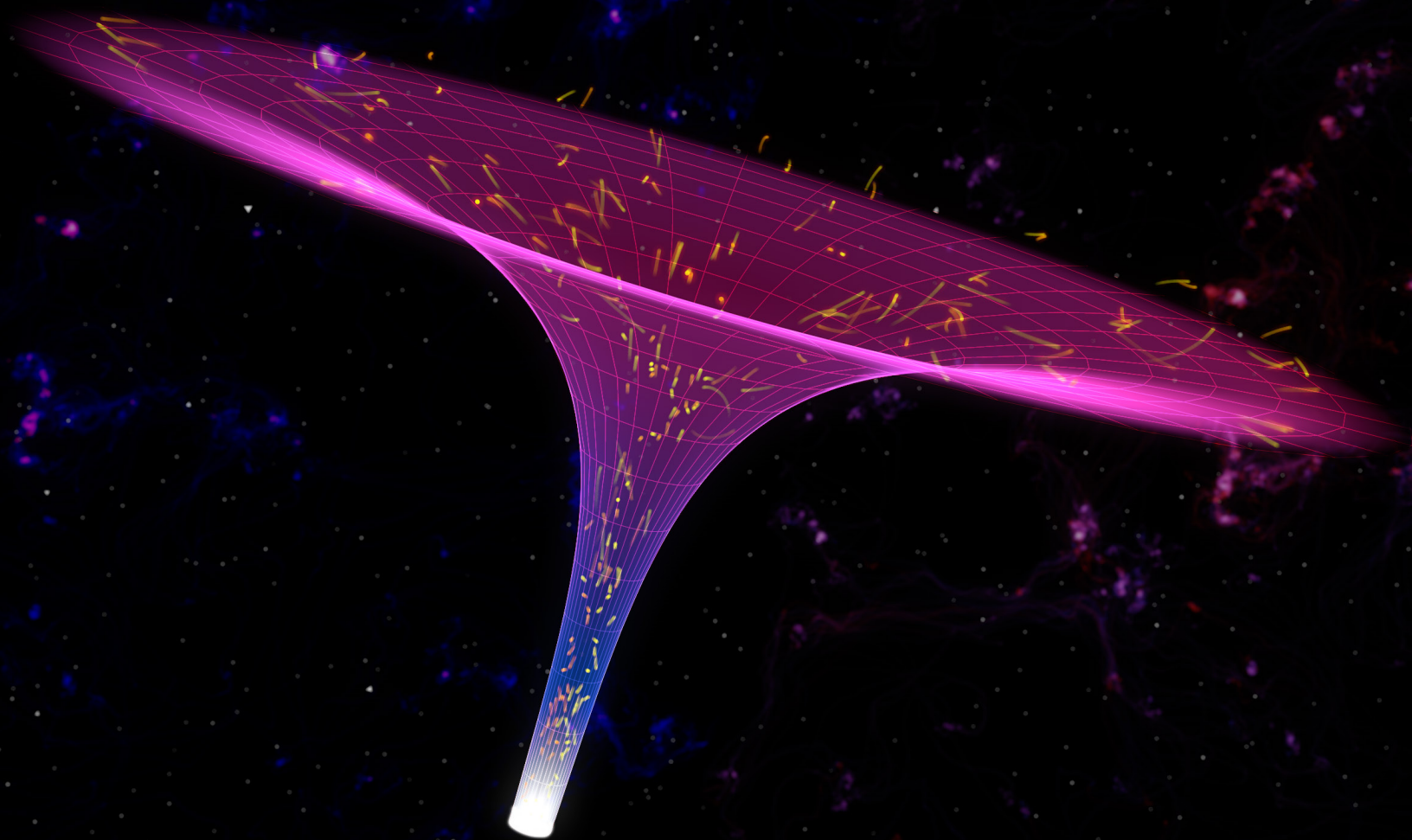


# LIGHT + MATTER

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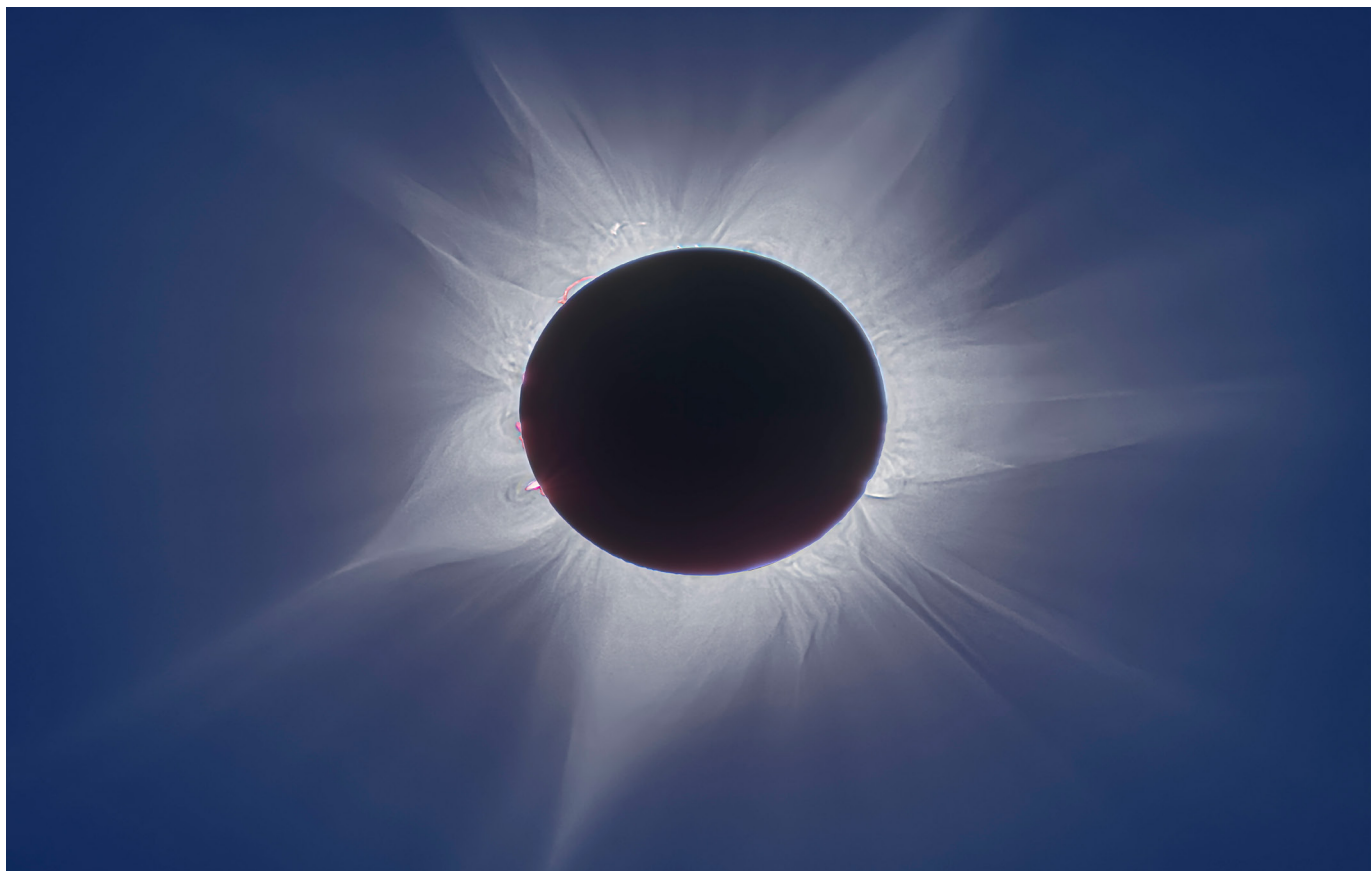


**Falling into a  
Black Hole  
pg. 1**

**JILA**  
CU Boulder and NIST

Total eclipse of the Sun observed on April 20, 2023 at Exmouth, Western Australia. Note that the corona is structured by the Sun's magnetic field and is white due to electron scattered solar photospheric emission. The next total solar eclipse will cross the United States on April 8, 2024.

Credit: JILA Fellow Adjoint, Jeffrey Linksy and Fred Espanak



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# Research Highlights



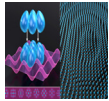
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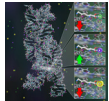
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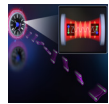
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# What Happens When You Fall into a Black Hole?

For decades, black holes have fascinated scientists and non-scientists alike. Their ominous voids, like an open pair of jaws, has inspired a whole wave of science-fiction featuring the phenomenon. Physicists have been similarly inspired, specifically to understand the dynamics of what is happening inside of the black hole, especially for objects that may fall in. The historical theories about black holes are closely linked to those within quantum physics and they suggest interesting phenomena. “The best models of black holes we have in general relativity, like the Kerr metric or the Reissner-Nordström metric, actually make some pretty crazy predictions,” explained JILA graduate student Tyler McMaken. “After you fall in, you eventually reach a spot, called the inner horizon, where we can enter into a wormhole, see a naked singularity [A region in space-time at which matter is infinitely dense], time-travel, and do a bunch of things that go against what we think should be physically possible.” To better understand the quantum mechanics of these black hole models, McMaken and JILA Fellow Andrew Hamilton looked into the quantum effects that may be happening around and inside a black hole. From their research, they found that there was

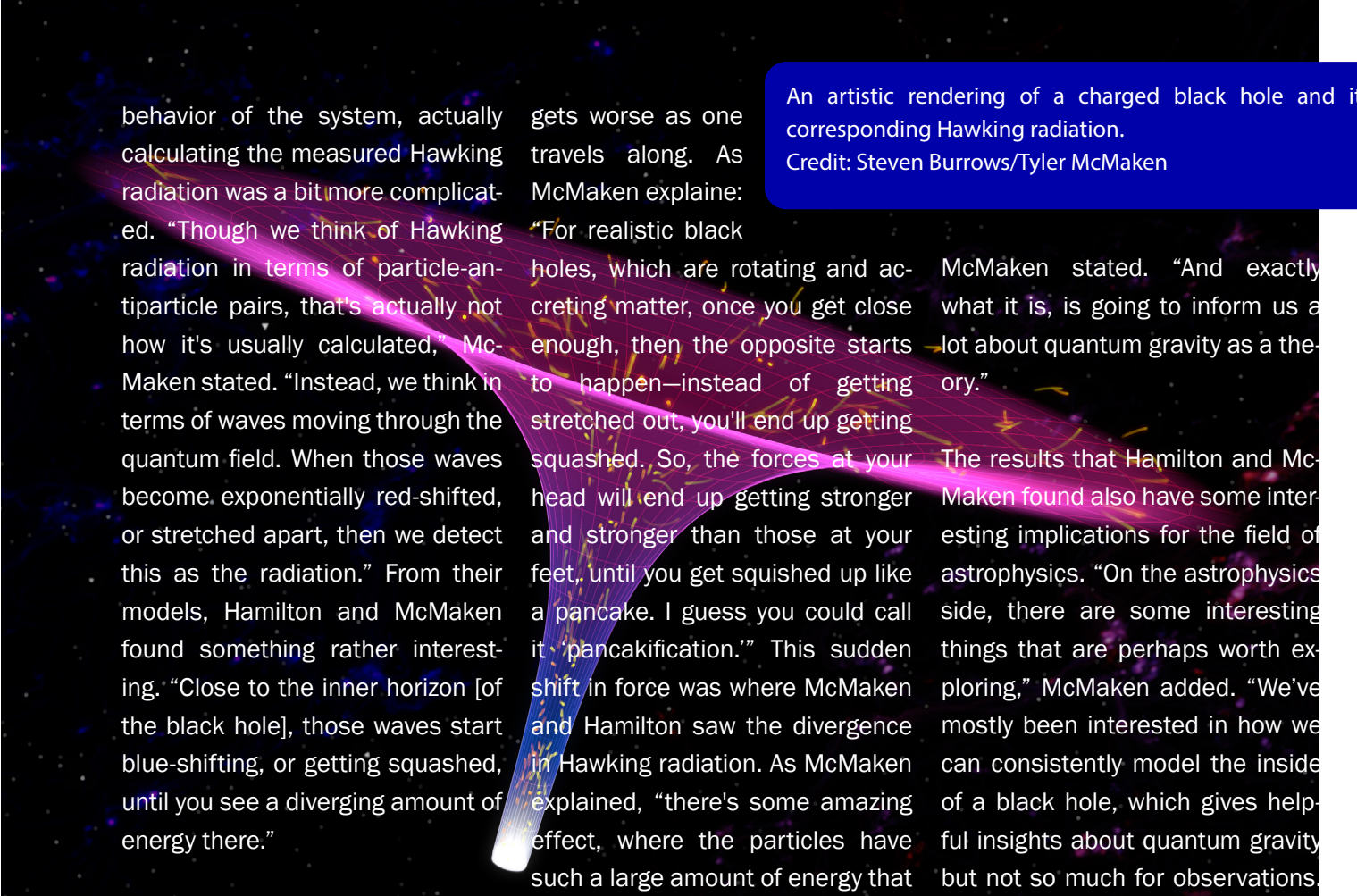
a divergence of energy into multiple levels at the inner horizon of the black hole, suggesting that quantum effects play a crucial role in how to model realistic black holes. “The exciting part of this research is the discovery that quantum effects save the day—as you approach the inner horizon, you’re met with a wall of diverging energy from Hawking radiation, so that any weird, causality-violating parts of the spacetime are completely blocked off and replaced with a singularity,” McMaken added. This diverging energy split the radiation into multiple levels. “Without a full theory of quantum gravity, we won’t know exactly what happens at this singularity, but we do know that just like the Big Bang singularity, or the singularity we might find in simpler spherical black holes, it marks the end of spacetime as we know it as the curvature exceeds the Planck scale.” The results of the study by McMaken and Hamilton were published in the journal *Physical Review D*.

## Looking into a Black Hole

The concept Hamilton and McMaken started with for their research seemed relatively straightforward. “We’re trying to figure out what happens if you add the effects

of quantum field theory to black holes,” explained McMaken. As a marker for how quantum field theory would affect things falling into the black hole, Hamilton and McMaken focused on the detection of Hawking radiation. Hawking radiation is created by the interactions of particles and antiparticles that surround the black hole. According to McMaken: “You have a sea of virtual particles and antiparticles that pop into existence from the quantum vacuum and then annihilate each other. Hawking radiation is what happens when one particle is just outside the horizon of the black hole, while the other gets absorbed inside the black hole [a Hawking pair]. They never get the chance to meet up and cancel each other out again.” As McMaken explained further, most physicists are interested in looking at Hawking radiation produced right at the horizon and detected at a far distance from a black hole. But these Hawking pairs are being ripped apart everywhere in the spacetime, and McMaken and Hamilton wanted to look at where the radiation is happening the most, right at the edge of the black hole’s inner horizon.

While Hawking radiation seemed to be a straightforward proxy for understanding the semiclassical



behavior of the system, actually calculating the measured Hawking radiation was a bit more complicated. “Though we think of Hawking radiation in terms of particle-antiparticle pairs, that’s actually not how it’s usually calculated,” McMaken stated. “Instead, we think in terms of waves moving through the quantum field. When those waves become exponentially red-shifted, or stretched apart, then we detect this as the radiation.” From their models, Hamilton and McMaken found something rather interesting. “Close to the inner horizon [of the black hole], those waves start blue-shifting, or getting squashed, until you see a diverging amount of energy there.”

## Falling into a Black Hole

This energy divergence, while at first confusing to the researchers, ended up being a crucial part of a black hole faller-in’s journey. “Conceptually, if you’re falling into a black hole, you’ve probably heard that you will get ‘spaghettified,’” McMaken said. “So if you’re falling in feet first, then the gravity is going to pull stronger at your feet than it will at your head, and you’ll end up getting stretched out like a spaghetti noodle. That same force is going to pull apart the Hawking pairs.” While this does not sound like a comfortable process, it only

gets worse as one travels along. As McMaken explains: “For realistic black holes, which are rotating and accreting matter, once you get close enough, then the opposite starts to happen—instead of getting stretched out, you’ll end up getting squashed. So, the forces at your head will end up getting stronger and stronger than those at your feet, until you get squished up like a pancake. I guess you could call it ‘pancakification.’” This sudden shift in force was where McMaken and Hamilton saw the divergence in Hawking radiation. As McMaken explained, “there’s some amazing effect, where the particles have such a large amount of energy that they still manage to escape the event horizon even though gravity is trying to squash them back together. And we end up calling this a negative temperature.” The idea of a negative temperature comes from Stephen Hawking, who proposed that the temperature of a black hole is related to its mass. Because black holes can have a negative mass (as they are absorbing other masses), they may also have a negative temperature. While the concept of negative temperature shows up in many different areas of physics, the researchers still aren’t entirely sure exactly what that means for the black hole system’s dynamics, even though they can observe and measure it. “Something has to happen there,”

An artistic rendering of a charged black hole and its corresponding Hawking radiation.  
Credit: Steven Burrows/Tyler McMaken

McMaken stated. “And exactly what it is, is going to inform us a lot about quantum gravity as a theory.”

The results that Hamilton and McMaken found also have some interesting implications for the field of astrophysics. “On the astrophysics side, there are some interesting things that are perhaps worth exploring,” McMaken added. “We’ve mostly been interested in how we can consistently model the inside of a black hole, which gives helpful insights about quantum gravity but not so much for observations.

But one of the things that we mentioned in our paper is that this negative temperature can be detected outside the black hole in certain cases. If you have a high enough charge—or by analogy if the black hole is spinning fast enough—then you should start to see negative temperatures even above the event horizon, which might affect how particles in the accretion disk interact with it.” While this study revealed a whole new batch of questions to be answered, it also upheld the black hole’s mysterious and strange reputation within the scientific community.

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Tyler McMaken and Andrew J. S. Hamilton. "Hawking radiation inside a charged black hole" *Physical Review D*. 107(8), 085010 (2023)

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Written by Kenna Hughes-Castleberry

# Using Frequency Comb Lasers as a Breathalyzer for COVID-19

JILA researchers have upgraded a breathalyzer based on Nobel Prize-winning frequency-comb technology and combined it with machine learning to detect SARS-CoV-2 infection in 170 volunteer subjects with excellent accuracy. Their achievement represents the first real-world test of the technology's capability to diagnose disease in exhaled human breath.

Frequency comb technology has the potential to non-invasively diagnose more health conditions than other breath analysis techniques while also being faster and potentially more accurate than some other medical tests. Frequency combs act as rulers for precisely measuring different colors of light, including the infrared light absorbed by biomolecules in a person's breath.

Human breath contains more than 1,000 different trace molecules, many of which are correlated with specific health conditions. JILA's

frequency comb breathalyzer identifies chemical signatures of molecules based on exact colors and amounts of infrared light absorbed by a sample of exhaled breath.

Back in 2008, Jun Ye and colleagues at JILA demonstrated the world's first frequency comb breathalyzer, which measured the absorption of light in the near-infrared part of the optical spectrum. In 2021 they achieved a thousand-fold improvement in detection sensitivity by extending the technique to the mid-infrared spectral region, where molecules absorb light much more strongly. This enables some breath molecules to be identified at the parts-per-trillion level where those with the lowest concentrations tend to be present. The added benefit to this study was the use of machine learning. Machine learning—a form of artificial intelligence (AI)—processes and analyzes a massive, complex mélange of data from all the breath

samples as measured by 14,836 comb “teeth,” each representing a different color or frequency to create a predictive model to diagnose disease.

“Molecules increase or decrease in their concentrations when associated with specific health conditions. Machine learning analyzes this information, identifies patterns and develops reliable criteria we can use to predict a diagnosis,” said Qizhong Liang, a graduate student in the Jun Ye group, who is lead author of a new paper presenting the findings. The research was conducted on breath samples collected from 170 CU Boulder students and staff from May 2021 to January 2022. Approximately half of the volunteers tested positive for COVID-19 with standard PCR tests. The other half of the subjects tested negative. The young study group had a median age of 23 years old, and all were above 18 years old. The general campus population was more than 90% vaccinated.

“I do think that this comb technique is superior to anything out there,” NIST/JILA Fellow Jun Ye said. “The basic point is not just the detec-

Rebecca Jacobson of NIST breathes into a bag to test the frequency comb breathalyzer.

Credit: Rebecca Jacobson/NIST



tion sensitivity, but the fact that we can generate a far greater amount of data, or breath markers, really establishing a whole new field of 'comb breathomics' with the help of AI. With a database, we can then use it to search and study many other physiological conditions for human beings and to help advance the future of healthcare." The JILA comb breathalyzer method demonstrated excellent accuracy for detecting COVID by using machine learning algorithms on absorption patterns to predict SARS-CoV-2 infection. H<sub>2</sub>O (water), HDO (semi-heavy water), H<sub>2</sub>CO (formaldehyde), NH<sub>3</sub> (ammonia), CH<sub>3</sub>OH (methanol), and NO<sub>2</sub> (nitrogen dioxide) were identified as discriminating molecules for detection of SARS-CoV-2 infection.

The team measured the accuracy of their results by creating a data graph comparing their predictions of COVID-19 against the PCR test results (which, it should be noted, have high but not perfect accuracy). On the graph, they computed a quantity known as the "area under the curve" (AUC). An AUC of 1, for example, would be expected for perfectly discriminating between ambient air and exhaled breath. An AUC of 0.5 would be expected for making random guesses on whether the individuals were born on odd or even months. The researchers measured an AUC of 0.849 for their COVID-19 predictions. An AUC of 0.8 or greater for medical diag-

nostic data is considered "excellent" accuracy.

In the future, the researchers could further increase the accuracy by expanding the spectral coverage, analyzing the patterns with more powerful AI techniques, and measuring and analyzing additional molecules, which could include the SARS-CoV-2 virus itself. Researchers would need to build a database of the specific IR colors absorbed by the virus (its spectral "fingerprint") to potentially measure viral concentrations in the breath.

The researchers also identified significant differences in breath samples based on tobacco use and a variety of gastrointestinal symptoms such as lactose intolerance. This suggests broader capability of the technique for diagnosing different sets of diseases. The research was published in the *Journal of Breath Research*, the official Journal of the International Association for Breath Research.

The researchers plan further studies to try to diagnose other conditions such as chronic obstructive pulmonary disease, the third leading cause of death worldwide according to the World Health Organization. The researchers have also recently boosted the comb breathalyzer's diagnostic power by expanding the spectral coverage to detect additional molecules. They plan to employ additional AI

approaches such as deep learning to improve its disease-detection abilities. Efforts are already under way to miniaturize and simplify the technology to make it portable and easy to use in hospitals and other care settings.

Ye said there is interest from the medical community in seeing the comb breathalyzer developed further and commercialized. Approval by the U.S. Food and Drug Administration (FDA) would be needed before the technology could be used in medical settings.

The most prevalent analytical technique in breath research now is gas chromatography combined with mass spectrometry, which can detect hundreds of exhaled molecules but works slowly, typically requiring tens of minutes. Its use of chemical process also unavoidably alters breath components and presents analytical challenges to identify breath profiles accurately. Frequency comb technology measures breath molecules in a non-destructive and real time manner and can promote a more accurate and repeatable determination of exhaled breath contents.

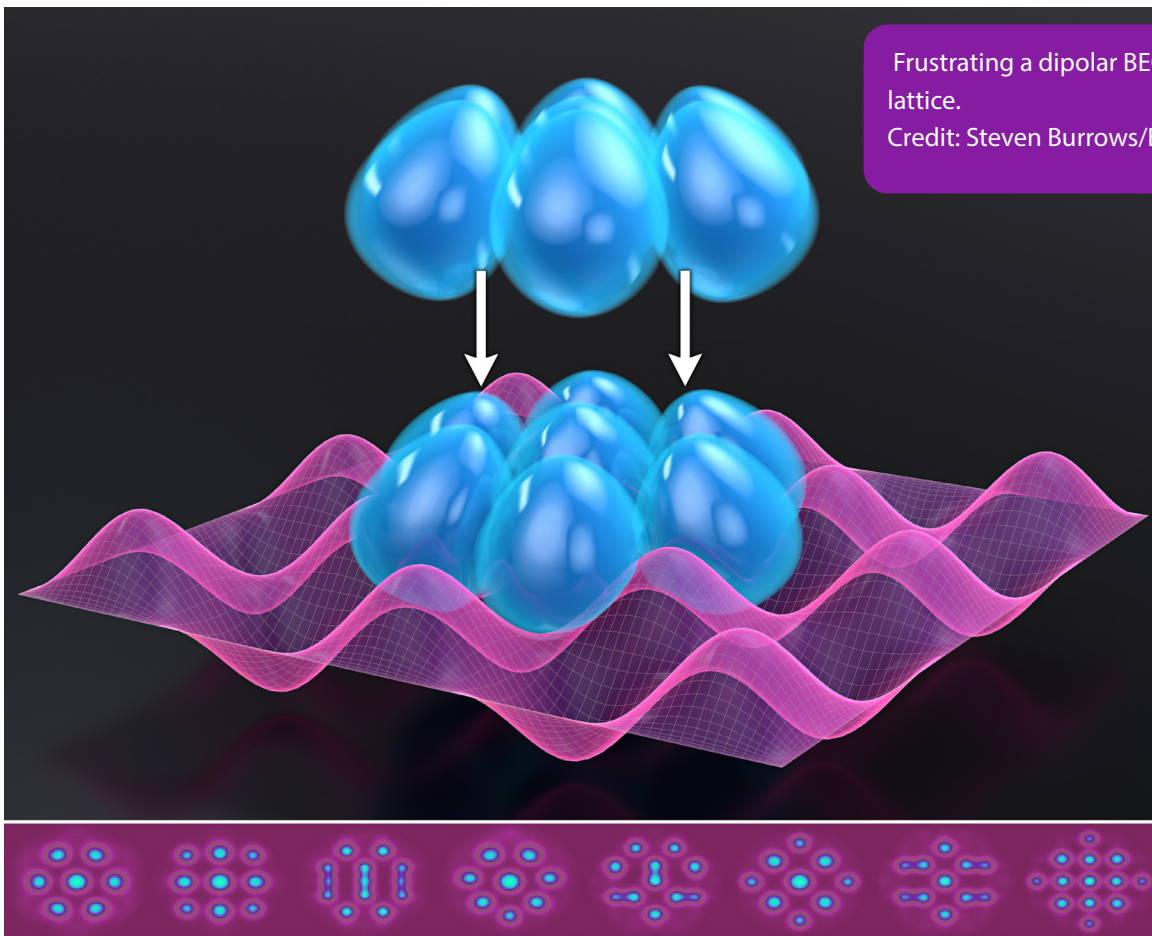
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Qizhong Liang, Ya-Chu Chan, Jutta Toscano, Kristen K. Bjorkman, Leslie A. Leinwand, Roy Parker, Eva S. Nozik, David J. Nesbitt, and Jun Ye. "Breath analysis by ultra-sensitive broadband laser spectroscopy detects SARS-CoV-2 infection." *Journal of Breath Research*. 17(3), (2023).

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Written by Rebecca Jacobson, Public Outreach Coordinator at NIST

# A Tale of Two Dipoles



Frustrating a dipolar BEC gas inside a square lattice.

Credit: Steven Burrows/Bohn Group

Condensate (BEC) dipolar gas. “We’re looking at these arrays of droplets, which have different symmetries,” Halperin explained. “But the most common one, or the one that’s been reproduced

Dipolar gases have become an increasingly important topic in the field of quantum physics in recent years. These gases consist of atoms or molecules that possess a non-zero electric dipole moment, which gives rise to long-range dipole-dipole interactions between particles. These interactions can lead to a variety of interesting and exotic quantum phenomena that are not observed in conventional gases.

One important area of research involving dipolar gases is the study of quantum phases of matter. In

particular, dipolar gases have been used to explore the behavior of so-called “quantum droplets”, which are self-adhering quantum states of atoms or molecules that arise due to the interplay between the molecule’s dipole-dipole interactions and quantum fluctuations. These droplets are stable and have been observed experimentally in a variation of two different systems. In a new paper published in *Physical Review A*, JILA Fellow John Bohn and graduate student Eli Halperin looked into the different patterns these droplets made, specifically within a Bose-Einstein

in the lab, is this six-fold, hexagonal array of droplets.” From their work, Halperin and Bohn found that the dipolar BEC gas droplets could be disturbed enough to form intermediate patterns and symmetries, thereby creating a method for fine-tuning these interactions.

## A Square Lattice and A Frustrated Gas

To look at how these symmetries formed within the BEC droplets, Halperin and Bohn used a method appropriately called “geometric frustration,” or simply, “frustration.”



As Bohn elaborated: “This idea of frustration is very important. The atoms in these experiments are left to themselves and may want to do six-fold symmetry. But instead, you might try to force four-fold symmetry on them. And now the atoms are under stress, so they’re going to make a compromise. The frustration here is that compromise.” To apply frustration to the gaseous system, Halperin and Bohn posited using a square optical lattice, a type of web made by using different lasers, as a weak constraining force on the BEC droplets. “If the square lattice is really strong, you don’t just get the BEC sitting in the lattice,” Halperin added, alluding to the strength of the lattice depending on the laser frequency. However, a weak square lattice creates a weak force on the BEC system, which keeps the BEC in the lattice, and the gaseous droplets begin to struggle with each other to balance out their energy levels in order to reach the lowest energy states.

## A Tale of Two Patterns

For Bohn and Halperin, this frustration caused some interesting effects. “We found this intermediate regime where it doesn’t always have six-fold symmetry or four-fold symmetry, it can have neither type of symmetry,” Halperin stated. This created different pattern regimes within the droplets, which the researchers mapped out, showing the different ground state of each

regime. “It can have different regions where one section arranges in one pattern and a different section arranges in a different pattern,” Halperin added. “This half and half system ends up being an overall lower energy than when one pattern dominates the whole gas.” Because the dipolar BEC droplets acted as a superfluid system, (where the system has no viscosity and can flow without losing kinetic energy) instead of having more distinct particles such as in other gases, this half and half pattern of droplet frustration suggested something new for further exploration of the dipolar BEC gas. “This frustration gives another kind of knob to turn when you’re looking at patterns that change in the BEC,” Halperin stated.

Besides being a fine-tuning knob, this process of frustration has bigger implications for the field of quantum physics. As Bohn added: “You see frustration all over physics. The interesting stuff happens when there’s two competing things going on and the system has to find its way in-between.” Dipolar interactions can lead to the formation of complex patterns and structures in the gas, such as long-range order or the formation of exotic phases such as super solids. These systems are of great interest to researchers studying condensed matter physics and are being explored in a variety of different experimental systems. Both

Bohn and Halperin are hopeful that other researchers could use their theory to further study this unique system.

## Directing Sound at Dipoles

Another way to perturb a dipolar gas is to push different types of waves through it. In the research done by Bohn and graduate student Reuben Wang, also reported in *Physical Review A*, the waves being utilized were sound waves. Instead of utilizing the dipolar BEC gas that Halperin used, Wang and Bohn instead studied the interactions of sound waves on a dipolar fermionic system. Fermionic gases are unique in that fermions are difficult to condense, due to the Pauli Exclusion Principle, which asserts that two particles cannot share identical quantum states. However, by cooling these fermionic gases to ultracold temperatures, researchers can coax the gas to condense into a BEC-type formation and study the gas as one cohesive unit. Above certain temperatures, the fermions are studied as separate units. As Wang explained: “We look at the dipolar gas molecules as distinct things that whiz around and are thermally distributed, but also collide with each other and interact in quantum ways, where the quantum ways are scattering between particles.” Besides the scattering interactions, Wang and Bohn also studied the dipolar interactions be-

studied the dipolar interactions between polar gases, also known as the mean-field. By taking the gases out of equilibrium, using sound waves, Wang and Bohn hoped to understand how these gases responded to the perturbation.

To disturb the system, the researchers decided to use sound waves, which are a type of compression wave. “Sound is a rather simple probe for this system,” Wang added. “We say: ‘Well, if I weakly poke it, there’s these linear excitations that go on top of the gas.’ So, we want to understand how this evolves with molecular collisions in the gas.” Looking at what would happen when sound waves penetrated the polar gas like ripples in a pond, Wang and Bohn were excited to see that the ripples were unequal. Instead of being symmetric in all directions, they found that the sound deformed the gas based on the directions of the dipole interactions. “The sound moves relatively faster to the direction in which the dipoles were aligned, and only slowly propagates in another direction, creating more oval-shaped ripples,” said Wang. “We’ve seen a somewhat similar thing in other literature on condensates.”

## Studying Gaseous Viscosity

Understanding how sound waves move through the dipolar fermionic gas suggested other implications

for studying these gaseous systems. As Wang explained, part of understanding dipolar gas dynamics was to look at their viscosity, which he described as a “...form of friction of the gas. It arises microscopically, from the bumping of all the different molecules and atoms in the system.” Viscosity can tell physicists more about the fluctuations within the system, giving more insight into interactions happening at the quantum level. Like liquids with different viscosities, or runniness, gases with different viscosities behave differently. However, finding viscosity was not a straightforward method. “The method for figuring out the viscosity of a gas is well established and really complicated,” Wang added. “But it’s so much more complicated when the gas is dipolar. Usually, people will just put a number into viscosity, because you need to have some friction coefficient. But in our case, the viscosity becomes this object, which is also characterized by different directions in space.” By using sound waves to disturb the gas, Wang and Bohn found a new method that could yield greater accuracy to calculations of the viscosity of a dipolar gas.

Thanks to the different disturbances they were able to create in dipolar gaseous systems, Bohn,

Halperin, and Wang were able to identify new dynamics within these special gases. Because dipolar gases are utilized in many different systems, from creating highly accurate atomic clocks to designing new types of sensors that are capable of detecting tiny variations in electric fields, understanding more about how these gases work can help advance many different subfields within quantum physics. As researchers continue to explore the properties of dipolar gases, we can expect to see many exciting new discoveries in the years to come.

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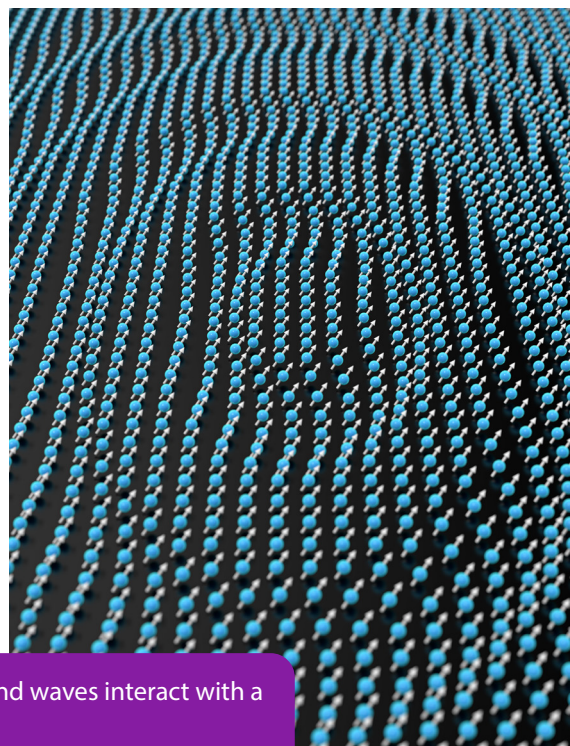
Eli J. Halperin, Shai Ronen, and John L. Bohn. "Frustration in a dipolar Bose-Einstein condensate introduced by an optical lattice" *Physical Review A*. 107, L041301 (2023).

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Reuben R. W. Wang and John L. Bohn. "Anisotropic acoustics in dipolar Fermi gases" *Physical Review A*. 107, 033321 (2023).

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Written by Kenna Castleberry



Looking at how sound waves interact with a dipolar BEC.  
Credit: Steven Burrows/Bohn Group

# Looking at a Cellular Switch

Although one might think it would be simple, the genetics of bacteria can be rather complicated. A bacterium's genes use a set of regulatory proteins and other molecules to monitor and change genetic expressions within the organism. One such mechanism is the riboswitch, a small piece of RNA that can turn a gene "on" or "off." In order to "flip" this genetic switch, a riboswitch must bind to a specific ion or molecule, called a ligand, at a special riboswitch site called the aptamer. The ligand either activates the riboswitch (allowing it to regulate gene expression) or inactivates it until the ligand unbinds and leaves the aptamer. Understanding the relationship between ligands and aptamers can have big implications for many fields, including healthcare. "Understanding riboswitches and gene expression can help us develop better antimicrobial drugs," explained JILA graduate student Andrea Marton Menendez. "The more we know about how to attack bacteria, the better, and if we can just target one small interaction that prevents or abets a gene from being translated or transcribed, we may have an easier way to treat bacterial infections."

To better understand the dynamics of aptamer and ligand binding, Marton Menendez, along with JILA and NIST Fellow David Nesbitt,

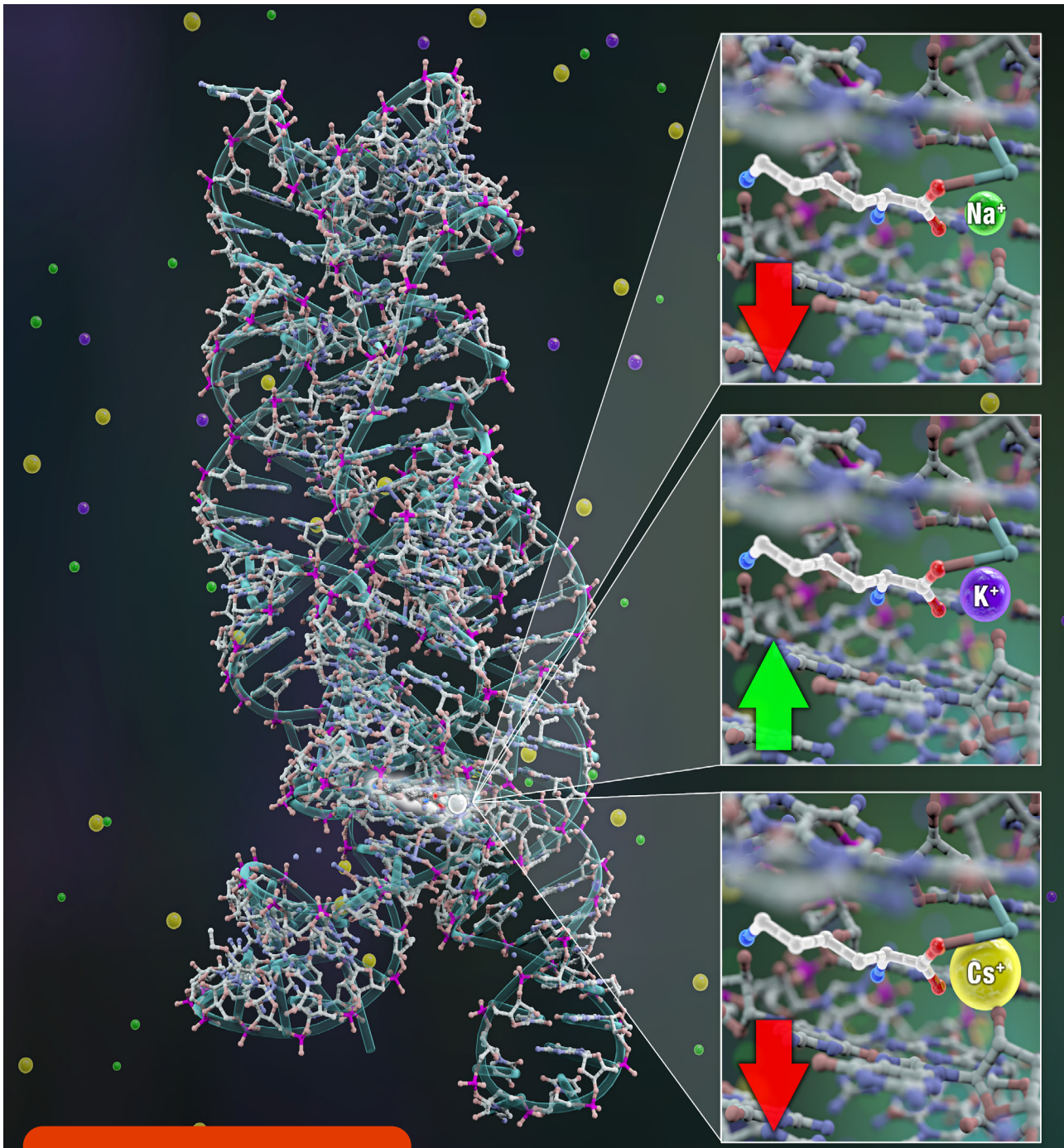
looked at the lysine (an amino acid) riboswitch in *Bacillus subtilis*, a common type of bacterium present in environments ranging from cow stomachs to deep sea hydrothermal vents. With this model organism, the researchers studied how different secondary ligands, like, potassium, cesium, and sodium, which are also positively charged, affect riboswitch activation, or its physical folding. The results have been published in the *Journal of Physical Chemistry B*.

## Pairing Up Molecules

"We know that cells are complicated; living systems are really complicated," Marton Menendez stated. "There's a lot going on in them. But when we're trying to study complicated processes, such as how exactly does DNA or RNA fold? we tend to simplify a lot. So, we usually end up reducing the system down to the simplest DNA/RNA structure we want to study and a few necessary salts." With this idea in mind, Marton Menendez and Nesbitt analyzed their bacterial system using single molecule FRET (fluorescence resonance energy transfer) microscopy. This type of microscopy uses pairs of fluorescent dye molecules to tag specific nucleic acid positions, for this study in particular, a larger RNA riboswitch, allowing researchers to study binding, folding, and unfolding in real time

For this particular riboswitch to work, lysine first binds to the aptamer, which causes the aptamer to fold around lysine. However, in the x-ray crystallography images of the riboswitch, a potassium ion was also bound in the aptamer. According to Marton Menendez: "You can take crystal structures of these pieces of RNA and analyze their content. If the something shows up in the crystal structure, like the potassium ion, it is likely to have been very tightly bound in the riboswitch, because it means that it stayed there a long time. This tells us that potassium can play a ligand-like role for our riboswitch."

Besides studying potassium as a potential ligand, the researchers also found that when potassium was bound to the riboswitch, it changed how the riboswitch interacted with lysine, the primary ligand. "We looked at how the riboswitch functions with respect to lysine and potassium because they affect each other," Marton Menendez said. "Mainly potassium can tweak some of the lysine's binding abilities. That's interesting because we think of riboswitches as extremely specific and working only with one specific target molecule." Instead, in the *B. subtilis* system, this riboswitch interacts with both lysine and potassium, cooperatively, with the presence of one species enhancing the impact



An artistic rendering of the bacterium's riboswitch and its interactions with three different potential ligands.

Credit: Steven Burrows and Nesbitt Group

of the other.

## A Complex Bacterial Evolution

The idea of RNA regulating its own gene expression suggests that the history of bacterial genetic evolution is more complicated than expected. “If you are an early bacterium, how do you regulate your own genes?” Marton Menendez asked. “There is a hypothesis that the ancient

world had only RNA, no proteins or DNA. So RNA alone was responsible for gene storage and regulation. Riboswitches are an example of how RNA can perform these regulatory functions without protein assistance.” As proteins and more complicated organisms emerged, it is easy to expect these genetic

systems to evolve to being more complicated, with a larger number of genes and corresponding regulatory proteins. However, results like Marton Menendez's and Nesbitt's suggest that there is more in the bacteria's genes than meets the eye.

With a more complicated relationship between ligands and aptamers, Marton and Nesbitt were interested to see if this relationship could be found in other bacteria related to *B. subtilis*. "There's also a version of a lysine riboswitch that exists in bacteria that live in habitats that are at 80 degrees Celsius, near hydrothermal vents on the sea floor," elaborated Marton Menendez. "We are preparing a paper comparing how regulation by the lysine riboswitches differs between the two bacteria."

## More Complicated and Cooperative Ligand Relationships

Curious about the flexibility in ligand binding to their aptamer, Marton Menendez and Nesbitt decided to see just how versatile the aptamer could be. "We were also interested to see if potassium ion could then be swapped out for something similar," Marton Menendez added. "The reason the riboswitch goes for lysine might have something to do with the fact that you've got potassium in the system. But, if you have something that's bigger

or smaller than potassium, the riboswitch may have higher or lower binding affinity to lysine." This experiment suggested an additional project looking at how closely connected the potassium and lysine were as ligands, and also to see if the aptamer would bind to other potential ligand-cation combinations of different sizes. Cations are small positively charged ions that organic systems use to regulate different molecular processes.

As Marton Menendez said: "We studied the size effects of ions binding to the riboswitch. The riboswitch typically binds lysine with potassium, so we tested cesium and sodium ions [common molecules within the bacterium] instead of potassium. However, it seems that cesium might be too big and sodium too small to allow lysine to bind properly." Analyzing the data, the researchers found that the aptamer was quite specific with respect to choice of cation preferentially binding to potassium and lysine as the "perfect Goldilocks combination of sizes." Most importantly, this finding suggests that riboswitch activity can be regulated with vastly more flexibility by responding cooperatively to more than a single ligand species concentration at a time. This cooperativity is a trick that Nature has long exploited for increasing functionality of proteins (e.g., oxygen bonding to hemoglobin in red blood cells), so it would seem an entirely plau-

sible strategy for nucleic acids as well.

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Andrea Marton Menendez and David J. Nesbitt. "Ionic Cooperativity between Lysine and Potassium in the Lysine Riboswitch: Single-Molecule Kinetic and Thermodynamic Studies" *The Journal of Physical Chemistry B*. 127(11):2430–2440. (2023).

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Written by Kenna Castleberry



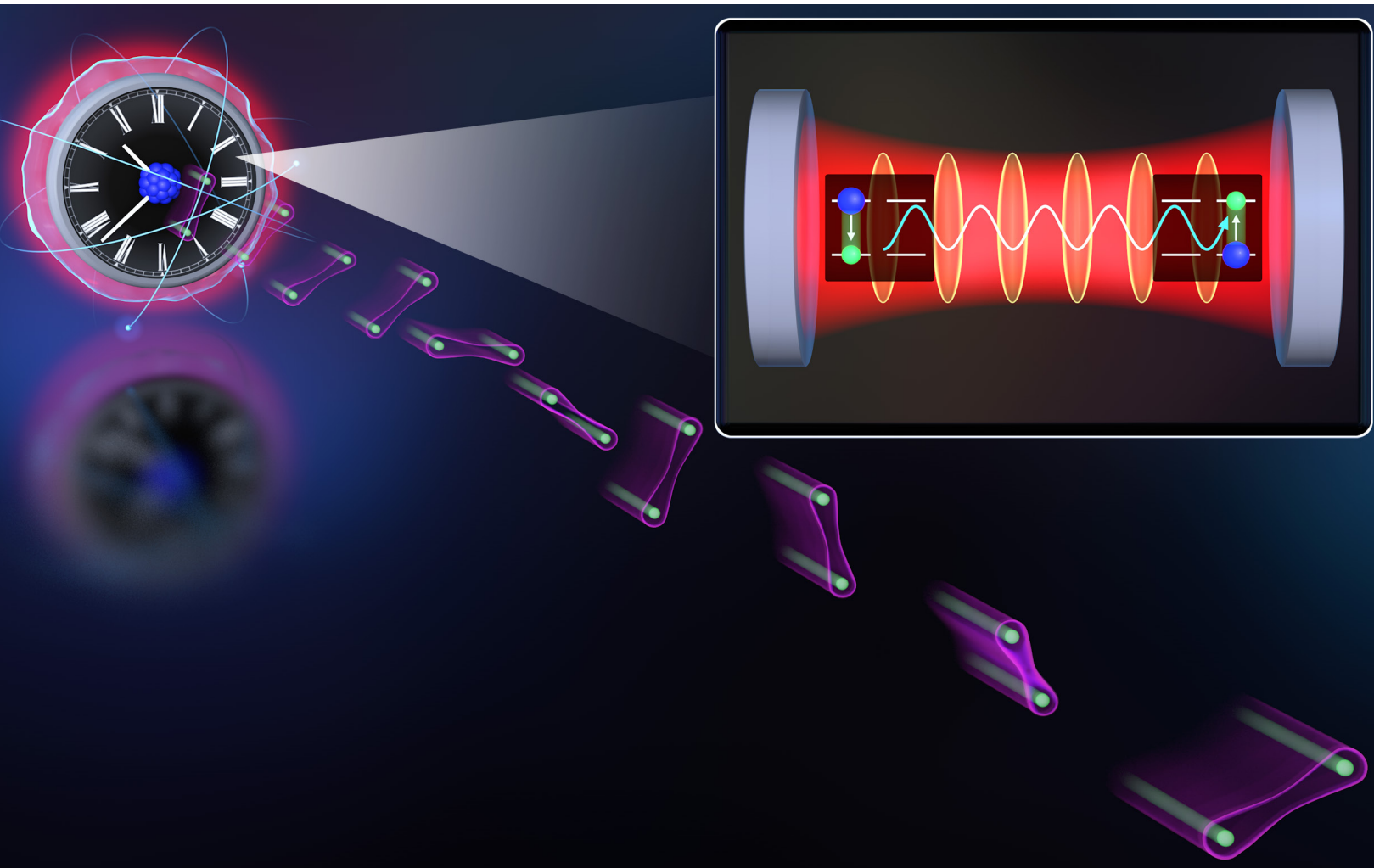
# Entangled Pairs Get Sensitive Very Fast

The best clock in the world has no hands, no pendulum, no face or digital display. It is made of ultracold atoms trapped by light. This atomic clock is so precise that, had it begun ticking when Earth formed billions of years ago, it would not yet have gained or lost a second. Nonetheless, this incredible clock, and all atomic clocks, operate with collections of independent atoms, and as a result, their precision is limited by the fundamental laws of quantum mechanics. One way to get around this fundamental quantum imprecision is to entangle the

atoms, or make them talk, in such a way that one cannot describe the individual atoms' quantum states independently of one another. In this case it is possible to create the situation where the quantum noise of one atom in the clock can be partially canceled by the quantum noise of another atom such that the total noise is quieter than one would expect for independent atoms. One type of entangled state is called a "squeezed state", which can be visualized as if one had shaped the quantum noise in a way that is narrower in one direction

at the expense of making the imprecision in the adjacent direction worse. Squeezed states have been realized in several labs around the world at groundbreaking precision levels recorded by several physics institutes, including at JILA in Boulder, Colorado. However, squeezing is experimentally challenging to create and there is a need for a variety of "flavors" of squeezing for different types of quantum sensing tasks.

A new approach recently described in *Physical Review Letters* explores



a new way to generate squeezing that is exponentially faster than previous experiments and generates a new flavor of entanglement: two-mode squeezing—a type of entanglement that is thought to be used for improving the best atomic clocks and for sensing how gravity changes the flow of time. This promising new approach was developed by a collaboration of JILA and NIST Fellows Ana Maria Rey and James K. Thompson, and their team members, along with Bhuvanesh Sundar, now at Rigetti Computing, and Dr. Robert Lewis-Swan, now an Assistant Professor at the University of Oklahoma.

## Two-Mode Squeezing

Squeezing is related to the Heisenberg Uncertainty Principle, which limits how accurately a researcher can measure two related properties—such as the momentum and position of a particle—such that researchers can only know more about one of the parameters than the other. Squeezing overcomes this limitation by making one of these variables more uncertain, allowing a more accurate measurement for one of the variables. “Squeezing has been used to improve the LIGO gravitational wave interferometer and the HAYSTAC dark matter detector,” Rey

explained. “It would be great to now leverage entanglement for a quantum enhancement in a state-of-the-art atomic clock”.

As seasoned researchers looking at quantum entanglement, Rey’s and Thompson’s teams, along with Lewis-Swan, understood how important it is to develop new forms of squeezing, providing new tools for canceling noise sources and enabling more precise atomic clocks for more advanced technologies and probing the universe. “The idea was to design a protocol that generates entangled states with minimal fuss, that actually sort of stands up to challenges of typical experiments,” Lewis-Swan added. “It actively considers typical technical constraints present in the lab. Our guiding principle was that the less things we need to do in the experiment, the better, and what is simpler than having the atoms just sit in the dark talking to each other. By reducing the number of manipulations, we reduce the ability of unwanted noise to creep in.”

JILA has already generated cutting-edge levels of spin squeezing. As Thompson explained: “My students have made squeezed states in that lab that have blown past the Standard Quantum Limit using light-matter interactions in optical cavities, but we work hard to achieve it by applying and measuring laser light.” In this new study, the researchers were curi-

ous if there were new squeezing approaches where the atoms just sit in the dark, swapping photons inside the cavity. By their predictions, the researchers believed this would reduce the experimental challenges for creating squeezing by orders of magnitude. “And not only that, but instead of just having vanilla-flavored squeezing, now we could have double-dutch chocolate squeezing called two-mode squeezing!” enthused Thompson.

This type of squeezing suggested a new way to compare the accuracy of quantum sensors. As Lewis-Swan stated, “One of the outstanding challenges right now in quantum science is developing new ways to generate entanglement to build better quantum sensors, such as atomic clocks. There are many ways people have thought about creating one-mode squeezing relevant for clocks, but two-mode squeezing would enable one to compare the ticking rate of atomic clocks more precisely to measure how general relativity affects the rate at which time passes at different heights in Earth’s gravity.” This comparison can help with many different aspects of quantum sensing. “Instead of comparing the combined rate at which two clocks are both ticking, what you can compare now is the difference in the ticking rates more precisely,”

Left: A representation of bosonic pair creation, which creates an entangled state between atoms.

Credit: Steven Burrows/Rey and Thompson Groups

precisely,” Lewis-Swan continued. “This can be really useful to cancel common noise. And essentially, via the squeezing process, we can entangle two ensembles and use each of them as a clock with superb relative performance.”

## Entangling Atomic Pairs in Two Different Ensembles

To generate squeezing expeditiously, the researchers leveraged a process known as bosonic pair creation. “The bosonic pair creation idea is well known in quantum physics,” stated Lewis-Swan. “It’s decades old and is pivotal for a lot of different applications in quantum science, from quantum communication to metrology and information processing. Here, we’re leveraging bosonic stimulation, where once you produce one pair, it’s easier and easier to produce more pairs. So basically, the number of pairs increases exponentially fast, and those pairs are entangled in a very useful way.”

Bosonic pair production is important in several different subfields of physics. As Rey elaborated, “Indeed pair production appears in many contexts in physics and keeps finding a wide range of applications in quantum technologies. For example, it manifests in high-energy physics when electron-positron pairs are spontaneously created in the presence of

a strong electric field. In general relativity, in the so-called Unruh thermal radiation—or generation of thermal radiation from vacuum when viewed in an accelerating reference frame.” Engineering pair creation in a fully controllable clock could therefore be fascinating and useful for many different applications.

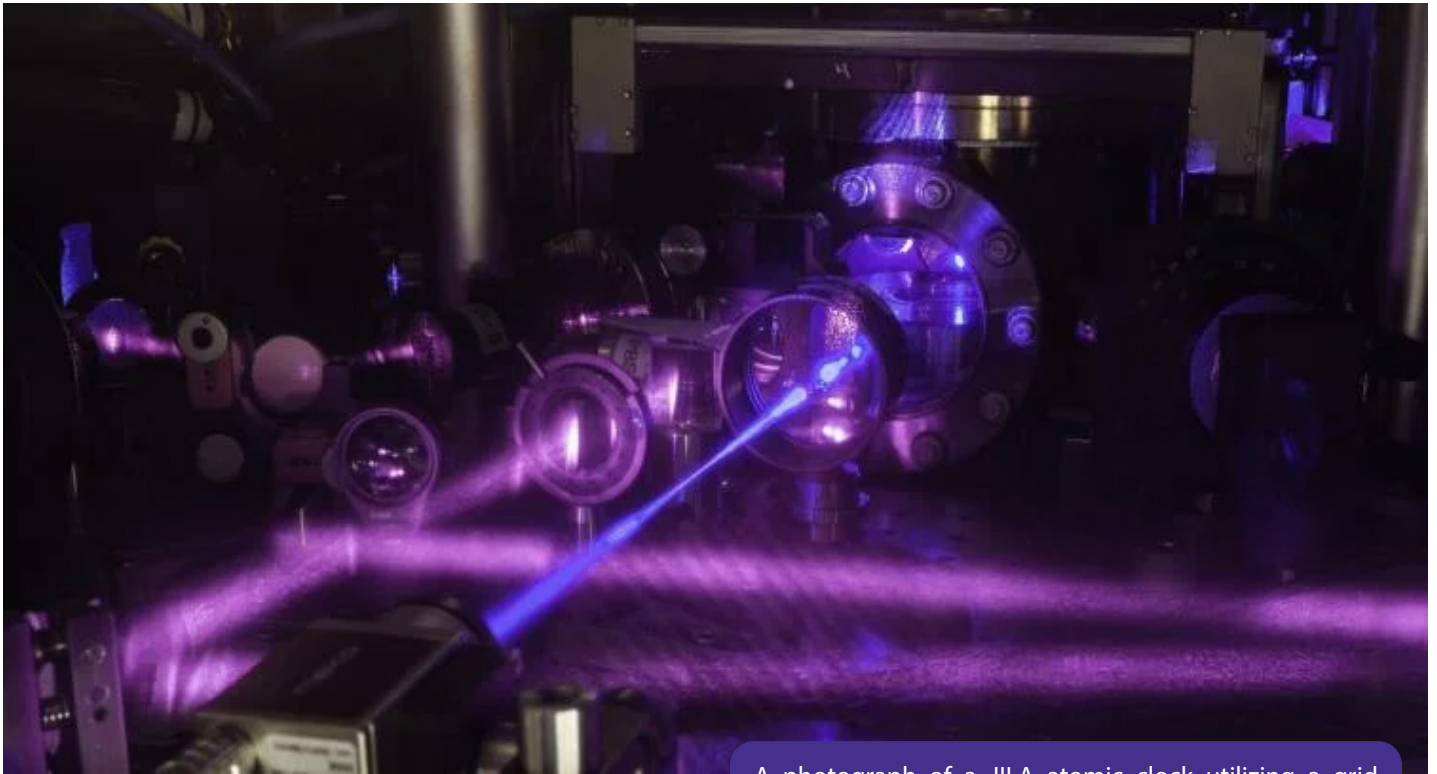
Even though pair creation is well known, what was missing was a feasible mechanism to generate it in state-of-the-art clocks, and more importantly, how to take advantage of the generated squeezed states for metrology in the presence of real sources of decoherence that disrupt the utility of the prepared state. Within the collaboration, first author Bhuvanesh Sundar looked at this particular problem, and thanks to the resulting calculations, the researchers could map out the best operating regimes for which an experiment can generate squeezing. “The ultimate limit that one can achieve for squeezing is called the Heisenberg limit,” Sundar elaborated. “We calculated how much squeezing we can generate by balancing the amount of unwanted environmental noise that creeps into the system versus how much entanglement we can try and create. We found out that the optimal scaling using pair creation doesn’t quite reach the Heisenberg limit, but nevertheless it is still better than (or comparable to) other competitive protocols that

researchers have used in the labs in the past.”

Beyond those calculations, the researchers also figured out multiple ways to take advantage of the squeezing. “In the past we have focused on finding ways to generate squeezing among a single large ensemble of atoms by having them essentially play catch with each other,” Lewis-Swan added. “One atom throws a photon into the cavity and another catches it. Here, the way we engineer pair production by using the internal electronic structure of the atoms leads us to naturally think about the atoms as being grouped into a pair of distinct ensembles that we can separately address. We can tune our system such that when an atom in one ensemble throws a photon it can only be caught by an atom in the other ensemble. This allows us to effectively make two entangled ensembles which can be used in parallel for precise measurements.”

The simplicity of the researchers’ protocol enables better scalability and facilitates experimental implementation, opening the door to advances in clock sensitivity and bandwidth, not only for improved traditional timekeeping applications, but also gravitational wave detection, precision tests of fundamental physics, and the search for new physics beyond the standard model.





Now that the protocol has been published, the researchers hope the next steps will be to test the protocol in a laboratory setting. Sundar added, “The ideas require minimal ingredients, so it should be possible in labs like Thompson’s. But you could also apply this to trapped ions or other systems that people use to build clocks.” As Thompson himself has had a history of working on squeezed states, he is looking forward to putting this new protocol into action. “It will be a lot of fun to think if these same ideas can be used to extend our recent squeezed matter-wave interferometer to make two-mode squeezed matter-wave interferometers for inertial sensing and gravimetry,” he stated. With atomic clocks and other quantum sensors being used around the world today, improving the sensitivity of these

devices allows us to glean more information about our environment and can improve other technologies we use regularly in our society.

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Bhuvanesh Sundar, Diego Barberena, Asier Piñeiro Orioli, Anjun Chu, James K. Thompson, Ana Maria Rey, and Robert J. Lewis-Swan "Bosonic Pair Production and Squeezing for Optical Phase Measurements in Long-Lived Dipoles Coupled to a Cavity." *Physical Review Letters*. 130, 113202 (2023).

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Written by Kenna Castleberry

A photograph of a JILA atomic clock utilizing a grid of ultra-violet laser beams. Multiple lasers of various colors are used to cool the atoms, trap them in a grid of light and probe them for clock operation. A blue laser beam excites a cube-shaped cloud of strontium atoms. Strontium atoms fluorescence strongly when excited with blue light, as seen in the upper right corner behind the vacuum window.

Credit: University of Colorado Boulder, G.E. Marti/JILA.

# CONTINUING THE JILA CUP



Above: JILA's COO Beth Kroger holds up the JILA Cup while rallying students, staff, and Fellows to compete in the JILA Cup trivia challenge.

Credit: Lauren Mason

In the world of physics research institutions, friendly and casual competitions between research lab groups can be an excellent way to encourage collaboration and creativity. At JILA, this means participating in the JILA Cup challenge.

Since 2017, the JILA Cup has been a key method for the community of JILA to support its researchers in an informal and unique way. Research groups within JILA challenge each other to the JILA Cup, usually in a one-on-one battle. The challenger decides the type of challenge that both teams must compete in, allowing the challenging group to pick something that plays to their strengths. Previous challenges included ultimate frisbee in

the Colorado snow and intense indoor volleyball matches. The winner of the last JILA cup, before the COVID-19 pandemic, was JILA and NIST Fellow Konrad Lehner's group.

Winning the JILA Cup is more than just a rite of passage. Winning groups hold onto the actual cup itself, a custom-made metal trophy welded and created by the JILA instrument shop. Using spare parts, such as copper rings and metal tubes, JILA's instrument makers created a one-of-a-kind trophy that perfectly reflects the innovative and creative atmosphere at JILA.

Unfortunately, thanks to the

COVID-19 pandemic, it would be four years before the JILA Cup competition resumed. As most researchers worked remotely, any chance of a competition happening was slim at best. Many worried that the tradition of the JILA Cup had died out altogether, becoming lost to history.

Those fears were assuaged in April of 2023, as Beth Kroger, JILA's COO, reinstated the JILA Cup tradition during an ice cream sundae event. In a speech inspired by the film *Braveheart*, Kroger rallied the crowd of students, staff, and Fellows, explaining the importance of this honored tradition: "We say eno

-ugh time has passed without a JILA Cup, and the reign of the Lehnert group is finally over!" Cheering and excited, the crowd was intrigued to find out how the next JILA Cup competition would be formatted.

While the Lehnert group could have challenged a different research group within JILA to the cup, as tradition dictated, Kroger instead wanted to make the rebirth of the JILA Cup something that was community wide, something that could include all research groups: a battle royale.

Working with JILA's Science Communicator Kenna Hughes-Castleberry, and Lauren Mason, the Associate Director of Communications and Operations at STROBE, an NSF center within JILA, Kroger decided to host a trivia competition where all research groups would be pitted against each other in the ultimate test of JILA history. Using archival JILA records, Hughes-Castleberry created a trivia contest that

spanned the entire history of JILA, from its founding in 1962 to its current status. Questions ranged from the number of instrument makers in the instrument shop to naming the first female chair at JILA.

For JILA Fellow Shuo Sun's group, which included staff members and researchers, their combined knowledge proved enough to win them the competition, and the highly coveted JILA Cup. JILA Chair Konrad Lehnert presented the cup to Sun after their victory was

declared. Everyone cheered the group on as they celebrated their victory.

In a later tweet of a picture of the JILA Cup, Sun relished his victory writing: "Guess who has the JILA Cup now?"

Written by Kenna Hughes-Castleberry

Below top: The Battle Royale trivia competition is underway as JILA research groups compete against each other to win the JILA Cup.

Credit: Christine Jackson

Below bottom: The winning team of the JILA Cup competition, headed by JILA Fellow Shuo Sun, includes (L to R) Curtis Breimborn, Thi Hoang, Jake Higgins, JR Raith, and Shuo Sun, who accepts the cup from JILA Chair Konrad Lehnert .



# LIFE AFTER JILA: LIZ SHANBLATT

While many JILA alumni go on to have more traditional physics careers, such as in quantum industry, other career paths that might not be as well-known offer some unique benefits. One of these career paths is in medical physics research. Medical physics is an important and rapidly growing field that is dedicated to the application of physics principles and techniques to medicine and healthcare. For JILA alumni Liz Shanblatt, a Staff Scientist and Collaboration Manager at Siemens Healthineers, medical physics became an interest only as she was nearing graduation and starting to look for jobs. “After graduation, I worked as a postdoctoral fellow at the Mayo Clinic Department of Radiology in Rochester, MN,” she explained. “There, I had the opportunity to learn about medical physics and clinical computed tomography (CT) research. The group I worked with at Mayo had a very close collaboration with Siemens Healthineers, testing and co-developing their latest scanners and al-

gorithms. To support this work, the group has an on-site CT Collaboration Scientist from Siemens. After finishing my fellowship, I began work with Siemens as one of the on-site CT scientists.”

While Shanblatt didn’t know about medical physics during most of her time at JILA, her work at the institute prepared her well for her future career in this field. “I worked in the Kapteyn/Murnane group on the imaging team,” Shanblatt stated. “My research was on ptychographic coherent diffractive imaging with an ultrafast laser-driven EUV source. This technique involves collecting the far-field diffraction pattern of a sample and computationally reconstructing the amplitude and phase of the object. My projects included developing imaging systems and algorithms for reflection-mode, dynamic, quantitative, and three-dimensional imaging.” Because x-ray-matter interactions, imaging system fundamentals, and image processing are all important aspects of CT physics, Shanblatt found that her work at JILA on these systems translated well to her current position. According to Shanblatt, “I learned a lot of valuable technical skills during my time at JILA, particularly relating to computational imaging, optics, x-ray physics, and imaging system design. More importantly, working

at JILA taught me how to think critically and problem solve, and how to effectively work with a team.

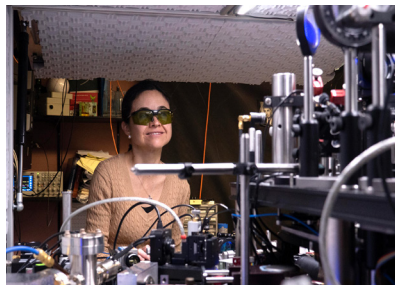
Now as a Staff Scientist and Collaboration Manager at Siemens Healthineers, Shanblatt enjoys being both a researcher and a leader. “My job is essentially a two-in-one: I work as both a scientist and collaboration manager,” she elaborated. “I work closely with an academic research group, supporting the CT research projects with both clinical products and prototypes. I advise on experiments, help troubleshoot hardware and software, and share the team’s feedback with my R&D Colleagues to support product development. I collaborate with radiologists, clinical medical physicists, students, and research fellows to drive CT research and innovate new techniques.”

When thinking back on her time at JILA, Shanblatt is grateful for the many different opportunities the institute presented her. “The research being done at JILA is highly collaborative and produces unique and impactful breakthroughs in many areas of science. JILA also trains well-prepared researchers who go on to work in many different fields of research in both academia and industry. I think that the variety of skills that a JILA researcher has the opportunity to learn helps to make alumni particularly well-suited to take on many different types of careers.”



Liz Shanblatt of Siemens Healthineers.  
Credit: Liz Shanblatt

# JILA FELLOW ANA MARIA REY IS ELECTED TO THE NATIONAL ACADEMY OF SCIENCES



JILA and NIST Fellow Ana Maria Rey in a laser laboratory. Credit: NIST/Rebecca Jacobson

Ana Maria Rey, a theoretical physicist and Fellow with the U.S. Department of Commerce's National Institute of Standards and Technology (NIST) and JILA, has been elected to the National Academy of Sciences, one of the highest professional distinctions for a scientist. JILA is a joint research institute of NIST and the University of Colorado Boulder.

"We are so proud of the incredible work Ana Maria Rey does on

behalf of the nation. Her research is helping us to understand how the world works at the most basic level, so that we can create innovative technologies and improve our quality of life," said Under Secretary of Commerce for Standards and Technology and NIST Director Laurie E. Locascio. "We also appreciate her tireless mentorship of the next generation of researchers."

As a theoretical physicist, Rey studies atomic, molecular and optical physics, condensed matter physics and quantum information science. The research team she leads develops new ways to control quantum systems, opening the way to new applications in measurement, quantum information and quantum simulation. Notably, her work contributed to the most accurate atomic clock ever developed.

Rey has published more than 200 papers, given hundreds of talks and lectures, and has been cited thousands of times. She has earned several prestigious accolades, including a MacArthur Fellowship, commonly known as a "genius grant," and the 2014 American Physical Society's Maria Goeppert Mayer Award. She is a recipient of the Presidential Early Career Award for Scientists and Engineers, the highest honor bestowed by the United States government on science and engineering professionals in the early stages of their independent research careers. She is also the first Hispanic woman to win the Blavatnik National Award for Young Scientists, in 2019.

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Written by Rebecca Jacobson of NIST

## JOSE D'INCAO BECOMES NEW ASSOCIATE JILA FELLOW

University of Colorado Boulder physics professor Jose D'Incao is the newest researcher to become an Associate Fellow of JILA. As D'Incao's research focuses on ultracold quantum physics, he has often collaborated with other JILA Fellows, such as Ana Maria Rey, Eric Cornell and Jun Ye. Now D'In-

cao will fit right in with the majority of JILA's Fellows who focus on quantum science. "For me to join JILA as a fellow is both an honor and a privilege," D'Incao stated. "An honor to be a fellow of an institution that stands firm to the highest standards of scientific research. A privilege to learn, exchange knowl-



JILA's newest Fellow, Jose D'Incao. Credit: JILA

edge, and share exciting scientific adventures within a unique collaborative environment."

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Written by Kenna Hughes-Castleberry

# NEWS

*U.S. Department of Defense under secretary visits JILA.* Heidi Shyu, the Undersecretary of Defense for Research and Engineering at the U.S. Department of Defense, visited JILA and the University of Colorado Boulder on April 21, 2023. She took a walking tour of labs, listened to research briefs, and was introduced to the many collaborations CU Boulder has with national laboratories, including the National Institute of Standards and Technology (NIST) and JILA.

*JILA and NIST Fellows Jun Ye's and David Nesbitt's frequency comb breathalyzer Apparatus is Highlighted in SPIE Photonics West Show Daily.* This highlight focuses on the recent advancements in the frequency comb breathalyzer apparatus that the researchers have built and tested, which looks at diagnosing COVID-19 and other diseases.

*JILA and NIST Fellows David Nesbitt's and Jun Ye's recent results in their breathalyzer study have also been highlighted in a new article in Scientific American.* "We are training our frequency comb nose using machine learning, and once it's trained, it becomes an electronic dog—with much greater sensitivity," Ye says in the article.

*JILA hosts Women in Science Panel to celebrate International Women in Science Day.* Some of

*the most important research and discoveries in science have been made by women.* The United Nations dedicated February 11 as "International Women and Girls in Science" day. To honor this tradition, JILA hosted an open-forum panel discussion with both JILA Fellows and JILA staff as speakers.

*University of Colorado Boulder Physics Professor Noah Finkelstein becomes the Faculty Director of the CUbit Quantum Initiative.* Finkelstein will lead CUbit's establishment of a coordinated educational approach that cultivates leaders of the next-generation quantum workforce.

*JILA held its first Great JILA Bake-off, highlighting the culinary talents of its many researchers.* From bread sculptures inspired by AMO physics to melt-in-your-mouth cookies (otherwise known as "biscuits"), the competition drew out the most creative of bakers from within JILA. COO Beth Kroger emceed the event, dressing up as Noel Fielding, the emcee from *the Great British Bakeoff*. Gayle Geschwind and Scott Brown judged the competition, tasting the many baked treats of the competition. The star baker

was awarded to graduate student Iona Binnie for her delicious chocolate cupcakes.

*JILA Fellow Heather Lewandowski's research highlighted in "Popular Science" Magazine.* JILA Fellow Heather Lewandowski helped lead a group of more than 1,000 undergraduate students in a study looking at the temperatures of the Sun's corona. Their research was featured in *Popular Science Magazine*, revealing the creativity and ingenuity of undergraduate students in scientific research.



Above: JILA graduate student Iona Binnie holds up her certificate announcing her Star Baker win.  
Credit: Kenna Hughes-Castleberry

Below: (left to right): Beth Kroger, Gayle Geschwind, Rebecca Yoho, and Scott Brown all examine Yoho's bread sculpture that was inspired by JILA's research.  
Credit: Kenna Hughes-Castleberry

# AWARDS

*NIST and the Department of Commerce awards JILA and NIST Fellows Jun Ye and Judah Levine Gold and Silver Medals for Scientific/Engineering Achievements. Ye was awarded a Gold Medal and was cited for: "the most precise measurement of the gravitational redshift using optical atomic clocks, further confirming Einstein's Theory of General Relativity." Similarly, Judah Levine was awarded a Silver Medal as part of a larger group cited for "strengthening the resilience of position, navigation, and timing infrastructure and services on which global commerce and national security."*

*Former JILA Researchers Tobias Bothwell and Colin Kennedy receive the 2022 PML Distinguished Associate Award. Both Bothwell and Kennedy were honored with a gold medal for this award, and were cited for "the most precise measurement of the gravitational redshift using optical atomic clocks, further confirming Einstein's Theory of General Relativity."*

*Associate JILA Fellow Shuo Sun has been awarded a 2023 Sloan Research Fellowship. Along with 124 other winners, Sun's work has been recognized as being of the highest quality. At JILA, Sun's research focuses on quantum optics, nanophotonics, and experimental quantum information science. His group studies strong light-matter*

*interactions at the quantum limit by coupling solid-state artificial atoms with nanophotonic structures.*

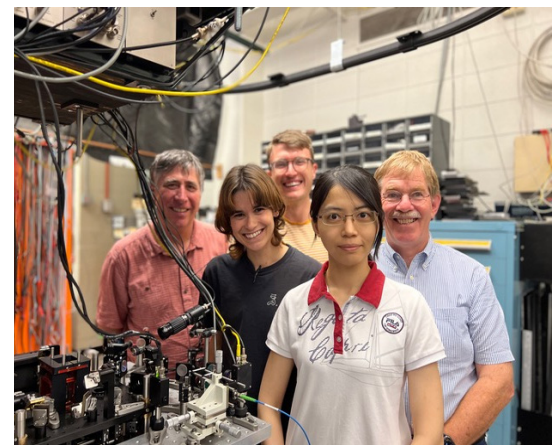
*NASA awards grant to group of quantum institutes, including JILA and the University of Colorado Boulder for researching quantum in space. NASA expects to award a \$15 million grant for five years to the group of universities and institutes, which includes JILA. "The award establishes the Quantum Pathways Institute, supported by a NASA STRI (Space Technology Research Institute), led by Prof. Srinivas Bettadpur of the University of Texas at Austin, Texas, with CU and UCSB as collaborating institutions," explained Dana Anderson, a JILA Fellow.*

*JILA graduate student Tyler McMaken has been awarded an honorable mention by the Gravity Research Foundation for his essay in their annual essay competition. Each year, the Gravity Research Foundation opens a competition that awards five essays encouraging discussion and thought on gravitation. Essays must be less than 10 pages and convey science in more accessible and engaging language than in a journal publication. McMaken, a graduate student in the laboratory of*

*JILA Fellow Andrew Hamilton, studies the gravitational and quantum effects around black holes.*

*JILA graduate student Connor Bice received the 2023 Richard Nelson Thomas Award. This annual award is given to the most outstanding graduate student in astrophysics at the University of Colorado Boulder in honor of Dr. Richard Nelson Thomas. JILA Fellow Juri Toomre, Bice's graduate advisor, presented the award, along with Dr. Nelson's widow, Nora Thomas. Both spoke of Bice's research rigor and dedication to the field of astrophysics. Bice's research focused on activities around m-dwarf stars.*

*JILA and NIST Fellow Konrad Lehnert receives a prestigious MURI award. Lehnert will be leading a Department of Defense (DoD) project focusing on quantum phononics to advance quantum information processing as part of a \$7.1 million government grant.*



The JILA team awarded part of the NASA grant. From left to right: Murray Holland, (front) Catie Ledesma, (back) Kendall Mehling, (Front) Liang-Ying (former JILA graduate student), and Dana Anderson.  
Credit: Dana Anderson/JILA



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](http://jila.colorado.edu)

