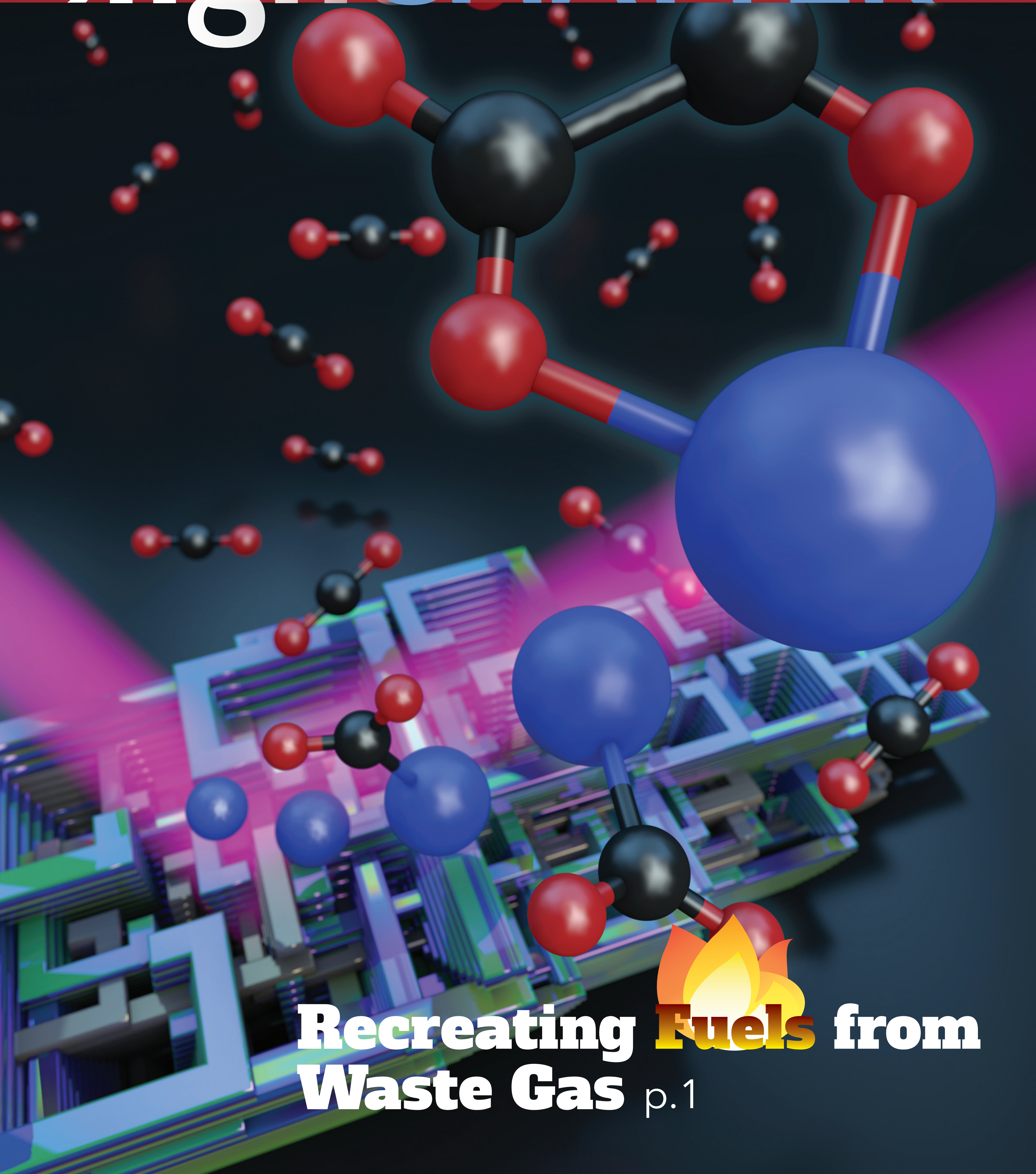
JILA light & MATTER

Spring 2017 | jila.colorado.edu



Recreating Fuels from Waste Gas p.1

Spring returns to the University of Colorado Boulder campus, the home of JILA. Credit: Kristin Conrad, JILA.

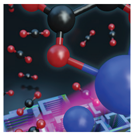
JILA Light & Matter is published quarterly by the Scientific Communications Office at JILA, a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology.

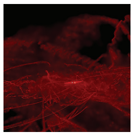
The editors do their best to track down recently published journal articles and great research photos and graphics. If you have an image or a recent paper that you'd like to see featured, contact us at: communications@jila.colorado.edu.

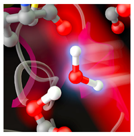
Please check out this issue of *JILA Light & Matter* online at https://jila.colorado.edu/publications/jila/light-matter.

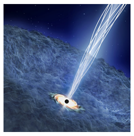
Kristin Conrad, Project Manager, Design & Production
Julie Phillips, Science Writer
Steven Burrows, Art & Photography
Gwen Dickinson, Editor

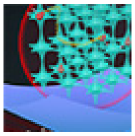
Stories











Features

Recreating Fuels from Waste Gas

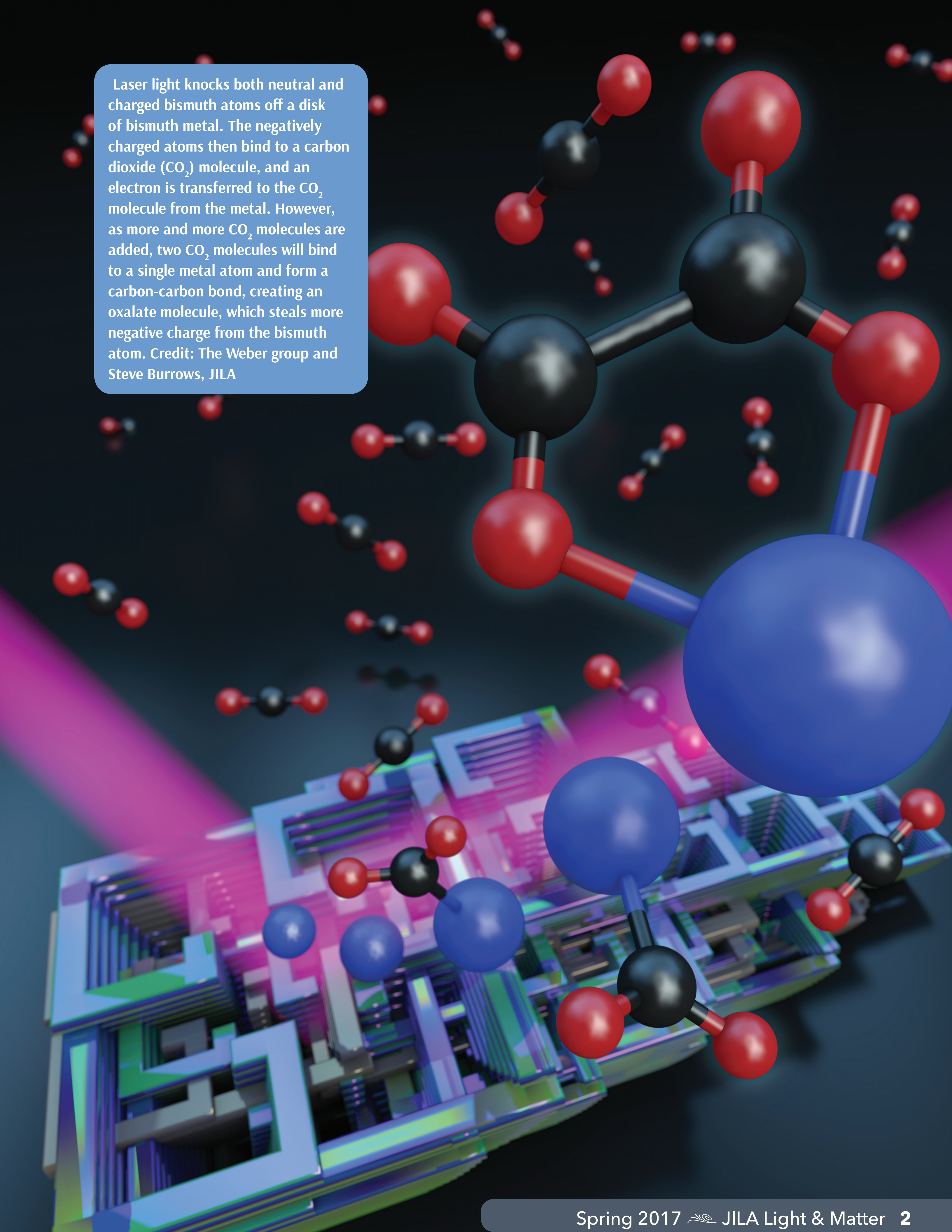
Graduate student Mike Thompson of the Weber group wants to understand the basic science of taking carbon dioxide (CO_2) produced by burning fossil fuels and converting it back into useful fuels. People could then use these fuels to generate electricity, heat homes and office buildings, power automobiles and trains, fly airplanes, and drive the industrial processes of modern life.

However, the conversion of CO_2 into useful fuels is a challenging problem in chemistry and chemical engineering. It takes energy to turn CO_2 into carbon monoxide (CO) and CO into natural gas (methane) and liquid fuels such as gasoline. The good news is that methods using electrochemical cells to transform CO_2 into CO could easily be powered by renewable energy from intermittent resources such as the Sun and the wind. Instead of adding more and more CO_2 from fossil fuels to the atmosphere, people could recycle CO_2 from burning fossil fuels using electrochemical cells and alleviate the progression of global warming.

The trick is figuring out how to lower the amount of energy needed for turning CO_2 into CO. Without chemical tricks, the energy cost turns out to be way too high to be economical yet. The trick that's needed is to use a catalyst. A catalyst is a metal or other substance that accelerates a chemical reaction without being affected. Fortunately, electrodes made of metals, such as gold, silver, or bismuth, can catalyze the transformation of CO_2 to CO. Bismuth has advantages over other metals, including (1) working as well, if not better, than gold, (2) being readily available in large quantities because it is a by-product of lead mining, and (3) costing nearly 350 times less than gold per gram. Because of these advantages, bismuth metal is under consideration for CO_2 conversion, but the molecular details of the process are not well understood. To gain a deeper insight into the process, the group recently began investigating the use of bismuth metal in CO_2 conversion catalysis on the molecular level.

The first step was acquiring a disk of bismuth that could be used to produce bismuth atoms. A trip to see Hans Green in JILA's instrument shop resulted in the discovery of some 20-year-old, high-purity bismuth shot (1–2 cm pieces of pure metal). Green added the shot to a tailor-made disk-shaped aluminum mold and heated it up on a hot plate. After the disk cooled, Green machined it to provide a smooth surface to make it possible for the laser beam to blow off atoms one by one.

The second step was to begin a study of the chemistry of CO_2 conversion by looking at how to transfer an extra electron to a CO_2 molecule. This step costs a lot of energy unless a catalyst is used. *(cont. page 3)*



Laser light knocks both neutral and charged bismuth atoms off a disk of bismuth metal. The negatively charged atoms then bind to a carbon dioxide (CO_2) molecule, and an electron is transferred to the CO_2 molecule from the metal. However, as more and more CO_2 molecules are added, two CO_2 molecules will bind to a single metal atom and form a carbon-carbon bond, creating an oxalate molecule, which steals more negative charge from the bismuth atom. Credit: The Weber group and Steve Burrows, JILA *(cont. from page 1)* "We study how a few CO_2 molecules bind to a single charged bismuth atom," Thompson explained. "The reason we do this is that actual electrochemical cells are very complex systems, so we're trying to simplify the system as much as possible so we can get at the heart of the interaction."

What Thompson and his colleagues learned from studying their bismuth-CO_2 cluster model system was that a CO_2 molecule docked onto a negatively charged bismuth atom through the carbon atom. The chemical bond between the bismuth atom and the CO_2 then allowed an electron to spend about 65% of its time on the CO_2 molecule. By the time the researchers positioned approximately four CO_2 molecules around the bismuth-CO_2 molecule, the extra electron was almost completely transferred to the attached CO_2 molecule. But when a fifth CO_2 molecule was added, suddenly two CO_2 molecules bound to the metal atom. The two CO_2 molecules also formed a carbon–carbon bond with each other, forming a molecule called oxalate. This reaction is similar to processes in a real electrochemical cell, where oxalate can also be formed. This is a significant finding because it shows that the Weber group's cluster model can be used to learn something about processes in electrochemical cells. And, with some additional work, there's a good chance this model system will also produce CO!

The researchers responsible for this intriguing work included graduate student Michael Thompson, Fellow Mathias Weber, and group collaborator Jacob Ramsay (University of Aarhus, Denmark). ✺

Michael C. Thompson, Jacob Ramsay, and J. Mathias Weber, *Angewandte Chemie International Edition* **55**, 15171–15174 (2016).

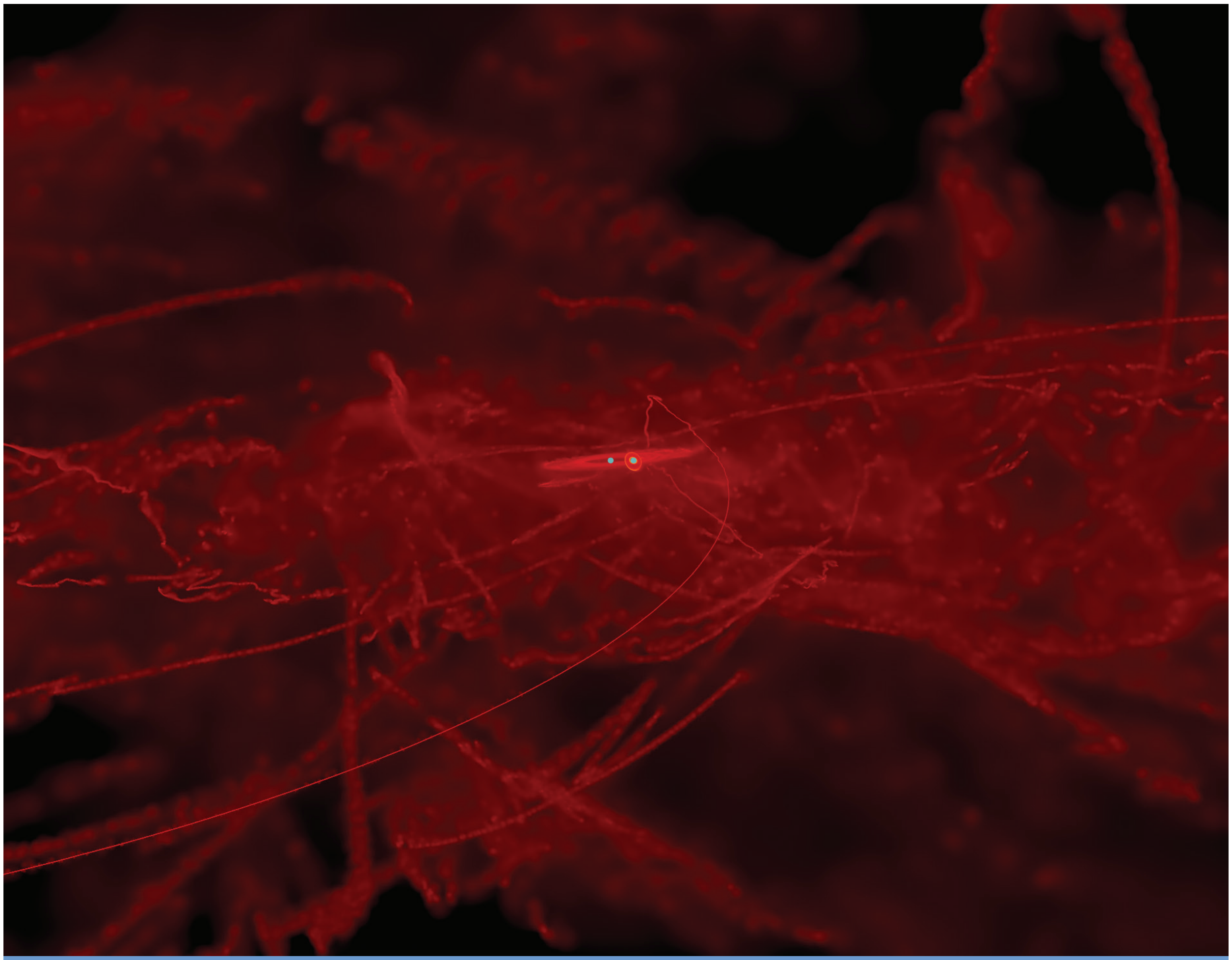
Dancing with the Stars

A new way to find pairs of black holes at the center of galaxies

Galaxy mergers routinely occur in our Universe. And, when they take place, it takes years for the supermassive black holes at their centers to merge into a new, bigger supermassive black hole. However, a very interesting thing can happen when two black holes get close enough to orbit each other every 3–4 years, something that happens just before the two black holes begin their final desperate plunge into each other. And, according to former JILA graduate student Eric Coughlin and his colleagues, if one of the black holes happens to tidally disrupt an errant star, the process will send out a signal that will allow Earthlings to "see" which galaxies contain these pairs of black holes.

"If two black holes happen to be that close together, and a star gets disrupted by one of the black holes, there's a reasonable probability that the debris stream will actually miss the black hole that disrupted it and hit the second black hole," said Mitch Begelman, Coughlin's thesis advisor at JILA. "You get this kind of dance between the two black holes, and of course you get fantastic flow patterns that are just neat." Begelman added that these flow patterns create a distinctive signal that there are two black holes involved in the tidal disruption of a single star.

Right now, existing space-based telescopes could detect one of these events every few years. However, in 2019 or 2020, the huge Large Synoptic Survey Telescope (LSST) will be launched. And, thanks to Coughlin's new study that tells astronomers what to look for, the LSST should be



Computer simulation of a tidal disruption event involving a pair of supermassive black holes in the center of a recently merged galaxy. The flow patterns create a distinctive signal of the presence of a pair of closely orbiting black holes. Credit: Eric R. Coughlin

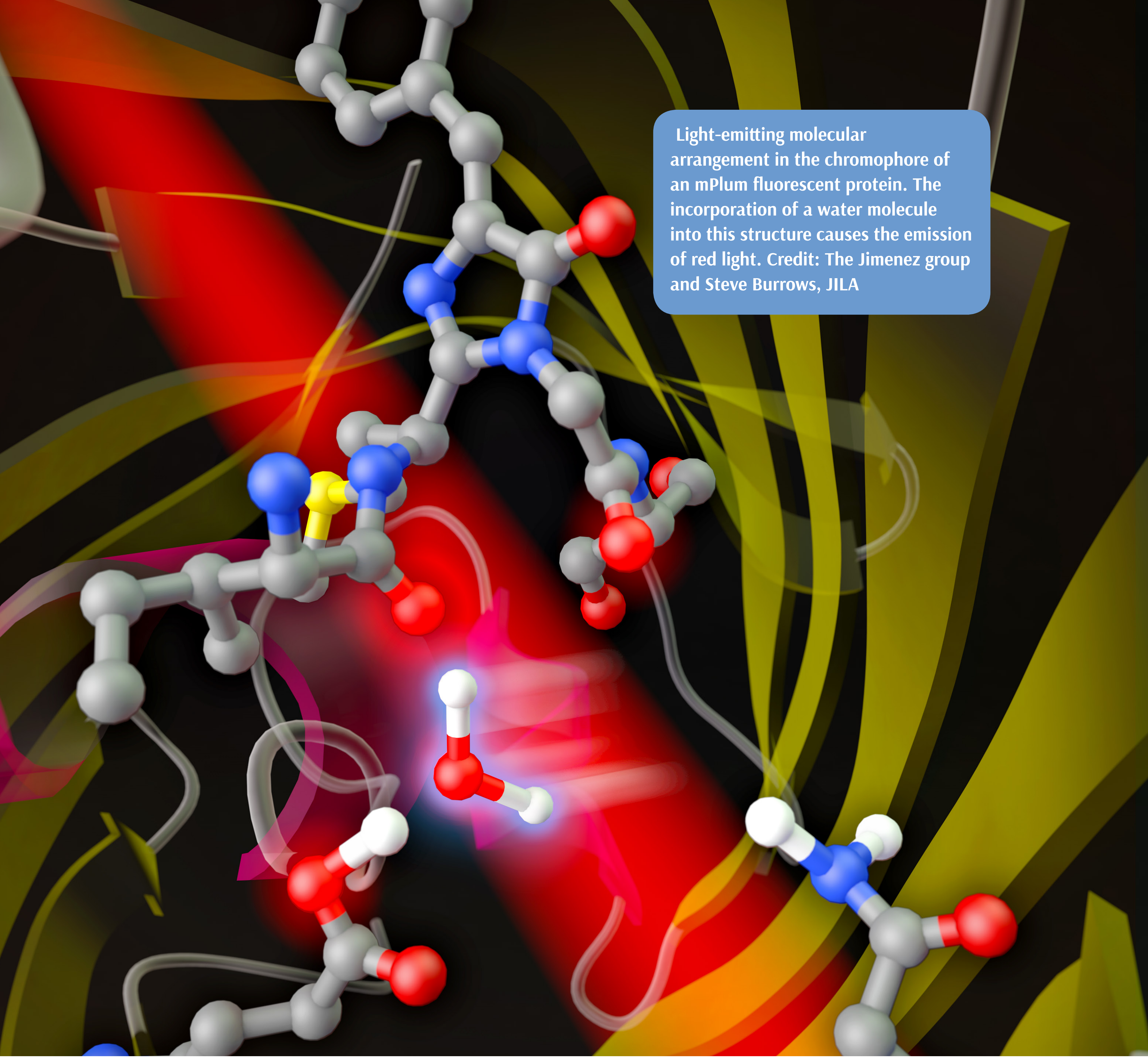
able to see a handful of the binary black-hole mergers every year among the many galaxies in our Universe.

"It is a notoriously difficult thing to discern the presence of one black hole, and this is a way to find two," Coughlin explained. "We think binary black-hole systems should be common, considering how we think our own galaxy evolved via multiple galactic collisions."

Coughlin said that astronomers now have a new probe in tidal disruption events, which are well understood, to learn something about the evolution of galaxies. As part of his research into tidal disruption events and how they can be used to identify pairs of black holes in the center of merging galaxies, Coughlin has created a stunning animation of the process in action.

The researchers responsible for this work include recently minted JILA Ph.D. Coughlin, recent visitor and former research associate Chris Nixon, and Fellows Phil Armitage and Mitch Begelman. ✺

E.R. Coughlin, Armitage, P.J., Nixon, C., and Begelman, M.C., *Monthly Notices of The Royal Astronomical Society* **465,** 3840-3864 (2016).



Light-emitting molecular arrangement in the chromophore of an mPlum fluorescent protein. The incorporation of a water molecule into this structure causes the emission of red light. Credit: The Jimenez group and Steve Burrows, JILA

The Red Light District

Far-red fluorescent light emitted from proteins could one day illuminate the inner workings of life. But before that happens, scientists like Fellow Ralph Jimenez must figure out how fluorescent proteins' light-emitting structures work.

As part of this effort, Jimenez wants to answer a simple question: How do we design red fluorescent proteins to emit longer-wavelength, or redder, light?

The reason for working on this problem is that far-red light emitted by fluorescent proteins would be more useful for "seeing" into the intact organs of live animals such as mice. Far-red light more readily passes through living tissue than do green or blue wavelengths, as those people who have covered a flashlight with their hands can attest.

There are two basic approaches to making red fluorescent proteins redder, according to Jimenez. The first one is to change the structure of the small group of atoms called the chromophore that absorb and emit light. In the past, researchers thought that that the longer-wavelength emission from red fluorescent proteins was due to a particularly strong interaction between specific atoms in the chromophore (known as acylimine) and atoms in the barrel-shaped protein surrounding the chromophore. This interaction supposedly gave the electrons in the chromophore more room to move around, which lowered the energy of the photons absorbed and emitted by the chromophore.

The second approach is to fine-tune the motions of the barrel around the chromophore. This approach is favored by the Jimenez group, which studied a protein called mPlum that emits the longest-wavelength red light of any of "mFruit" family of fluorescent proteins. The Jimenez group's experiments show that mPlum's redder emission is due to the flexibility of interactions between the barrel and chromophore's acylimine atoms.

"Water is available in and around the barrel, and water can pop in and pop out as the (floppy) side chain rotates," Jimenez explained. "This rotation is correlated with the red shift." In other words, after mPlum absorbs a photon, a water molecule gets in between the chromophore and a sidechain of the protein, causing the chromophore to fluoresce red rather than orange light.

The Jimenez group recently measured this process in detail and determined that after the mPlum's chromophore is excited with a short pulse of laser light, it takes precisely 37 picoseconds (10^{-12} s) to convert from a structure without water to a lower-energy structure containing a water molecule.

Following this enlightening experiment, the group collaborated on an analysis of a fluorescent protein known as TagRFP675, which emits even redder light than mPlum. TagRFP675 has two different interactions between the acylimine group of its chromophore and the protein barrel, both of which can interact with water and with other protein structures, with everything in constant motion. The question was whether the two interactions in TagRFP675 responsible for the redder emission occurred via the same mechanism identified for mPlum.

"Two interactions turned out to be too much of a good thing," Jimenez said, adding that the system is so complex that it emits light from multiple structures simultaneously, and it's difficult to nail down which ones are responsible for the reddest emission.

"We discovered that there may be an avenue to making a more red-shifted fluorescent protein by learning how to lock down, or immobilize, one of the structures in TagRFP675," he said.

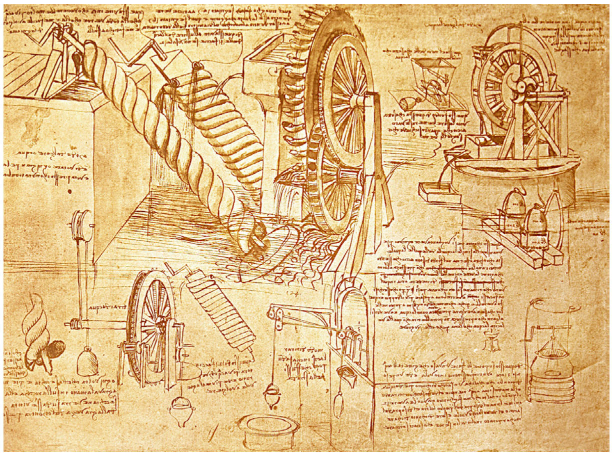
Jimenez worked on the mPlum and TagRFP675 projects with recently minted JILA Ph.D. Patrick Konold, graduate student Samantha Allen, and colleagues from Pohang University of Science and Technology (South Korea), Florida International University, Virginia Tech, the Massachusetts Institute of Technology, and Albert Einstein College of Medicine. ✺

Eunjin Yoon, Patrick E. Konold, Junghwa Lee, Taiha Joo, and Ralph Jimenez, *The Journal of Physical Chemistry Letters* **7**, 2170–2174 (2016).

Patrick E. Konold, Eunjin Yoon, Junghwa Lee, Samantha Allen, Prem P. Chapagain, Bernard S. Gerstman, Chola K. Regmi, Kiryl D. Piatkevich, Vladislav V. Verkhusha, Taiho Joo, and Ralph Jimenez, *The Journal of Physical Chemistry Letters* **7**, 3046–3051 (2016).

Puzzle - Name the Artist

1. ______________________________

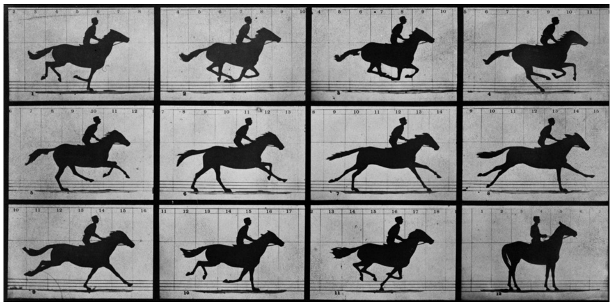


2. ______________________________

3. ______________________________

Give the name of each artist that painted these well-known images of science and engineering. Known spelling variations will be accepted since painters often changed the spelling of their names. The first person or group, who has not won a Light & Matter contest within the past year, who turns in the correct answers to Kristin Conrad (S264) will win a $25 gift card.

4. ______________________________



5. ______________________________

6. ______________________________

Confessions of a Solar Eclipse Junkie

Why I look forward to August 21, 2017, and beyond

by Jeffrey L. Linsky

I am an astrophysicist, which is a fancy word for an astronomer who uses physics to understand the Universe. Like the proverbial bus driver on a busman's holiday, I use my limited free time to observe one of the most spectacular astronomical phenomena that Nature has to offer: total eclipses of the Sun. You can do this too. No telescope or any equipment is required, but you must be at the right place at the right time and know what to look for.

On a whim, I traveled to my first eclipse in Maine. Even though I was totally unprepared for the experience, I was instantly hooked. Even though clouds partially obscured the Sun, my first view of the solar corona and the changing environment all around me made a deep and lasting impression. Subsequent eclipses observed under perfect conditions in remote places reinforced the joy and privilege of experiencing such an incredible event. My wife Lois quickly acquired the passion for traveling to and experiencing eclipses. We have now seen eight of them together, and she is eagerly planning for the next one.

Solar eclipses occur when the Moon moves in front of the Sun for a short period of time. At any place on the Earth total eclipses are rare events, but a total eclipse usually occurs somewhere about once a year. The path of totality is generally thousands of miles long and about 100 miles wide. Outside of the path, the Moon will only cover a part of the Sun, producing a partial eclipse.

The location of an eclipse path is determined by the orbit of the Moon and not by our desire to observe the eclipse from a nearby comfortable site. In fact, the best eclipses in terms of duration and clear sky often occur at very remote locations. I list the nine eclipses that I have seen in a table on page 12. Certainly, Svalbard (latitude 78 degrees between the North coast of Norway and the North Pole), Easter Island (the most isolated island on the Earth), and the Sahara desert in Libya qualify as very remote places, and some of the other locations are far from airports and familiar cities. I include two pictures of amateur eclipse observers waiting for totality at several of these sites. One must travel to where the eclipse and cloud gods dictate and be there at the right time.

Photograph of the Sun during the eclipse on February 26, 1998. At this time the Sun was less active and less red emission from the chromosphere was seen.

My wife Lois and I have had the privilege of observing many total eclipses, most with perfectly clear sky and excellent visibility, but some with clouds obscuring part of the time during totality. We have been incredibly lucky to see totality between rain showers in Finland and on the beach in Australia where people half a mile away saw only clouds. Not far away from us in Shanghai it rained all day, but we saw most of the eclipse near Hangzhou, China. The prediction for the eclipse day in Svalbard was clouds, but we had three perfect days of sunshine.

Traveling to very remote places has many benefits. We observed the June 21, 2001 eclipse about a

Setting up equipment before the eclipse on Easter Island July 11, 2010, under the watch of a friendly Moi statue.

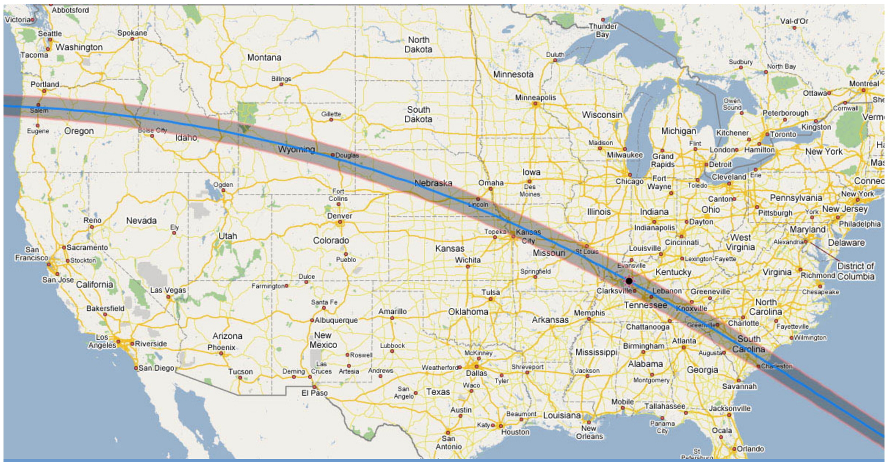
three hours drive east of Harare, Zimbabwe in a remote area near the border with Mozambique on the Ruya river. We saw a beautiful total eclipse in the yard of Maname school. What an interesting time talking with the teachers and students in English (Zimbabwe had been a British colony). They could not stop describing their school about which they were very proud. The students wanted to know what our children learn in school and what kind of work we do. They were amazed to see people coming from very far away to their school. That evening back in Harare we saw on television President Mugabe and family watching the partial phases with eclipse glasses from the State House lawn, but they missed the great event not that far away. On that trip we explored the world famous Victoria Falls and historic Greater Zimbabwe.

This last March we traveled to Indonesia to observe a three–minute eclipse from the Sultan's palace on Tindore, one of the "spice islands" that rarely sees any western tourists. We showed children and adults how to image the partially eclipsed Sun by making a small hole between four fingers. They then did the experiment themselves. This trip provided many opportunities to talk with Indonesian people who loved seeing Americans and taking pictures of us with them. We had a long talk with a high school chemistry teacher who had never met an astronomy professor and wanted to know what American universities are like. We also visited a number of the islands in this large and very diverse country.

Jeffrey and Lois Linsky at a sign warning of polar bears outside of the town of Longyearbyen, Norway. Svalbard is a set of islands located at 78 degrees North latitude. We observed the eclipse nearby with perfect sky, but it was very cold.

There has not been a total eclipse in the United States since July 1963 when the eclipse path traversed central Maine, or in July 1991 when the eclipse path crossed the big island of Hawaii. The next total eclipse is being called the Great American Eclipse, because on August 21, 2017, the eclipse path will cross the US from Salem, Oregon to Charleston, South Carolina, including Grand Teton National Park in Wyoming, St. Louis, Missouri, and Nashville, Tennessee.

A word to the wise - don't expect to drive to anywhere in the totality path on the morning of the eclipse because you will likely be caught in huge traffic. Our bus never made it to the center of the totality path on March 29, 2006, because of the first ever traffic jam in the middle of the uninhabited



Eclipse path during the Great American Eclipse that will occur on August 21, 2017. The blue line is the central location, and the outer edge of the grey area marks the outer limit for seeing the total eclipse as it traverses the US in about three hours from Oregon to South Carolina. Totality is longest along the blue line and becomes shorter away from the blue line. The maximum duration of totality is 2 min 40 sec in western Kentucky. The lowest probability for clouds is in the Western US.

Sahara desert. Many millions of people live along the totality path, and many more will travel to see the total eclipse in all of its glory. My wife and I plan to be at Jackson Lake, Wyoming to see the event. In the Buffalo area the eclipse will be partial with a maximum of only 77% of the Sun obscured by the Moon. Partial eclipses are not spectacular events like total eclipses.

What to Bring for an eclipse

Bring a portable chair, eclipse glasses, binoculars, and appropriate liquid refreshment to celebrate a hopefully successful eclipse. Be prepared to move just before the eclipse starts to avoid clouds if necessary.

What can you expect to see during a total solar eclipse? Totality is preceded by about 80 minutes of partial eclipse as the Moon gradually covers the Sun. During this time the air cools with less sunlight to heat it, and shadows take on an unusual appearance as illumination by a sliver of the Sun produces shadows that are much sharper than usual. As the Sun dims, birds become quiet, and twilight appears in the West as darkness rushes towards you at more than 1000 miles/hr. Just before totality begins, you may see shadow bands that look like bright and dark snakes running across the ground.

For a few seconds before second contact, small beads of sunlight called “Bailey’s beads” peak through low areas at the limb of the Moon.

Totality begins as the Moon now completely covers the Sun. Take off your dark eclipse glasses and look directly at the Sun. Notice the clumps of red light at the solar limb which is emission by atomic hydrogen in solar structures called prominences. Above the solar limb on all sides, you will see the solar corona as a white envelope that may have a few spike-like structures called streamers extending well above the limb. Look at the sky away from the Sun. If the sky is clear, you will see a few planets, probably Mercury and Venus, but perhaps also Mars, Jupiter, and Saturn. Look to the horizon and you will see multicolored twilight in all directions, a phenomenon that can only be seen during total eclipse.

Now the 2–5 minutes of totality is almost gone at the fastest rate you will ever see time fly. At the end of totality, bright sunlight emerges above a crater at the Moon’s limb, producing the spectacular diamond ring effect for a few seconds. Totality is now over, the sequence of partial phases reverses, and the world returns to normal. The loss of sunlight produces noticeable cooling. During the Svalbard eclipse the temperature dropped from 0 degrees to -14 degrees F.

I have some suggestions for eclipse chasers. Don't waste your time taking a photograph of the totality. The time during totality is too short to play with a camera. Experts can obtain far better pictures than you can, and great pictures are available on the internet. The best use of your time is to look with your unaided eyes or with binoculars at everything that is going on around you. Definitely wear eclipse glasses with very dark lenses if you look at the Sun during the partial phases, but take off these glasses during totality as the eclipsed Sun is no brighter than the full Moon.

Travel to near the center of the eclipse path to get the longest duration of totality, but go a day before to avoid the traffic. Finally, think through what you will do just before and during totality as the sequence of events goes very fast and there is no opportunity for a repeat performance until the next eclipse, which could be in a remote location and perhaps very cloudy. For more information including exact times and locations of future eclipses, go to the NASA website by Googling "Solar Eclipse August 2017." You too may become addicted to eclipses. ✺

Total Solar Eclipses I have seen and plan to see

Date	Where	Description	Duration of Totality (min:sec)
July 20, 1963	Central Maine	Partly cloudy	0:58
July 22, 1990	Eastern Finland	Between clouds	1:31
June 21, 2001	Zimbabwe	Excellent	3:20
Mar 29, 2006	Sahara Desert Libya	Excellent	4:06
July 22, 2009	near Hangzhou China	Some clouds	5:34
July 11, 2010	Easter Island Chile	Very good	4:50
Nov 13, 2012	Palm Cove Australia	Between clouds	2:00
Mar 20, 2015	Svalbard Norway	Excellent	2:29
Mar 09, 2016	Tindore Island Indonesia	Excellent	3:04
Aug 21, 2017	Jackson Lake Wyoming	TBD	2:18
Apr 08, 2024	Nichols School	TBD	4:13

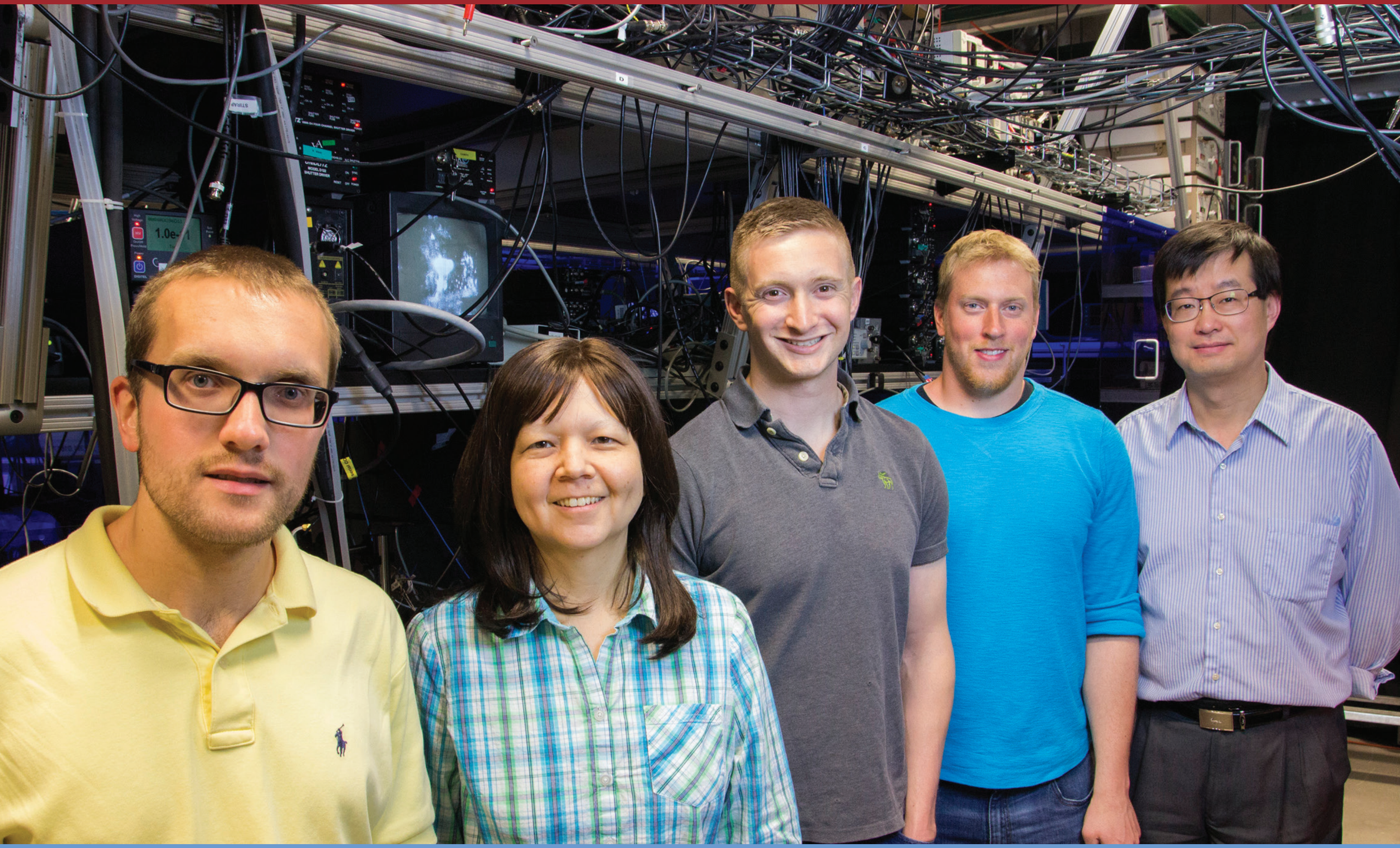
BIO: Jeffrey Linsky is a Research Professor Emeritus at the University of Colorado Boulder. He graduated The Nichols School (Buffalo, New York) in 1959. He then went to the Massachusetts Institute of Technology and Harvard where he received his PhD in Astronomy. He has been an astrophysicist in Boulder since 1968 specializing in the outer atmospheres of stars, the gas between stars, and most recently the effects of stellar radiation on the atmospheres of planets now being discovered in orbit about these stars. He is now officially retired but works full time. Since many of his former students are faculty members at different universities, he keeps meeting previously unknown graduate students and their students at scientific meetings.

TYPES OF ECLIPSES: Eclipses are total when the Moon is relatively close to the Earth and is, therefore, slightly larger than the Sun. Annular eclipses occur when the Moon is further away from the Earth and too small to occult the entire Sun, leaving a narrow ring of sunlight around the dark Moon.

ECLIPSE PHASES: The term contact is commonly used to identify the different phases of a solar eclipse. First contact refers to the time when the Moon first begins to cover the Sun. Second contact refers to the time when the Moon first completely covers the Sun. Third contact refers to the time when the Moon last covers the entire Sun, and fourth contact is the time when the Moon completely uncovers the Sun. Totality is the time between second and third contact. The partial phases are between first and second contact and between third and fourth contact.

OBSERVING PARTIAL PHASES: Buy inexpensive eclipse glasses with their very dark plastic lenses because normal sunglasses are too transparent for observing the partial phases. With eclipse glasses you can directly observe the partial phases safely. If you want to photograph the partial phases without destroying your camera or cell phone, put a very dark filter in front of your camera's lens. You can see multiple images of the partially eclipsed Sun by holding a strainer or sieve from your kitchen above a white cloth or shirt on the ground.

SHADOW BANDS: This strange effect occurs a few seconds before second contact when light from the thin sliver of the Sun shines through the Earth's turbulent atmosphere producing light and dark bands that rapidly move across the ground. The effect is similar to looking at a distant light through the steam rising above boiling water, except that the light is a line not a circle and the boiling water is moving through your line of sight. Shadow bands are best seen by looking at a white cloth or shirt placed on the ground when there are no clouds in front of the Sun.



(l–r): Steve Moses, Deborah Jin, Matt Miecnikowski, Jake Covey, and Jun Ye in the new Cold Molecule lab (Spring 2016). Credit: Steve Burrows, JILA

Molecules on the Quantum Frontier

Deborah Jin, Jun Ye, and their students wrote a review during the summer of 2016 for *Nature Physics* highlighting the accomplishments and future directions of the relatively new field of ultracold-molecule research. The field was pioneered by the group's creation of the world's first gas of ultracold potassium-rubidium (KRb) molecules in 2008.

The molecules were made by first creating weakly bound pairs of K and Rb atoms from an ultracold atomic mixture and then using lasers to transfer the atom pairs to their ground state, where they became tightly bound molecules. It sounds simple, but figuring out this process took the Jin-Ye team more than five years of dedicated effort. Making ultracold molecules was, and remains, an extremely challenging endeavor.

For nearly six years following this noteworthy feat, the Jin-Ye collaboration was the only group in the world that had produced stable ultracold polar molecules in the quantum regime. The first cold-molecule experiments at JILA included studies of ultracold chemistry and collisions in which molecular interactions are governed by universal quantum rules. More recent work has focused on the creation of new types of quantum systems, including molecules confined in a deep three-dimensional optical lattice, where spin-exchange couplings make the molecules behave like tiny quantum magnets. In late 2015, the group reported the production of a gas of polar molecules in its lowest possible energy state.

> The molecules were made by first creating weakly bound pairs of K and Rb atoms from an ultracold atomic mixture and then using lasers to transfer the atom pairs to their ground state, where they became tightly bound molecules. It sounds simple, but figuring out this process took the Jin-Ye team more than five years of dedicated effort. Making ultracold molecules was, and remains, an extremely challenging endeavor.

“It was six years before anyone else made ultracold polar molecules,” said Ye. “But by 2015, there were four groups starting to get results with these molecules, one at the Massachusetts Institute of Technology led by Martin Zwierlein, a second group at the University of Innsbruck headed by Hanns-Christoph Nägerl, a third at the University of Durham (U.K.) led by Simon Cornish, and a fourth led by Dajun Wang at The Chinese University of Hong Kong.”

Two of these groups have strong connections to JILA. Cornish worked as a postdoc with Carl Wieman in 1999–2000 and came to JILA again as a Visiting Fellow in 2015. Wang was a postdoc in the Jin-Ye group from 2007 to 2010.

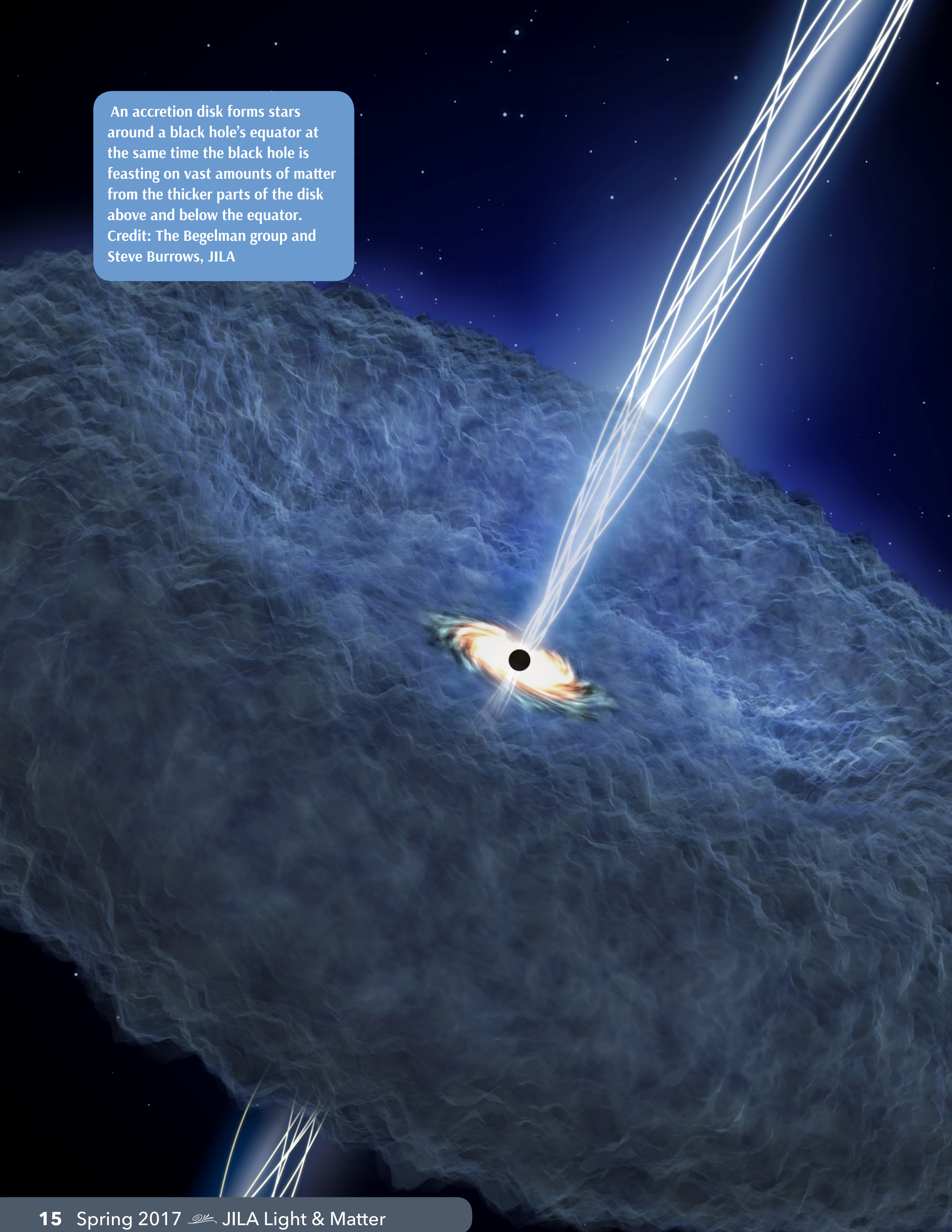
New research groups entering the ultracold-molecule field should spark rapid progress in the near future as researchers continue to improve their control of the molecules. For example, the JILA group has just completed a new ultracold-molecule apparatus that may one day lead to experimental observation of the growth and propagation of quantum entanglement. Eventually the JILA researchers want to enhance their quantum control and observation by building a quantum gas microscope for observing individual molecules in the optical lattice.

As the field grows, new ultracold-molecule investigations are focusing on new kinds of molecules, including sodium-rubidium, sodium-potassium, rubidium-cesium, and ytterbium-cesium. The new molecules are one reason the paper concludes with an optimistic forecast for the future:

“The field of ultracold polar molecules shows no signs of slowing down, and there should be many fruitful experiments in the next few years.”

The article, entitled “New frontiers with quantum gases of polar molecules,” appeared online in Nature Physics on December 16, 2016. Its authors included recently minted JILA Ph.D. Steven Moses, graduate student Jake Covey, CU graduate student Matthew Miecnikowski, and Fellows Deborah Jin and Jun Ye. This was the final paper that Jin worked on before her untimely death in September 2016. ✺

Steven A. Moses, Jacob P. Covey, Matthew T. Miecnikowski, Deborah S. Jin, Jun Ye, *Nature Physics* **13**, 13–20 (2017).



An accretion disk forms stars around a black hole's equator at the same time the black hole is feasting on vast amounts of matter from the thicker parts of the disk above and below the equator. Credit: The Begelman group and Steve Burrows, JILA

BLACK HOLES CAN HAVE THEIR STARS AND EAT THEM TOO

Fellow Mitch Begelman's new theory says it's possible to form stars while a supermassive black hole consumes massive amounts of stellar debris and other interstellar matter. What's more, there's evidence that this is exactly what happened around the black hole at the center of the Milky Way some 4–6 million years ago, according to Associate Fellow Ann-Marie Madigan.

Relatively recently on the cosmic scale of things, the sleeping giant at the center of our Galaxy roared to life as an active galactic nucleus (AGN), swallowing enough matter to increase its size by more than 10% and creating a necklace of new stars around its equator.

"You can form some stars along the equator of the black hole's thick inner disk, but most of the matter flows into the black hole from above and below the equator," Begelman explained. "It works this way because we now know that magnetic fields can expand vertically and puff up the disk. This process allows the matter above and below the inner disk to feed the black hole."

In this scenario, the upper and lower parts of the "accretion disk" look like wedges that expand vertically from the inner disk at angles of approximately 50 degrees. The whole structure looks like a doughnut without an outer edge that extends outwards a million times the radius of the black hole. The huge amount of gas in these regions flows into the black hole at the same time stars are forming around the equator.

> "With our new model, we can say how bright that AGN would have been," Begelman said.

"What we didn't understand was that a black hole that was forming stars could also accrete," Begelman said. "Now we understand for the first time that you can have your stars and eat them, too." Begelman clarified that black holes don't actually eat the stars, but rather the gas left over from making stars.

Interestingly, the black hole at the center of our Milky Way Galaxy may have been an AGN 4–6 million years ago. The smoking gun is a necklace of stars around our own, now rather sedate black hole. The disk of stars is located exactly where Begelman's new model predicted it would be.

"With our new model, we can say how bright that AGN would have been," Begelman said. "Right now the center of the Milky Way has a luminosity of about 100 Suns, but a few million years ago when it was an AGN, it would have been as bright as a billion Suns." Begelman added that about 1% of the mass of the central black hole was turned into stars during that episode. At the same time, the black hole grew about 10%. In other words, the beautiful necklace of stars we see today is just the leftover crumbs from the most recent feeding frenzy of our Galaxy's central black hole.

Begelman collaborated on this work with his colleague Joseph Silk of the Institut d'Astrophysique de Paris, Université Pierre et Marie Curie. ✺

Mitchell C. Begelman and Joseph Silk, *Monthly Notices of the Royal Astronomical Society* 464, 2311–2317 (2016).

The Beautiful Ballet of Quantum Baseball

The Rey and Ye groups discovered the strange rules of quantum baseball earlier this year. But now, quantum baseball games happen faster, and players (dipolar particles) are no longer free to move or stand wherever they want. Players must not only be stronger to jump and catch the balls (photons), but also more organized. At the same time, they must be good spinners. And, only a small amount of disorder is tolerated! The fast spinning of the players and their fixed positions have made quantum baseball a whole new game!

The players not only stay in one place, but also remain close to each other, forming a fixed and ordered pattern. The players can throw balls to each other, but since the players stand closer to each other than they did before, the balls move faster and hit harder.

However, the players must also know how to spin on their toes, just like ballet dancers! The reason the players have to spin en pointe is that balls now also spin. Because the balls spin, the players must start spinning as they catch them. With these new rules, the balls and players can execute an intricate dance in which they all rotate in the same direction, which causes exotic massless quantum particles (called Weyl particles) to show up in the quantum baseball field. These red particles appear inside the playing field in the picture.

The players still exchange balls because dipoles interact through exchanging photons. But, now the balls spin as they fly across the playing field. When a player throws the ball, the player who catches it can't run after the ball because she is frozen in place. All she can do is to jump and spin—if the ball is spinning. She can spin even if she spins in the opposite direction of the ball.

"It's the same balls we used for the first quantum baseball game, but now the players need to be ordered," explained Fellow Ana Maria Rey. "Before the players were everywhere, but now they have to be organized. A lattice (crystal of light) forces the players to be in specific positions. They don't run, only jump and spin."

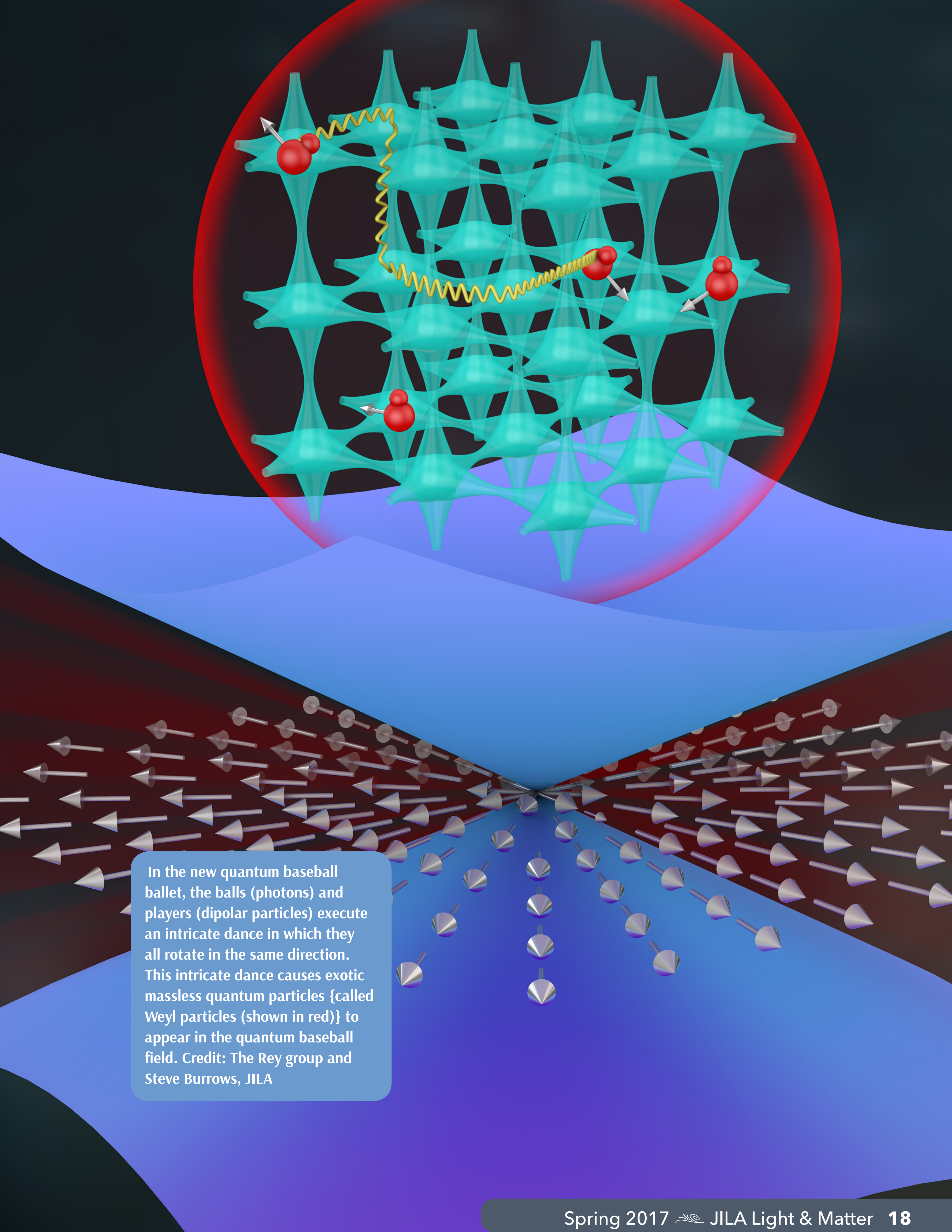
The beautiful ballet of quantum baseball is the result of a quantum connection between spin and motion (known as spin-orbit coupling) that occurs as players jump and spin. Exactly what happens in the game depends on the location of the players and the velocity of the balls.

What's interesting is that for specific ball velocities, where the players stand as well as their spinning and jumping can make them more coordinated. When the players get more coordinated, the ball can be in the air for a much longer time before being dropped. The collective behavior that gives the team better catching capabilities is called subradiance.

Subradiance allows the players to coordinate their spinning in such a way that they all circulate in the same direction, and Weyl particles emerge in the field. Weyl particles have been seen in solid-state systems and predicted to emerge in complicated cold-atom settings, but seeing them in a simple, natural game like quantum baseball was a surprise. Naturally, the Rey group has already spoken with the Ye group about doing an experiment to confirm this provocative finding.

The researchers responsible for uncovering the latest rules of quantum baseball include senior research associate Michael Wall, graduate student Bihui Zhu, former University of Colorado Boulder research associate Sergey V. Syzranov, University of Colorado Boulder associate professor of physics Victor Gurarie, and Fellow Ana Maria Rey. ✺

Sergey Syzranov, Michael L. Wall, Bihui Zhu, Victor Gurarie, and Ana Maria Rey, *Nature Communications* **7**, 13543 (2016).



In the new quantum baseball ballet, the balls (photons) and players (dipolar particles) execute an intricate dance in which they all rotate in the same direction. This intricate dance causes exotic massless quantum particles {called Weyl particles (shown in red)} to appear in the quantum baseball field. Credit: The Rey group and Steve Burrows, JILA

Going Viral: The Source of a Spin-Flip Epidemic

For a long time, there's been a mystery concerning how tiny interactions between individual atoms could lead to really big changes in a whole cloud of independent-minded particles.

The reason this behavior is mysterious is that the atoms interact weakly, and only when they are very close to each other. Yet, the atoms clear across the cloud seem to know when it's time to participate in some big-deal quantum behavior such as simultaneously all changing the direction of their spins.

Now graduate student Andrew Koller and his colleagues in the Rey group have solved the mystery! The atoms coordinate their behavior over long distances through energy space! No matter what energy state an atom is in, eventually it will slosh into another atom, sharing information about its spin state. If one atom passes close to another atom, it may rotate its spin a little and keep going. Then it passes the next atom, and rotates its spin a little and keeps going. Eventually the atoms can talk to all the other atoms in the cloud if the interactions between the atoms are weak.

However, if the interactions are strong, an atom running into another atom will not be able to keep going. Both atoms will bounce off each other like billiard balls. When this happens, interatomic communication spreads one collision at a time, rather than all at once over long distances.

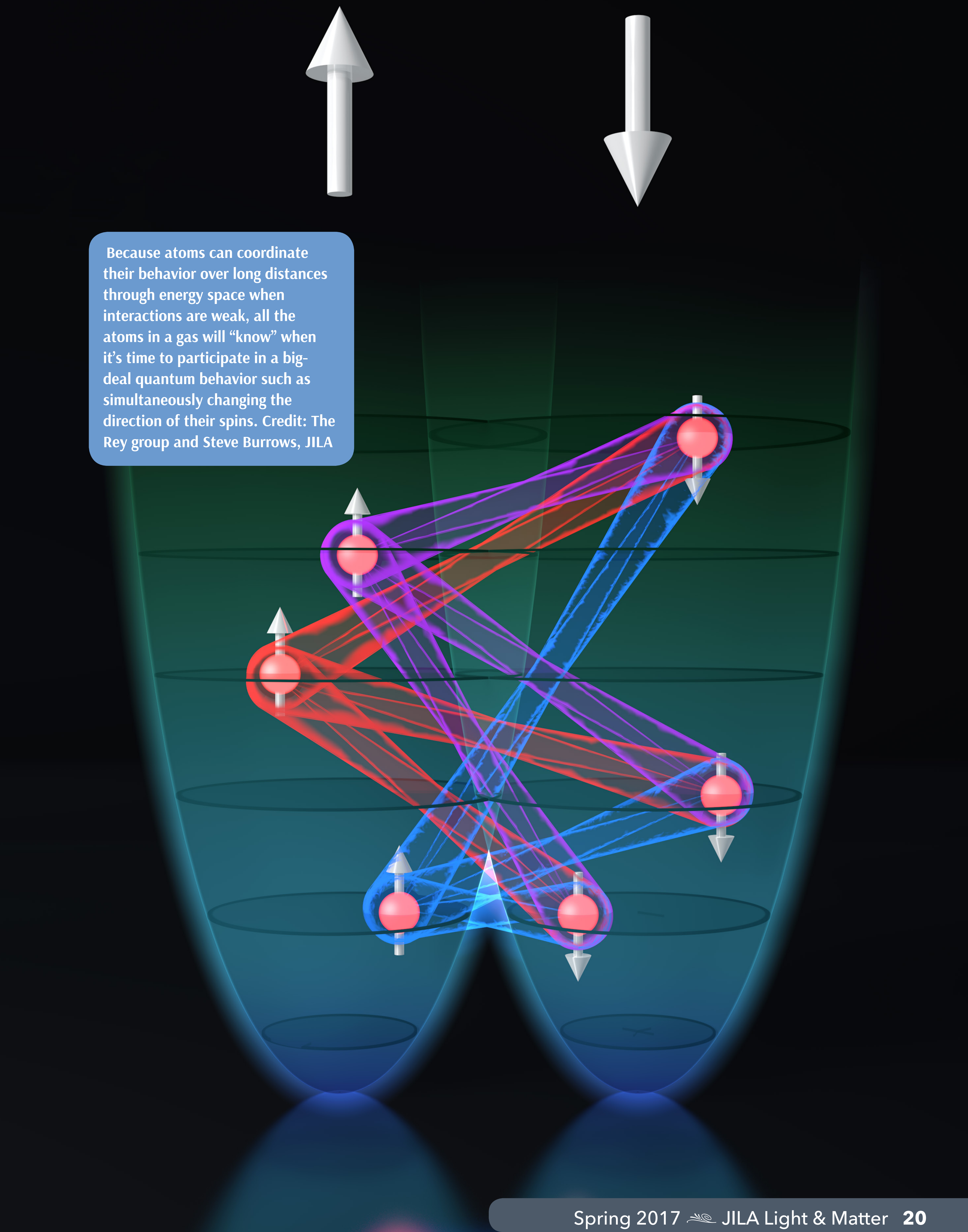
"Think about how you can spread information," explained Koller. "One way is word of mouth: each individual tells something to one other individual. The information spreads, but at a steady rate. And what's said might change a little each time. A second way to pass along information is to post something online and watch it go viral. People share it with their friends, who share it with their friends, and pretty soon everyone knows the same information."

Word of mouth communication is like strong interactions between atoms. In this case, the information propagates steadily from one atom to the next. In contrast, spin correlations in a weakly interacting cloud of atoms emerge from individual weak interactions that somehow go viral.

Atoms can communicate both ways, but, unlike people, they don't spread misinformation. Atoms can only tell other atoms whether to be spin up or spin down.

The researchers responsible for this idea about interatomic communication include Koller, former senior research associate Michael Wall, Fellow Ana Maria Rey, and Josh Mundinger of Swarthmore College. ✺

Andrew P. Koller, Michael L. Wall, Josh Mundinger, and Ana Maria Rey, *Physical Review Letters* **117**, 195302 (2016).



Because atoms can coordinate their behavior over long distances through energy space when interactions are weak, all the atoms in a gas will "know" when it's time to participate in a big-deal quantum behavior such as simultaneously changing the direction of their spins. Credit: The Rey group and Steve Burrows, JILA

IN THE NEWS

A selection of news, awards, and what is happening around JILA

CHRISTINA PORTER WINS 2017 KAREL URBANEK BEST STUDENT PAPER AWARD AT SPIE CONFERENCE

Christina Porter has won the 2017 Karel Urbanek Best Student Paper Award. The award consists of a wall plaque, honorarium, and trophy. The award was presented on Thursday March 2, 2017, at this year's Metrology, Inspection, and Process Control for Microlithography conference at the SPIE Advanced LIthography in San Jose, California. The award is sponsored by KLA-Tencor.

Porter's paper was entitled "Sub-wavelength transmission and reflection-mode tabletop imaging with 13-nm illumination via ptychography CDI." The paper was judged along with Porter's oral presentation to earn her the prestigious award. Porter was co-first author with Michael Tanksalvala on the winning paper. Additional authors included Dennis F. Gardner, Michael Gerrity, Giulia F. Mancini, Xiaoshi Zhang, Galen P. Miley, Elisabeth R. Shanblatt, Benjamin R. Galloway, Charles S. Bevis, Robert Karl, Jr., Daniel A. Adams, Henry C. Kapteyn, and Margaret M. Murnane.

The Karel Urbanek Best Student Paper award recognizes the most promising contribution to the field by a student. The award is based on the technical merit and persuasiveness of the paper presented at the conference.

MARGARET MURNANE AWARDED THE 2017 FREDERIC IVES MEDAL/QUINN PRIZE BY OSA

Margaret Murnane has been awarded the 2017 Optical Society of America's (OSA's) Frederic Ives Medal/Quinn Prize. The award recognizes overall distinction in optics and is the highest award given by OSA. The award was given to Murnane "for pioneering and sustained contributuions to ultrafast science ranging from femtosecond lasers to soft x-ray high-harmonic generation to attosecond studies of atoms, molecules, and surfaces."

Murnane is the first woman to receive this Medal in its nearly 90-year history.

As the 2017 medalist, Murnane has been asked to present a plenary address at OSA's Annual Meeting, to be held September 17–21 at the Washington Hilton in Washington, DC.

The Frederic Ives Medal was endowed in 1928 by Herbert E. Ives, a distinguished charter member and OSA president in 1924 and 1925. The award is named for his father, Frederic Ives, who invented modern photoengraving and made pioneering contributions to color photography, three-color process printing, and other branches of applied optics. The prize is now funded by the Jarus W. Quinn Ives Medal Endowment, which was raised by OSA members at the time of Quinn's retirement in recognition of his 25 years of service as OSA's first Executive Director.

RALPH JIMENEZ AWARDED DEPARTMENT OF COMMERCE BRONZE MEDAL

Ralph Jimenez received a Department of Commerce Bronze Medal for Superior Federal Service at a ceremony held in mid-December 2016. The Medal is the highest honor presented by the National Institute of Standards and Technology (NIST). Under Secretary of Commerce for Standards and Technology and NIST Director Willie E. May presided over the awards ceremony, which was held concurrently at NIST's Gaithersburg, Maryland, and Boulder, Colorado, campuses.

Jimenez received his Bronze Medal Award "for pioneering innovative tools for transforming the measurement, characterization and collection of biomolecules and cells for applications in industry, medicine, and research." He was recognized for leading a multidisciplinary program combining ultrafast lasers, custom microfluidics, biochemistry, and directed evolution to measure and use large biomolecules and living cells for a range of applications, including more efficiently making biofuels, revealing the details of how enzymes work within cells, as well as developing new molecular tools for nondestructively imaging and measuring chemical reactions within living cells. His accomplishments include:

- Inventing a new high-throughput cytometer that uses ultrafast lasers and microfluidics to nondestructively identify and collect individual living cells with unique and highly desirable properties,

- Pioneering methods to measure complex three-dimensional motions of large biomolecules, such as enzymes and proteins, in their natural cellular environments, and

- Developing and characterizing fluorescent proteins for use in measurements of chemical and physical reactions within living cells.

Jimenez' innovations and patented innovations are accelerating the ability of basic and applied researchers to study, understand, and apply their new understanding of the biochemistry of cells in both normal and diseased states.

DEBORAH JIN AND KATHARINE GEBBIE FEATURED IN SCIENTIFIC AMERICAN TRIBUTE

Deborah Jin and Katharine Gebbie are two of 10 prominent scientists featured in "Gone in 2016: Notable Women in Science and Technology" written by Maia Weinstock. The article appeared online in Scientific American blogs on December 28, 2016. Jin, who died on September 15, 2016 at age 47, was a visionary researcher in ultracold atomic physics. Gebbie, who died on August 17 at age 84, began her career as an astrophysicist at JILA, then rose through the ranks at the National Institute of Standards and Technology to become director of NIST's Physical Measurement Laboratory. The loss of both women in 2016 was a great blow to JILA scientists and staff alike.

MARKUS RASCHKE ELECTED FELLOW OF THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Markus Raschke has been elected a Fellow of the American Association for the Advancement of Science (AAAS), according to an AAAS news release published on the web on November 21, 2016. Former JILAn Steven Cundiff was also elected a Fellow of the AAAS this year.

The new Fellows are among the 391 AAAS members elected Fellows by their peers. The honor recognizes distinguished efforts to advance science, either scientifically or socially. The new 391 Fellows elected in October 2016 were recognized for their contributions to innovation, education, and scientific leadership.

They will be honored at a ceremony on Feb. 18, 2017, at the AAAS Annual Meeting in Boston, where they will be presented a rosette pin. The pin's gold and blue colors signify science and engineering, respectively.

The tradition of electing AAAS Fellows began in 1874 to recognize members for their scientifically or socially distinguished efforts to advance science or its applications.

HENRY KAPTEYN PROFILED IN PNAS

The Proceedings of the National Academy of Sciences has just published a profile of Fellow Henry Kapteyn, a recently elected member of the National Academy of Sciences. The profile presents highlights of Kapteyn's life as well as his long and productive career in developing ultrashort-wavelength lasers, including table-top x-ray lasers. Many of Kapteyn's achievements occurred during a long and fruitful collaboration with his wife, Fellow Margaret Murnane. The profile accompanies Kapteyn's Inaugural Article entitled "A new regime of nanoscale thermal transport: Collective diffusion increases dissipation efficiency."

The article describes how the Kapteyn/Murnane group uncovered a regime of nanoscale thermal transport in which nanoscale heat sources cool more quickly when placed close together than when they are widely separated. This work opens the door to new ways of managing heat in nanosystems and may affect the design of integrated circuits, thermoelectric devices, nanoparticle-mediated thermal therapies, and clean-energy technologies such as photovoltaics.

A COOL NEW IPAD APP FOR KIDS—INNOVATIVE APP OFFERS NEW PLATFORM FOR PHET INTERACTIVE SIMULATIONS

Science, Technology, Engineering, and Mathematics (STEM) education just got a big boost from a new iPad App developed by the PhET Interactive Simulations project at the University of Colorado. The 99¢ App is an extension of the award-winning collection of computer simulations of topics in science and mathematics produced by the project.

The project was founded in 2002 by former JILAn and Nobel Laureate Carl Wieman, who obtained funding for it from his own Nobel Prize, the NSF Directors award, and the Kavli foundation. The project has also received support from JILA's Physics Frontier Center. Wieman still serves as the PhET project's senior advisor.

"I was inspired to create PhET because of developing interactive simulations to explain my research on laser cooling and evaporative cooling to make a Bose Einstein Condensate," Wieman said. "I noticed in talks that when I using using the sims, everyone in the audience would be paying attention, and questions afterwards reflected something about what the simulations were showing. "What was particularly striking to me was that this was equally true with an audience of physics professors as with an audience of seventh graders." Wieman added than many audience members, including kids and their parents, would go home and play with the sims and email him.

Since its inception the PhET project has produced 134 simulations of topics in physics, chemistry, biology, earth science, and mathematics–all available to students with a computer for free online. More than 40 of these simulations have now been redone for use with the iPad App.

"The App serves several purposes," explained Ariel Paul, who is the project's Director of Development and runs day-to-day operations. "One is sustainability. As more people purchase the App, the money we earn helps fund reprogramming more simulations for the iPad. And, this means more simulations get included with the App."

A second advantage of the iPad App is off-line use.

With the iPad App, it is a seamless process for students, teachers, and parents to work together to learn STEM topics. A third advantage is that having an iPad App means more people browsing the App Store have the chance to discover just how much fun it is to learn science.

The new iPad App was designed and coded by five University of Colorado undergraduate students as part of the computer science Capstone Senior Project. The project's goal was to integrate computer-science majors into commercial projects, providing them with real-world experience.

Recent CU graduates Andrew Arnopoulos, Ellie Daw, Luis Olivas, Eric Rudat, and Sheefali Tewari spent two semesters applying their design and coding skills to enhance the long-range impact of the PhET project. Thanks to their efforts and some tweaking by a third-party contractor, the new iPad App is opening new and exciting opportunities for the use of PhET by students, teachers, and parents.

PhET Director Kathy Perkins, Associate Professor of Physics

Ariel Paul, PhET's Director of Development

"We wanted to connect more directly with parents seeking educational tools, and provide kids with an easy way to access PhET simulations at home, on a road trip, or anywhere," said PhET Director Kathy Perkins, Associate Professor of Physics and the mother of eight-year-old twins. Perkins said that because the App is educational and only costs 99 cents, she wouldn't think twice about buying it.

"Even students as young as 4–5 years old get something out of playing with the App because they can start to begin to explore on their own," added Paul. "We're finding that even with Sims designed for older children, there are a lot students who can get a lot out of them at a younger age. Plus parents today want to make sure if their children are on an iPad and using an App that it has educational value."

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 and Biochemistry; and Molecular, Cellular, and Developmental Biology as well as in the School of Engineering. NIST's Quantum Physics Division members hold adjoint faculty appointments at CU in the same departments.

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 seven broad categories: Astrophysics, Atomic & Molecular physics, Biophysics, Chemical physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information.

To learn more visit:
jila.colorado.edu