physics for decades. According to first author Tanya Roussy: "Dark matter is one of the biggest unsolved mysteries in modern physics. And the problem is that it could be anything. We don't know what it is." Dark matter is a tricky thing to study ---so far, the only way to detect its presence is through its gravitational signatures in astrophysical measurements. Being able to detect dark matter through its couplings to earth-bound ordinary matter or fields would allow physicists to better understand the particle nature of dark matter, which is essential for understanding the majority of matter in our universe.

How to find something invisible

Searching for the nature of dark matter wasn't straightforward or easy. Roussy explained: "You kind of have to look everywhere, which is really hard. If we had some kind of guess for what it might be, we could narrow our search and maybe find it. So being able to do searches over a really big parameter space is really important right now. In the case of dark matter, we consider mass. So, there's 40 orders of magnitude that the mass could be in. And that's really, really big. So being able to search over something like seven orders of magnitude is a nice way to put a dent in that search."

When trying to measure an elusive particle, sensitivity is key. JILA's team leveraged a very sensitive measurement they already had to look for signatures of their dark matter candidate: their ongoing electron electric dipole moment measurement (eEDM). JILA fellow Konrad Lehnert noted that "the main significance of this paper is that the Cornell and Ye group experiment that tries to measure EDM would also be sensitive to axion-like particles." If the dark matter in our universe was actually made up of axion-like particles, things like the eEDM would actually "wiggle" in time as the dark matter waves passed by them, like a rubber duck bobbing on the waves in a bathtub. According to Roussy: "We took an old data set and reanalyzed it...until now we always assumed our signal was constant in time. Instead we said, 'what if it actually wiggles in time?' So, we were basically checking for a wiggle in the signal." Lehnert's group had experience in other axion search experiments and assisted with the data analysis.

This collaboration allowed the team to develop a set of protocols for using eEDMs to detect axion-like particles. "What we did was put together a recipe that other people can use to do these kind of searches on their own, if they have sensitive measurements of this sort." Roussy commented. "We think is better than many oth-



A representation of time oscillations in the EDM due to interactions with the dark matter particles around the EDM

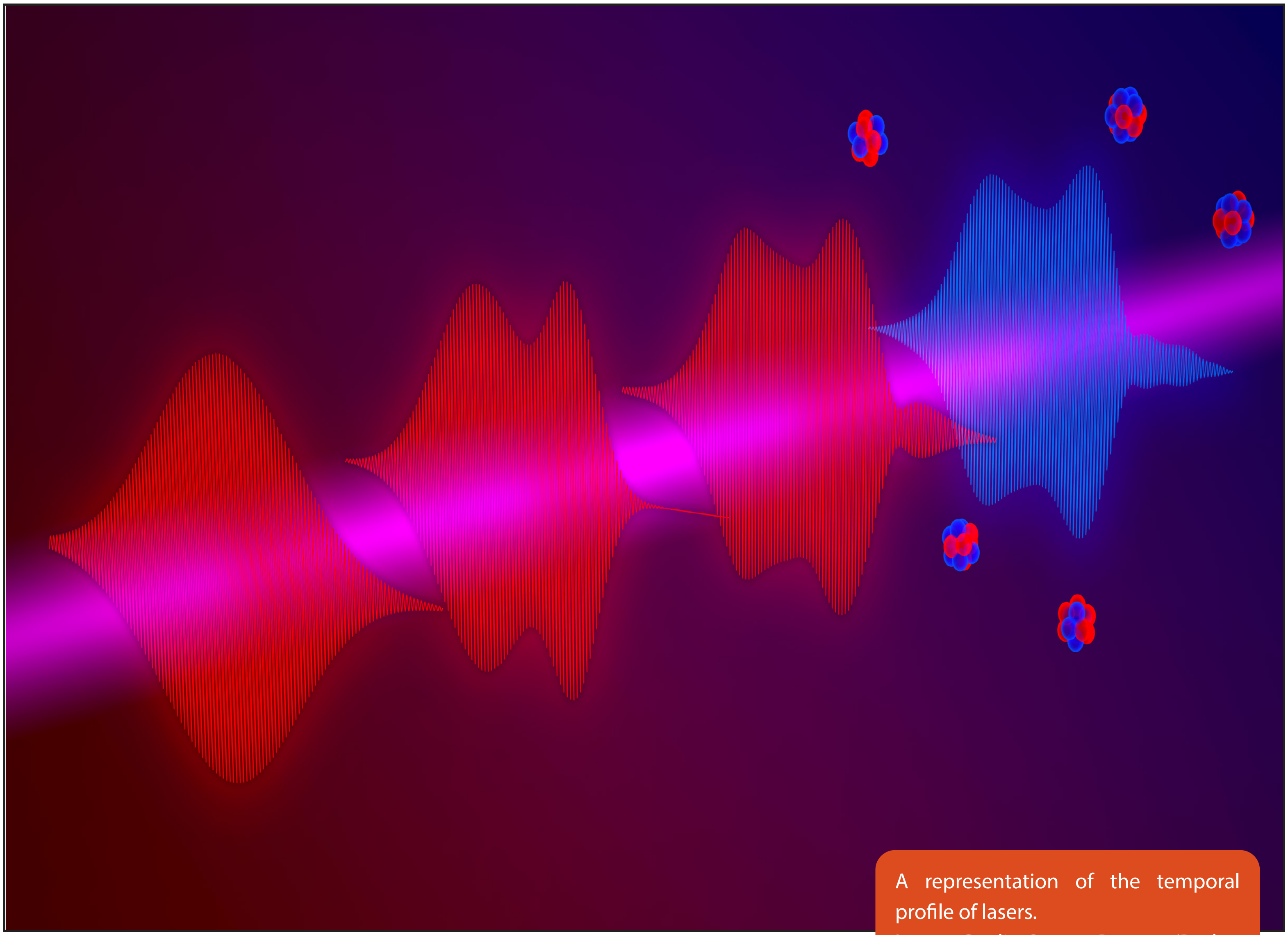
Image Credit: Steven Burrows/Ye, Cornell, and Lehnert Group

er recipes that are out there because it solves some problems that people have been ignoring until now." These protocols will hopefully assist other labs in searching for the nature of dark matter, and advance scientific knowledge about dark matter in a more efficient way.

Roussy, Tanya S., Daniel A. Palken, William B. Cairncross, Benjamin M. Brubaker, Daniel N. Gresh, Matt Grau, Kevin C. Cossel, Kia Boon Ng, Yuval Shagam, Yan Zhou, Victor V. Flambaum, Konrad W. Lehnert, Jun Ye, and Eric A. Cornell. "Experimental Constraint on Axionlike Particles over Seven Orders of Magnitude in Mass." Physical Review Letters 126(17): 171301 (2021).

Written by Kenna Castleberry

Reconstructing Laser Pulses



A representation of the temporal profile of lasers.
Image Credit: Steven Burrows/Becker and Jaron-Becker Groups

Many physicists use lasers to study quantum mechanics, atomic and molecular physics and nanophysics. While these lasers can be helpful in the research process, there are certain constraints for the researcher. According to JILA Fellow Andreas Becker: "For certain wavelengths of these laser pulses, such as deep ultraviolet, you may not know, or not be able to measure, the temporal profile." The temporal profile of a laser pulse is, however, important for researchers when analyzing data. "A lot of people cannot fully analyze their data, because they don't know the details of the pulse that was used to produce the data," said graduate student Spencer Walker. As a way to research this constraint, the Becker and Jaron-Becker laboratories collaborated to publish a paper in *Optics Letters*, suggesting a possible solution.

With a Little Help from Chemistry

When looking for a possible solution to solving the temporal profile problems at certain wavelengths, Spencer Walker and former graduate student Ran Brynn Reiff turned to simulations, statistics, and other research areas. Becker explained: "it was so essential to have Brynn Reiff there. He was simulating these kinds of pulses for his whole Ph.D., and from his work we could simulate how these pulses look without using experiment." Key in their studies was to use the ionization signal produced by duplicates of the unknown simulated pulse, which were delayed in time relative to each other---a method called autocorrelation. The process of ionization happens when an atom or molecule acquires a positive charge by losing electrons when interacting with the laser pulses.

In their calculations, the team compared the ionization signal from the unknown pulse to those calculated from theoretical temporal profiles using Gaussian functions. Gaussian functions have many applications, for example, in statistics they are used as the density function of the normal distribution of data. First author Spencer Walker applied these Gaussian functions in a particular way to the simulations in order to suggest theoretical temporal profiles of laser pulses. "I really just got the idea from chemistry," Walker stated. "Chemists represent the quantum mechanical electronic wave function using Gaussian functions. We took the electric field of the laser and decided to expand it using Gaussian functions as well. And since for the ionization probability we had analytic formulas when using Gaussian functions, we were able to do calculations much faster than if we had to do the entire problem numerically." From the Gaussian functions and the ionization signal via the electric field, the team was able to reconstruct the temporal profiles of the unknown pulses.

The Next Steps

After the team identified a new way to reconstruct temporal profiles of unknown laser pulses, the next steps would be to turn to their experimental colleagues. "We're looking forward to someone testing our theory with an experiment," Becker added. Time will reveal if their theory will help make other research easier. "Basically, just knowing what the pulse actually looks like is very important for a lot of applications," Reiff explained. "It's important for all sorts of very precise sensing and probing applications, where if you know exactly what your pulse looks like, then you can shine your laser on something that you don't know, and get a lot of information on the unknown object from knowing about your laser pulse. The more you know about your pulse, the more control you have over the pulse, the more you can do with it." As the JILA theorists continue looking into methods to measure temporal profiles, their research will have a positive impact on other research using lasers to study physics and other subjects.

Walker, Spencer., Reiff, Ran Brynn., Jaron-Becker, Agnieszka, Becker, Andreas. " Characterization of vacuum and deep ultraviolet pulses via two-photon autocorrelation signals." Optics Letters. (46)13: 3083 (2021).

Written by Kenna Castleberry

NIST's Quantum Crystal Could Be a New Dark Matter

Physicists at the National Institute of Standards and Technology (NIST) have linked together, or "entangled," the mechanical motion and electronic properties of a tiny blue crystal, giving it a quantum edge in measuring electric fields with record sensitivity that may enhance understanding of the universe.

The quantum sensor consists of 150 beryllium ions (electrically charged atoms) confined in a magnetic field, so they self-arrange into a flat 2D crystal just 200 millionths of a meter in diameter. Quantum sensors such as this have the potential to detect signals from dark matter—a mysterious substance that might turn out to be, among other theories, subatomic particles that interact with normal matter through a weak electromagnetic field. The presence of dark matter could cause the crystal to wiggle in telltale ways, revealed by collective changes among the crystal's ions in one of their electronic properties, known as spin.

As described in the Aug. 6 issue of Science, researchers can measure the vibrational excitation of the crystal—the flat plane moving up and down like the head of a drum—by monitoring changes in the collective spin. Measuring the spin indicates the extent of the vibrational excitation, referred to as displacement.

This sensor can measure external electric fields that have the same vibration frequency as the crystal with more than 10 times the sensitivity of any previously demonstrated atomic sensor. (Technically, the sensor can measure 240 nanovolts per meter in one second.) In the experiments, researchers apply a weak electric field to excite and test the crystal sensor. A dark matter search would look for such a signal.

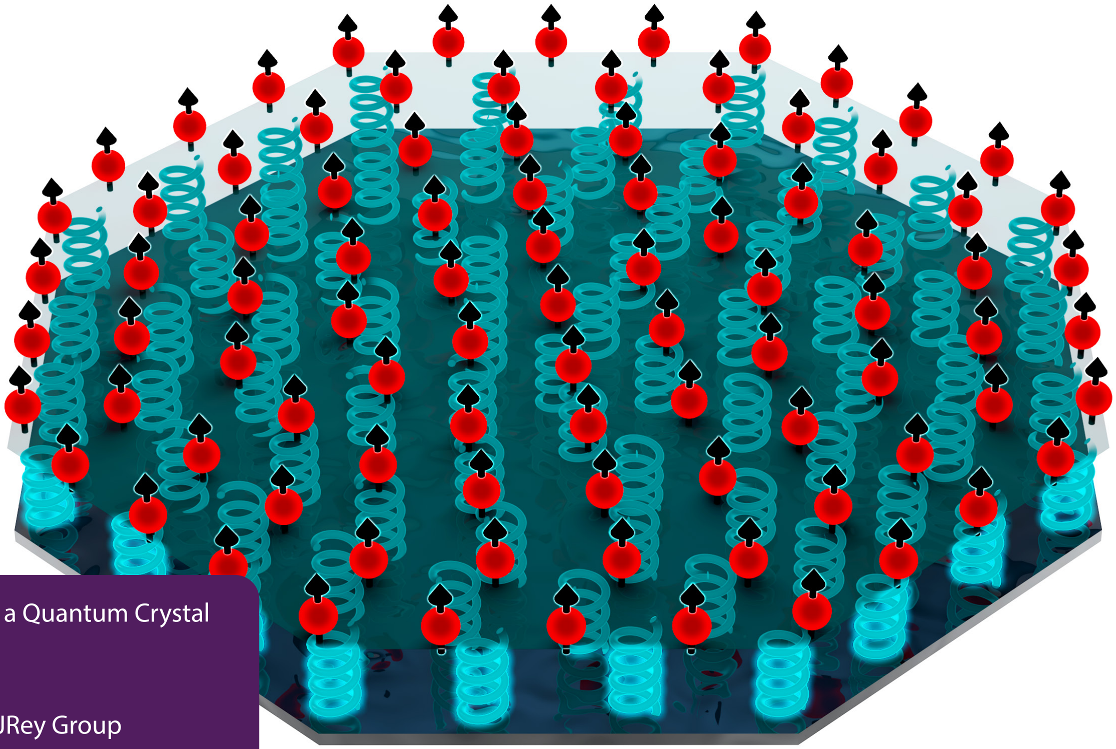
"Ion crystals could detect certain types of dark matter—examples are axions and hidden photons —that interact with normal matter through a weak electric field," NIST senior author John Bollinger said. "The dark matter forms a background signal with an oscillation frequency that depends on the mass of the dark matter particle. Experiments searching for this type of dark matter have been ongoing for more than a decade with superconducting circuits. The motion of trapped ions provides sensitivity over a different range of frequencies."

Bollinger's group has been working with the ion crystal for more than a decade. What's new is the use of a specific type of laser light to entangle the collective motion and spins of a large number of ions, plus what the researchers call a "time reversal" strategy to detect the results.

The experiment benefited from a collaboration with NIST theorist Ana Maria Rey, who works at JILA, a joint institute of NIST and the University of Colorado Boulder. The theory work was critical for understanding the limits of the laboratory setup, offered a new model for understanding the experiment that is valid for large numbers of trapped ions, and demonstrated that the quantum advantage comes from entangling the spin and motion, Bollinger said.

Rey noted that entanglement is beneficial in canceling the ions' intrinsic quantum noise. However, measuring the entangled quantum state without destroying the information shared between spin and motion is difficult.

"To avoid this issue, John is able



An Illustration of a Quantum Crystal

Image Credit:
Steven Burrows/JRey Group

to reverse the dynamics and disentangle the spin and the motion after the displacement is applied," Rey said. "This time reversal decouples the spin and the motion, and now the collective spin itself has the displacement information stored on it, and when we measure the spins we can determine the displacement very precisely. This is neat!"

The researchers used microwaves to produce desired values of the spins. Ions can be spin up (often envisioned as an arrow pointing up), spin down or other angles, including both at the same time, a special quantum state. In this experiment the ions all had the same spin—first spin up and then horizontal—so when excited they rotated together in a pattern characteristic of spinning tops.

Crossed laser beams, with a difference in frequency that was nearly the same as the motion, were used to entangle the collective spin with the motion. The crystal was then vibrationally excited. The same lasers and microwaves were used to undo the entanglement. To determine how much the crystal moved, researchers measured the ions' spin level of fluorescence (spin up scatters light, spin down is dark).

In the future, increasing the number of ions to 100,000 by making 3D crystals is expected to improve the sensing capability thirtyfold. In addition, the stability of the crystal's excited motion might be improved, which would enhance the time reversal process and the precision of the results.

"If we are able to improve this aspect, this experiment can become a fundamental resource for detecting dark matter," Rey said. "We know 85% of the matter in the universe is made of dark matter, but to date we do not know what dark matter is made of. This experiment could allow us in the future to unveil this mystery."

Co-authors included researchers from the University of Oklahoma. This work is supported in part by the U.S. Department of Energy, Air Force Office of Scientific Research, Defense Advanced Research Projects Agency, Army Research Office and National Science Foundation.

K.A. Gilmore, M. Affolter, R.J. Lewis-Swan, D. Barberena, E. Jordan, A.M. Rey and J.J. Bollinger. Quantum-enhanced sensing of displacements and electric fields with two-dimensional trapped-ion crystals. Science, 373(6555): 673 (2021).

Written by Laura Ost, NIST Writer

The Gap in Quantum Understanding: How to Accurately Communicate Quantum Ideas

The word "quantum" can be mysterious and unfamiliar to the general public. Most of the public's exposure to quantum technology has been Hollywood-ized and framed as a "catch-all" for hard-to-define scientific processes. From attempting to explain time travel within the TV show *Quantum Leap*, to the quantum realm of Marvel's *Avengers* series, the word "quantum" is used to fill in the explanation gaps. As the majority of viewers accept "quantum" as this catch-all, it creates a disconnection between the word's true definition and an understanding of the scientific processes behind it. Asking any non-physist if they know what "quantum entanglement" is, or if they can define "quantum superposition" will quickly reveal this lack of understanding. This misunderstanding causes problems, as quantum technology is quickly being developed and commercialized. With the "boom" in quantum technology predicted by experts, it is important to realize the repercussions of this misunderstanding. Particularly, writers, scientists, and citizens need to be aware of how to communicate and invoke to the public, an appreciation of the true science of quantum physics.

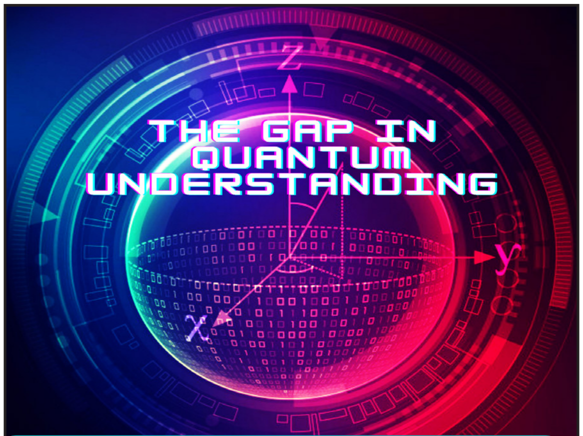
The misunderstanding of the science of quantum physics not only stems from misinformation peddled by Hollywood, but also from a lack of accurate writings about the field and its' technology. Any skilled science writer will tell you that writing about quantum technology in an accurate and accessible way, within a word-limit, is extremely difficult. Explaining the processes of superposition or quantum tunneling requires an in-depth, lengthy description. To aid in giving a human touch to quantum based articles, many writers interview key scientists. Even then, the publication of quantum articles can seem dry or boring compared to the glamorized, CGI-designed, inaccurate "quantum" scenes of movies and TV shows (Mount, Baer, & Lupoli 2021)

A further cause for the misunderstanding of quantum physics originates from the weird and unorthodox processes within the quantum world (Greene & Rogan 2021). Studying the quantum world is not intuitive, and many researchers have difficulty communicating the weirdness of quantum physics because it's not relatable to everyday experiences. For example, the quantum phenomenon of superposition, where a particle can be in two places at once, is difficult to relate to something that typically happens in an individual's day-to-day proceedings.

Another reason for the general misunderstanding is the lack of actual education of quantum physics in the majority of the public. Only a minority of people, specifically those getting higher education degrees, are exposed to quantum physics, leaving the remaining majority unsure of actual quantum physics processes and the current ongoing research.

What is Quantum Hype?

Quantum technology hype is a symptom resulting from this misunderstanding of quantum physics. This hype is defined as the expectations of the general public about technology. Consequently, most of the public doesn't have a clear grasp of what innovative new quantum technologies are capable of. According to Co-Founder and Cheif Technology Officer of ColdQuanta (a company that commercializes in quantum technology) and Fellow at JILA at the University of Colorado Boulder, Dr. Dana Anderson: "...especially of quantum computing, there was a lot of hype. There was also a lot of misunderstanding on the side of the buyers into the whole idea of what quantum can bring."



The Bloch sphere, shown here, is a representation of a qubit, the fundamental part of a quantum computer.

Quantum hype rose significantly when Google announced its partnership with NASA and Oak Ridge National Laboratory to achieve "quantum supremacy" in 2019. According to a 2020 study, quantum computing is on the upward trend of the Gartner Hype Chart (a model to describe the collective expectations of developing technology by the public). As quantum technology continues to advance, the visibility and expectations of this technology by the public increases (Smith, 2020). While the increase in interest is beneficial for companies investing in quantum technology, this interest can also be extremely detrimental to accurately communicating these quantum processes. *The Quantum Daily* science writer and Penn State professor Matt Swayne has found this to be a problem in his own work. "My issue is how do I write something that is enthusiastic and something that is interesting but is not hype. So, the real struggle for us going forward is balancing enthusiasm, interest, and hype."

How to Communicate Quantum

There isn't one right way to accurately communicate about the science of quantum physics. According to Swayne: "I always like to contextualize the information to someone's life. Unless you've personally been quantumly entangled, I wouldn't know how to describe that. Some of the analogies are fitting, such as superposition. I've tried to explain superposition as, instead of a light going on and off, it's more of a dimmer, where you can tweak the light." Many science writers and scientists have found success in using analogies to explain these difficult processes. In my work as the Science Communicator at JILA, I've worked on quantum research articles with scientists who have suggested analogies such as quantum gas pancakes, electric field knobs, or even describing entanglement as tying a knot with a string. However, these analogies can also be troublesome as they can dilute the accuracy of the science. Swaney's light analogy is helpful, "but of course there are people who will say that's not correct." This makes the communication of quantum science even more tricky.

Because quantum processes are extremely difficult to visualize; the processes become distant and foreign. Analogies help to make the quantum processes easier to visualize and understand. A study by Mount et al. in 2021 from the *Strategic Management Journal* found that the more distant a novel technological idea is from the individual, the more likely this novel idea will be perceived negatively. This becomes important for communicators of quantum physics, especially those marketing or investing in the technology. Making this mysterious and unfamiliar world more approachable for the audience adds stronger connections and contextual clues that aid understanding. When the reader becomes part of the science it makes the communication more impactful and memorable to the audience. To make quantum physics and quantum technology more understandable to a public audience, communicators must contextualize the science in the audiences' life. The science will become more relatable and understandable, while maintaining scientific accuracy.

Greene, B. & Rogan, J. (Host) The Joe Rogan Experience, Episode 1428. [Audio Podcast], Spotify Radio. (2020)

Mount, M. P., Baer, M., & Lupoli, M. J. Quantum leaps or baby steps? Expertise distance, construal level, and the propensity to invest in novel technological ideas. 42(8): 1490 (2021)

Smith, F. L. III, Quantum technology hype and national security. Security Dialogue, 51(5), 499–516.(2020)

Written by Kenna Castleberry

Introducing JEDI

What is JEDI?

JILA Excellence in Diversity and Inclusivity (JEDI) is a self-nominated group of JILAns focused on advancing effective diversity and inclusivity through education, activities within JILA, and collaboratively with the CU community. JILA actively seeks and supports diversity and inclusivity as an integral element of excellence for a collaborative and world-leading research institute JEDI includes JILA Fellows, Staff, Students and Postdocs. JEDI works closely with other equity and diversity groups within JILA and at CU Boulder generally, including Women of JILA and APS-IDEA. JEDI has been active in JILA since late 2018!

What has JEDI accomplished already?

- JEDI has worked with JILA leadership to help form a hiring committee, which is looking into JILA's current hiring policies and encouraging reforming some outdated practices. This is the first committee within JILA that has both students and fellows. The committee is hoping to provide recommendations for more equitable hiring practices within the coming months.
- An onboarding antiracism training has been created by members of JEDI to show JILA's dedication to education about difficult issues. We hope to implement this training for all new JILAns soon, and we plan to make additional training for other issues our community faces.
- JILA has welcomed Teresa Wroe from CU's Office of Institutional Equity and Compliance (OIEC) and Regan Byrd, an outside consultant, to provide education and trainings on various difficult issues to the entire JILA community. These trainings have included bystander intervention and factors involved

Members of JEDI, inlucding staff and students in oppression.

- We also have had a few fun events! We hosted a JILA community event in August 2019 to help bring the JILA community together, and we helped make possible a screening of the movie *Picture a Scientist* during the pandemic. We've also made graduate student and postdoc Slack channels on the JILA Slack in order to foster community within these groups.
- JEDI has helped reform the visiting fellows program to encourage more visitors from minority institutions. This will help JILAns form more collaborations with professors from these universities and increased diversity will boost the research both at JILA and elsewhere.

What are JEDI's future plans?

- Affinity Groups: JILA is looking to start affinity groups as a way to empower JILAns who aren't in the majority and to serve as a welcoming community for new JILAns.
- a designated "safe space" for JILAns within that group who share a particular identity, such as race or gender.
- These groups will be formed by JEDI and then will self-organize afterwards, with support from JEDI available as needed.
- The eight groups include: women, BIPOC, first generation, international, LGBTQ+, neurodiversity, non-native English speakers, and working parents.
- Week of September 13: All-JILA kickoff meeting to inform everyone about these groups and what affinity groups are
- Week of September 20: First group meetings
- These groups will also be given a space within JILA to meet and make their own.
- We are working with Regan Byrd, an outside consultant, to improve the JILA community in all possible aspects. She conducted focus groups and one-on-one interviews and has come up with a list of suggestions and recommendations for us to implement - we will need a lot of help tackling this list! She also has highlighted areas where JILA is excelling.
- We hope to continue having various targeted training for students, staff, and fellows, including training on microaggressions, allyship, and bystander training. We are also working on improving JILA's offering of professional development opportunities, including mentorship training.
- We are working on an updated JEDI website to showcase JILA's dedication to EDI issues - we are always looking for new content for our website and twitter!

Get Involved

- Contact us jila_jedi@lists.colorado.edu
- Attend a meeting - there is no time commitment! Come to as many or as few meetings as you're able to each semester
- We're always open to any ideas, suggestions, questions, or comments from the community! Feel free to email us!

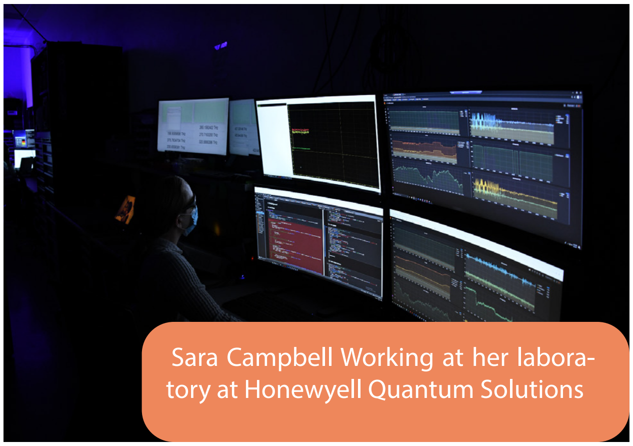
Life After JILA

One goal that JILA alumni have in common is to end up in successful jobs, whether in industry or academia. Such is the case for Sara Campbell, an employee at Honeywell Quantum Solutions who works on quantum computing. "We've released two commercial systems, system model, H0 and H1, and I'm building and getting ready for the next model, H2," Campbell said excitedly. As the quantum computing sector swells with activity and capital, Campbell's job becomes more important than ever.

Campbell has followed a desire to make a positive impact on society throughout her whole life, and including her time at JILA. She enjoyed working on some of the most cutting-edge physics during her work as a Ph.D. student at JILA. "My favorite thing was all the shared resources, like the machine shop and the electronic shop," stated Campbell. "Jun Ye was my advisor and I worked on one of the strontium experiments." Sara jokes, "The big thing I did as a grad student was disassemble the world's most accurate clock at the time." More seriously, she explains, "I think collisions between strontium atoms were sort of a thing that could limit clock performance, or limit how many atoms you could have total. So, rebuilding our experiment as a degenerate gas experiment should help long-term clock development efforts, as well as provide a fun playground for quantum physics." Campbell would take this interest in quantum engineering with her when she transitioned out of JILA. Campbell said, "After I graduated, I did a two-year postdoc at UC Berkeley, actually in electron microscopy, pretty different. We made the world's most intense laser in order to manipulate the electron wavefunction to extract more information from fragile biological samples."

The community at UC Berkeley taught Campbell essential skills, and she was grateful for the opportunity to learn about electron microscopy and proteins. After her Ph.D. and postdoc, Campbell wasn't quite sure what step she wanted to take next. "I was thinking about what I wanted to do, career wise. And so many of my former JILA colleagues were working at Honeywell, and they all seemed really happy. I just wanted to make an impact and do something that hopefully would be really useful," Campbell beamed. She then observed, "It seemed to me that in especially in biology and medicine, a lot of the more recent breakthroughs were computational, even in my field of electron microscopy of biological macromolecules. And so, as a hardware person, I thought, 'how do you like help with that effort?' I thought working at Honeywell was sort of the best option for me." Campbell said that she applied to Honeywell during the second year of her postdoc, and was fortunate enough to get accepted.

She enjoys the work she does at Honeywell, knowing it is impacting our understanding of quantum computing, and is helping to advance technology. When asked about what advice she would give to those looking forward in their careers, Campbell replied, "Don't put too much pressure on yourself to make the right choice right now, because I don't think there's a single right choice. You can always do something for a while and then try something else later."



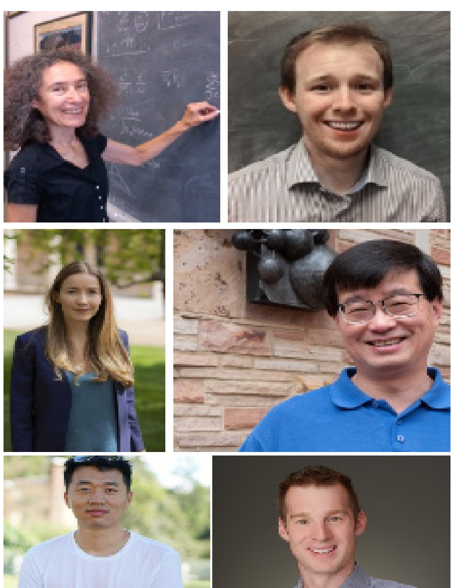
Sara Campbell Working at her laboratory at Honewyell Quantum Solutions

News and Awards

Former JILAn Philip Makotyn joined CUbit Quantum Initiative as executive director. In an interview with science writer, Daniel Strain, Makotyn said: “I’m thrilled to join CU Boulder and the CUbit Quantum Initiative. The university has a world-leading set of researchers and institutes pushing the frontiers of quantum physics and engineering."

Former JILA Fellow Ellen Zweibel has been elected to National Academy of Sciences. Zweibel was a faculty member at the University of Colorado, Boulder for over 20 years. Zweibel's successful research was previously recognized when she was awarded the American Physical Society's Maxwell Prize for Plasma Physics in 2016.,,

Awards



Clockwise from top: Former JILA Fellow Ellen Zweibel, JILA Student William Milner, JILA Fellow Jun Ye (taken by NiST), CUbit Director Philip Makotyn, JILA Fellow Shuo Sun, and JILA Fellow Ann-Marie Madigan

JILA and NIST Fellow Jun Ye won the 2021 Julius Spriner Prize! The Julius Springer Prize for Applied Physics recognizes researchers who have made an outstanding and innovative contribution to the field of applied physics. It has been awarded annually since 1998 by the editors-in-chief of the Springer journals *Applied Physics A – Materials Science & Processing and Applied Physics B – Lasers and Optics.*

Ann-Marie Madigan won the 2021 Vera Rubin Early Career Prize. CU Boulder astrophysicist Ann-Marie Madigan has taken home a prestigious prize in recognition of her research exploring the dynamics of objects in space—from stars circling black holes to icy dwarf planets in the outer solar system.

NIST and JILA Fellow Jun Ye is Highlighted as one of the Department of Commerce's AANHPI Pioneers. The Department of Commerce is proud to join the Nation in recognizing the Asian American, Native Hawaiian, and Pacific Islander (AANHPI) Heritage Month, also known as Asian American Pacific Islander (AAPI) Heritage Month. Observed annually in May, AANHPI Heritage Month is a time to reflect upon and celebrate the remarkable role of the AANHPI community in our Nation’s history. Dr. Jun Ye has been highlighted as a leader within these pioneers.

JILA Student William Milner won the 2021 GPMFC Student Poster Prize at DAMOP. The Group for Precision Measurement and Fundamental Constants (GPMFC) Student Poster Prize awarded Milner's poster at DAMOP, the major annual meeting of the American Physics Society's Division of Atomic, Molecular & Optical Physics.

JILA Fellow Shuo Sun won the Ralph E. Powe Junior Faculty Enhancement Award. Sun and fellow recipients will receive $5,000 in seed money for the 2021--22 academic year to enhance their research as they launch their academic careers. Each recipient’s institution matches the award, and winners may use the $10,000 grants to purchase equipment, continue to research or travel to professional meetings.

JILA Fellow Shuo Sun is awarded a prestigious W.M. Keck Foundation Grant. Sun received a $1 million grant from the W.M. Keck Foundation to develop a first-of-its-kind quantum simulator that could be used to develop novel materials and, in the future, lead to the development of a high-performance quantum computer.

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