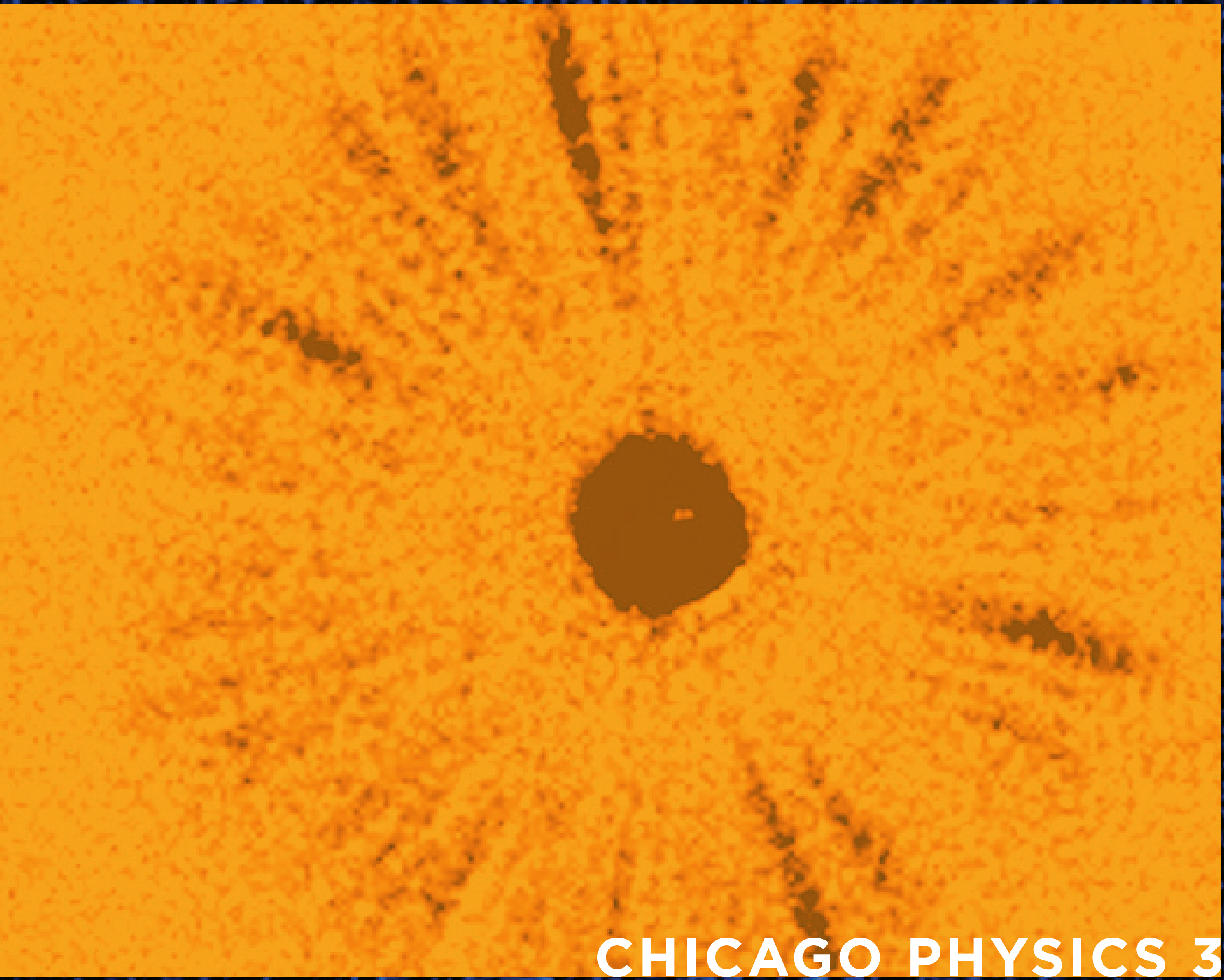
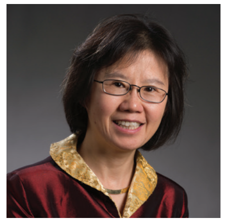
THE UNIVERSITY OF CHICAGO | Department of Physics



CHICAGO PHYSICS 3

Quantum Worlds

Welcome to the third issue of Chicago Physics! This past year has been an eventful one for our Department and we hope that you will join in our excitement.



In our last issue, we highlighted our Department's research on topological physics, covering the breadth of what we do in this research area from the nano to the cosmic scale and the unity in the concepts that drive us all. In the current issue, we will take you on a journey to the quantum world.

The year had several notable events. The physics faculty had a first-ever two-day retreat in New Buffalo, MI. We discussed various challenges in our department in a leisurely, low-pressure atmosphere that allowed us to make progress on these challenges. This retreat also helped us to bond!! We were pleased that many family members joined lunch and dinner. This was immediately followed by a two-day retreat of our women and gender minority students.

We were thrilled that John Goodenough, an alumnus of our Physics Department (SM'50, Phd'52), jointly with M. Stanley Whittingham and Akira Yoshino, was awarded the 2019 Nobel Prize in Chemistry "for the development of lithium-ion batteries".

The Heising-Simons Foundation has granted us $300,000 for an endowment to support the annual Maria Goeppert-Mayer Lecture Series at the University of Chicago. The lectures are given by outstanding women physicists in honor of Maria Goeppert-Mayer, who won the 1963 Nobel Prize in physics for developing the nuclear shell model while at UChicago and Argonne National Laboratory. We celebrated this news with Donna Strickland from University of Waterloo, the third Maria Goeppert-Mayer Lecturer and the third female Physics Nobel Prize winner.

The University has renamed the Physics Research Center that opened in 2018 as the Michelson Center for Physics in honor of former faculty member Albert A. Michelson, a pioneering scientist who was the first American to win a Nobel Prize in the sciences, and the first Physics Department chair at the University of Chicago. The pioneering work of Michelson is fundamental to the field of physics and continues to support new discoveries more than a century later.

This year we also welcomed back our own David Saltzberg (Ph.D., 1994) as the annual Zachariasen lecturer who told of his experiences as the scientific advisor for the wildly popular television show, The Big Bang Theory.

We celebrate new members of the Department in this issue. We also celebrate here the lives of Riccardo Levi-Setti, Clemens Roothaan, and Courtenay Wright who died during the past year and who left their indelible imprint on our Department and on physics globally. We miss them, and we are proud of them.

We hope that the stories we share will inspire you to become more involved and engaged in the Department. Please keep in touch and let us know what you think.

Yours sincerely,

YOUNG-KEE KIM

Louis Block Distinguished Service Professor
Chair, the Department of Physics

COVER PHOTO: CHENG CHIN,
Professor
Department of Physics, the University of Chicago

Dean's Letter

When I started as Dean of the Physical Sciences Division in July, NASA was preparing to launch the Parker Solar Probe, a spacecraft designed to make critical observations of the Sun. The probe is the first NASA spacecraft to be named after a living person, my colleague and professor emeritus at the University of Chicago, Eugene Parker. Parker developed the theory of the solar wind in 1955 and helped define the field of heliophysics. The timing of this NASA mission seemed especially significant as I took the helm of a Division with a rich history of shaping and defining fields. There are numerous University of Chicago physicists who have paved the way for researchers across the globe, including Albert A. Michelson, who started the Department of Physics, Robert Millikan, Arthur H. Compton, Maria Goeppert-Mayer, S. Chandrasekhar, Enrico Fermi, Chen Ning Yang, Tsung-Dao Lee, and so many more. As Dean of the PSD, I have the unique opportunity to support the next generation of field-defining scientists who are following in these esteemed footsteps. Last year alone, researchers in the Department of Physics made numerous exciting break-throughs, including recreating cell division outside of a cell for the first time, catching the rare decay of xenon-124, using gravitational waves to provide a measure of the universe's expansion, and discovering new forms of quantum behavior. This fruitful intellectual environment would not be possible without attention to equity, diversity, and inclusion. This fall, the PSD hired a Director of EDI to build on the foundation established by our departments, institutes, and centers. The Department of Physics has been a model for its programming and support of women and underrepresented minorities, and we look forward to a continued partnership that ensures all our constituents feel supported and valued. I'm excited and proud to serve such a preeminent department at UChicago and anticipate a future filled with innovation and discovery.

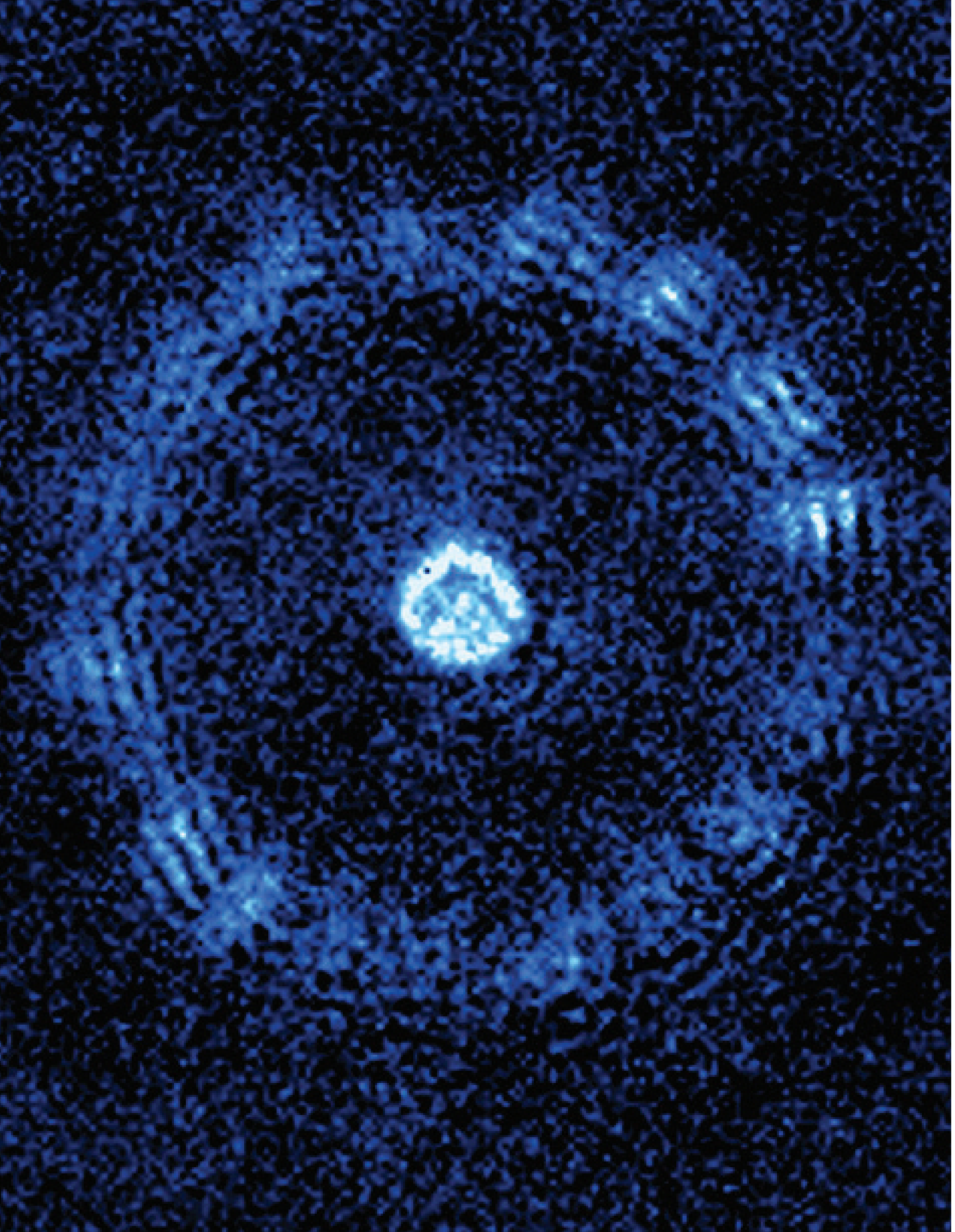
ANGELA OLINTO

Dean,
Division of the Physical Sciences

Editor's Note

I am teaching the introductory course in quantum physics this quarter – which we obstinately title "Modern Physics," despite that it is firmly anchored in a revolution that began at the end of the 19th Century. The students' skepticism reminds me just how weird quantum mechanics is, despite that it is one of the most rigorously tested theories we have. The revolution continues into what I suppose one might dub "post-modern physics", as we now understand that quantum theory pervades the universe, from the very small and cold, to the very large and hot. In this volume we get a perspective from three Chicago physics groups on their own work. Cheng Chin explains how one can use atoms at nano-Kelvin temperatures to build a remarkable laboratory to study quantum phenomena, and even to simulate cosmology. Kathy Levin explains how one can coax a superconducting device to make pairs of Majorana fermions, particles that are their own antiparticles. And completing the circle, Savdeep Sethi offers us a tour of how the newly discovered "dark energy" may provide some guidance as to how our universe might be selected from the ridiculously large number of possible universes that conventional string theory allows.

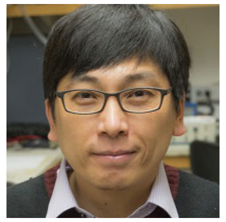
PETER LITTLEWOOD



Contents

Exploring Novel Quantum Phenomena of Atoms and Molecules at Ultralow Temperatures

CHENG CHIN



The availability of atoms cooled to nano-Kelvin temperatures initiates an exploration into a new world where the dynamics of particles are fully governed by quantum mechanics. Quantization of motion, matter-wave interference and entanglement, among other bizarre behaviors that defy our intuition are now right in front of our eyes. In our laboratory, we develop new tools to control the interactions of atoms, and to analyze their evolution. Novel quantum dynamics were observed that offer insight into other phenomena in nuclear physics, condensed matter physics, and even cosmology. I will outline some of the intriguing findings from our labs, as well as ongoing endeavors searching for new beasts in this new quantum wonderland.

Our first step into the quantum world is to cool atoms toward absolute zero temperature. This is achieved in our lab by laser cooling and evaporative cooling. One benchmark is around 0.1 micro-Kelvin, where the thermal motion of atoms undergoes an abrupt change, or a phase transition, into quantum degeneracy. Such a transition, signified by the condensation of bosonic atoms in the ground state, also called Bose-Einstein condensation (BEC, 2001 Nobel Prize). For cold fermions, they form a degenerate Fermi gas (DFG), resembling electrons in a solid. In our labs, we investigate BECs of cesium-133 atoms, and DFGs of Li-6 atoms, as well as mixtures of the two atomic species. The typical number of atoms in a sample is between 1,000 and 100,000, and they are spatially trapped by powerful laser beams.

How do we measure such low temperatures? A standard approach is to release the atoms into free space by abruptly turning off the lasers that confine the atoms. The lower the temperature, the slower the atoms expand in free space, and we can infer the temperature from the measurement of the expansion rate. At the lowest temperature of few nano-Kelvins, Cs atoms move with an average speed of 1mm per second, similar to a snail! An alternative method we developed is to image the atoms directly without the expansion. Temperatures can be extracted from the thermal fluctuations and correlations of the atoms.

It turns out that lasers can do much more than just cooling atoms. First, lasers can exert a conservative force on the atoms, also called an optical dipole force. Depending on the wavelength of the laser, we see that the optical dipole force can either attract or repel atoms. The stronger the laser intensity the larger the dipole force is. An important application of such an optical force is the optical tweezer (awarded Nobel prize in 2018), where tightly focused laser beams can attract and capture small objects toward the foci of the laser beams. Another application is to overlap multiple laser beams on the atoms; the interference of the lasers forms a periodic potential on the atoms, called an optical lattice. In an optical lattice, the atomic motion is quantized and can simulate electrons in a crystal material.

At UChicago, we developed a new scheme to generate arbitrary optical potentials based on Digital Micromirror Device (DMD). A DMD is equipped with millions of movable micro-mirrors, and is widely used in overhead projectors to generate images and videos on the screen. In our lab, we project the light on the atoms instead. Creating a quantum system in such a programmable potential opens up enormous applications and interests, leading to one of the most active research areas toward quantum control of atoms.

Another intriguing control on the cold atoms is over their interactions. To do so, an external magnetic or optical field is applied to induce a resonant coupling between atoms and molecules. Such a coupling is called the Fano-Feshbach resonance, near which, interactions between two atoms can be continuously tuned to be repulsive, attractive or exactly zero. Tuning the fundamental interactions in a quantum system is a unique and wonderful feature of the cold atoms. Think about what one can do if the interactions between electrons in a material can be changed at will!

What do we learn from tuning the interactions between atoms? Plenty, and one example is how does a quantum system evolve from the weak- to strong-coupling regimes (See Figure 1). Furthermore, one can tune the interactions to simulate another quantum system. As an example, Cooper pairing of electrons in superconductors can be simulated based on ultracold fermionic atoms with attractive interactions. Many of our experiments make creative use of Feshbach resonances to discover and explore novel quantum phenomena, as we will elaborate below.

Last but not least, the control of kinetic energy beyond the conventional dispersion $E=p^2/2m$ has become a very hot topic in quantum gas research. Modifying the kinetic energy term of a particle might sound weird, but such non-standard kinetic energy actually underlies the physics of charged particles in an electromagnetic field, or more generally, baryons in a dynamic gauge field. In our lab, we specialize on the control of dispersion based on resonant modulation of optical lattice potential and magnetic modulation of atomic interactions. Full control of the dispersion in a many-body system leads to a wealth of non-classical behaviors, of high interest to the condensed matter physics and high-energy physics communities.

In summary, we have prepared a many-body quantum system with optical or magnetic control of its entire Hamiltonian, including the potential energy, interaction energy and kinetic energy. These controls are all based on some form of resonant couplings induced by external fields. The result is a new generic platform of a quantum system with broadly programmable properties to explore quantum physics in different regimes. The platform is ideal to test theoretical conjectures that require careful tuning of the parameters. In the following, I will outline a few stories and future directions in which our group is involved based on such quantum simulation platforms.

One of the most fundamental questions we ask ourselves is the origin of the complexity in our world. Looking back to the earliest moment in our universe with telescopes, we see in the cosmic microwave background (CMB) radiation that the universe at the time

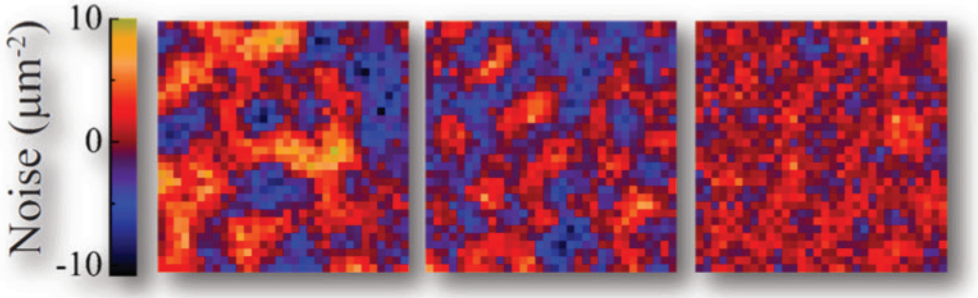


Figure 1

Density fluctuations and correlations in a Bose-Einstein condensate. By tuning the atomic interactions via a Feshbach resonance, atoms in a Bose-Einstein condensate acquires different forms of spatial correlation. The interactions is compared to the kinetic energy, which yields a dimensionless parameter g=0.05 (left, weak interactions), 0.26 (middle, medium interaction) and 1.3 (right, strong interaction). Each image is 30x30 micron^2.

was much more uniform with fluctuations around 0.01%. Today the fluctuations are much larger. Where did the fluctuations come from and how do they amplify? One cosmological model suggested by A. Sakharov in 1965 is based on the interference of acoustic waves that came about after the cosmological inflation.

When my former student Chen-Lung Hung (now a professor at Purdue University) and I looked at the images of cold atoms in our lab, an idea came upon us. Can we possibly produce the condition to generate Sakharov acoustic oscillations and watch how fluctuations amplify? After intensive discussion with experts on CMB and quantum physics, we realized that what we needed to do was quickly quench the atomic interactions using the Feshbach resonance and monitor the density fluctuations of the atoms in the subsequent dynamics. Indeed we observed the amplification and propagation of acoustic waves, which underlie the Sakharov oscillations. This was our first attempt to connect cold atoms to cosmological models.

Another interesting model to describe the emerging structure in the early universe was proposed by T. Kibble in 1984. Topological defects can form in the early universe when the system trespasses the critical regime of a phase transition, and the defects being the origin of complexity. In later years, the Kibble mechanism is also applied to phase transitions in condensed matter. In our lab, we precisely simulate the transition dynamics across a critical point by tuning the optical lattice potential at the speed that we can fully control. We observed the emergence of topological defects, confirmed the expected scaling laws proposed by Kibble, and showed that such dynamics is indeed universal.

Our last example is the famous inflation model. The model suggests that the structure in CMB originates from quantum fluctuations, which are exponentially amplified during the inflation epoch. To understand the nature of such amplification process, we presented an experiment based on atomic condensates in time-dependent optical lattices. When the lattice modulation exceeds a threshold, the atomic dispersion simulates the inflation energy landscape and parametrically amplifies the quantum fluctuations. We indeed observe a sudden and exponential increase of quasiparticles, which we called inflatons. An in-depth analysis of the dynamics in both real and momentum space confirms the quantum nature of the structure and it evolution in our system.

Experiments frequently come across unexpected observations, which is one of the most intriguing aspects of research. One such observation occurred recently in our lab. In 2017, my former students Logan Clark and Lei Feng and postdoc Dr. Anita Gaj observed a shocking pattern of jets of atoms shooting out of the condensate in random directions. This phenomena was later called "Bose Fireworks" because of its visual resemblance, see Figure 2. The jets were never seen or predicted in the past.

In the experiment, they applied a periodically modulated magnetic field to the condensate and, above a critical value of the modulation strength, the jets emerged all of sudden. The origin of the queer pattern of Bose fireworks puzzled the entire group for many months. What do we understand the firework patterns? It turned out the best way to understand was to perform more experiments. First of all, from the strength of the emission, we showed quantitatively that the pattern originates from quantum fluctuations. Secondly, we found that the jets are formed in pairs, propagating in opposite directions in the beginning, and, as time evolves, the jets develop more intricate structures. Details of such dynamics are still be studied in collaboration with my colleague Professor Kathryn Levin and her postdoc Dr. Han Fu.

As we continue working on the Bose fireworks, its connections with other physical processes surface. The pair formation of jets in our experiment resembles that in particle physics, where "di-jets" of pions moving in opposite direction emerge in many heavy-ion and proton scattering processes. Such a connection was pointed by Dr. M. Arratia, a particle physicist working at UC Berkeley.

Furthermore, analyzing many fireworks emission images, we found that the emitted atoms follow a thermal distribution. Interestingly, such a distribution can be understood in terms of the Unruh effect discussed in the context of quantum gravity. Below I introduce the Unruh effect and our idea to simulate quantum physics in curved spacetimes. I assume readers are similar with basic relativity and quantum mechanics.

William Unruh conjectured in 1976 that vacuum in the Minkowskii space (where speed of light is constant) may appear to be a vibrant source of thermal particles if the observer is no longer in the inertial frame. The temperature of the particles measured by an observer, called the Unruh temperature, is proportional to the acceleration of the observer. The Unruh radiation shares the same root as the Hawking radiation that, near a blackhole, a thermal source of particles are spontaneously formed in vacuum. The two systems are equivalent within a local patch of spacetime by Einstein's equivalence principle.

Our fireworks experiment simulates the Unruh radiation in the following way. The modulated magnetic field we apply to the condensate evolves the sample in exactly the same way as boosting the sample to a non-inertial frame with high acceleration. Mathematically, this means the equivalence of the time evolution $U(\tau)=e^{-iH\tau/\hbar}$ of a quantum state ψ and the frame transformation R_A of the same state:

$$U(\tau)\psi=e^{-iH\tau/\hbar}\psi\equiv R_A\ \psi,$$

where H is the Hamiltonian associated with the field modulation, τ is the evolution time, and R_A is the operator that transforms the observer into a non-inertial frame with acceleration A. A larger value of H or τ effectively boosts the observer to a frame with larger acceleration.

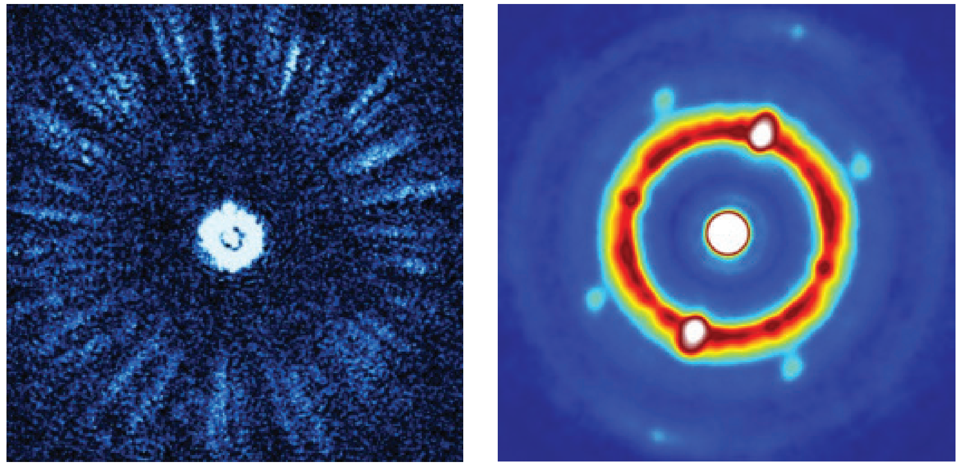


Figure 2

Bose fireworks and the hidden correlation pattern

(Left) Bose fireworks emission pattern. The central white circle is the Bose-Einstein condensate of cesium atoms and the needle-like jets are matterwave emissions from the condensate. The image is based on a single image.

(Right) Based on few hundred images, an intricate correlation between the jets in the momentum space is identified based on a pattern recognition algorithm.

In our experiment, a very high acceleration of 10^15 m/s^2 can be simulated with a moderate magnetic field modulation, and indeed an emission of thermal atoms at temperatures as low as 2 micro-Kelvin is recorded! The measurements are in excellent agreement with Unruh's prediction. Remarkably if one wishes to generate the same Unruh radiation by physically accelerating the sample. The required acceleration (10^15 m/s^2) is extremely challenging to realize.

Thus an unexpected observation in the lab, the Bose fireworks, turns out leads to new doors to quantum simulate jet formation in scattering of high energy particles, as well as Unruh radiation in gravitational physics. This is one of the most rewarding findings in experimental research, which is to discover new phenomena and to realize its relevance to other branches of physics.

Beyond the two highlights I mentioned, there are few other examples of quantum simulation in our works that link to other physics disciplines, e.g., Efimov physics in nuclear physics, and two-dimensional materials and quantum critical dynamics in condensed matter physics. Reaching out to experts in different fields is a key part of our research life, and we are frequently on a steep learning curve to identify potential meeting points between interesting phenomena in nature and our cold atom quantum simulator.

Here are selected few topics on our to-do list: (1) Mediated interactions. How do we understand mediated interactions in magnetic materials, superconductors or even color superfluids? Can we also simulate the celebrated Yukawa potential and Ruderman-Kittel-Kasuya-Yoshida mechanism? (2) Dynamic gauge field. Can quantum simulation shed light on lattice gauge field theories in particle and high-energy physics, which are frequently computationally intractable? (3) Pattern formation and recognition. How can one understand and control the patterns that spontaneously form in a uniform system? This is a fundamental question in hydrodynamics and morpho-genesis. Can we create, identify and control the patterns in an atomic quantum gas?

Acknowledgement

The most creative ideas, including the two research highlights we discussed here, come from the young members in our group, who joins us with fresh and fearless mind. I am in debt to their creativity that extends our research into new dimensions and their hardworks to bring the idea to fruition. We greatly appreciate theoretical collaborators, especially Kathryn Levin, Robert Wald, Fu Han and others on the projects we mentioned here. And finally UChicago and the funding agencies for their generous investment.

The Excitement Behind Topological Superconductors

KATHRYN LEVIN; FNU SETIAWAN & EREZ BERG

The concept of Majorana fermions is due to the Italian physicist Ettore Majorana, who, during his brief career also worked closely with Enrico Fermi. In 1937, he predicted that there exist particles which are their own antiparticles. These particles are now referred to as Majorana fermions. In the elementary-particle physics context, the proposition that neutrinos may be Majorana fermions remains to date unresolved experimentally. However, it was realized in recent years that Majorana fermions can also exist as zero-energy states bound to defects in condensed matter systems, i.e., at the edges or in the vortices of "topological" superconductors. These Majorana bound states are not only of fundamental interest but also hold a potential application for a fault-tolerant topological quantum computation.

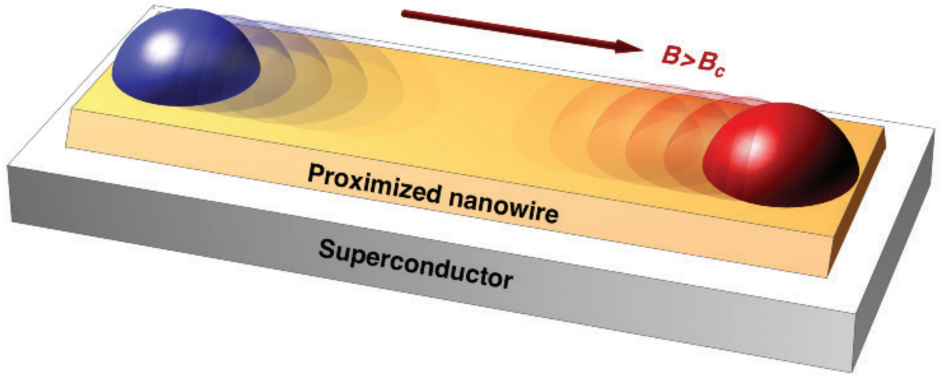


Figure 1

Majorana bound states (blue and right bumps) appear at the end of the nanowires when the magnetic field B is tuned above a critical value Bc. Picture taken from San-Jose et al., Scientific Reports 6, 21427 (2016).

A topological superconductor which possesses a p-wave pairing (with antisymmetric electron pairs, in contrast to symmetric (s-wave) pairing in a conventional superconductor) is rare in nature. However, it can be engineered by placing a conventional superconductor in proximity to a non-superconducting (appropriately chosen) material. Under ideal circumstances, superconductivity will "leak" out of the conventional superconductor and this can induce topological order in materials with sufficiently strong spin-orbit scattering via the so-called "proximity effect".

Of greatest interest are one-dimensional systems such as nanowires which, for practical reasons, often involve semiconductors. In this setup, the Majorana bound states appear at the ends of the nanowire where they are most accessible and can be most easily manipulated. This also requires the application of a sufficiently strong magnetic field ($B > B_C$) applied parallel to the nanowire B_C [see Fig. 1]. The first experimental evidence for Majorana bound states was observed in this nanowire setup and has since triggered a tremendous worldwide experimental effort to realize Majorana bound states in condensed matter systems.

In different collaborations, researchers at the University of Chicago have investigated an alternative to this nanowire architecture.

This new design involves a two-dimensional semiconductor proximitized by two spatially separated superconductors which form a Josephson junction [see Fig. 2]. This architecture has the advantage that the Majorana bound states can be made to appear in the channel between the superconductors; this happens at relatively small magnetic field strengths when the two host superconductors have opposite Josephson phase. Not only does it give added flexibility, but this change in design introduces a way to avoid some of the deleterious effects of applying strong magnetic fields, which are found, without fail, to undermine superconductivity.

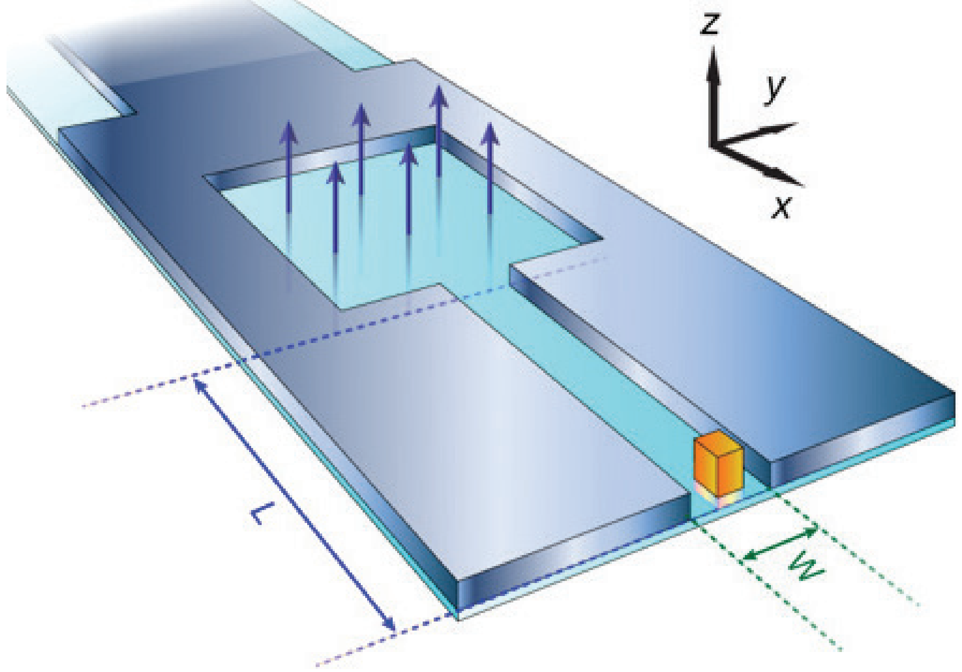


Figure 2

A topological Josephson junction made from a two-dimensional semiconductor (cyan) proximitized by two superconductors (steel blue) whose ends connect to form a flux (blue upward-pointing arrow) loop. Picture taken from Ren et al., Nature 569, 93 (2019).

> “These Majorana bound states are not only of fundamental interest but also hold a potential application for a fault-tolerant topological quantum computation.”

In collaboration with experimentalists we show that the recent experimental tunneling conductance data [see Fig. 3] measured in the proximitized Josephson junction are consistent with theoretical expectations, in particular, the presence of a Majorana bound state is signified by the appearance of a peak in the conductance at zero voltage bias which appears only when a magnetic field (of sufficient strength) is present.

An obvious set of questions emerges when thinking about this problem more deeply. The Majorana bound states appear in the channel between the two conventional superconductors in a medium that is missing the attractive interactions which are needed to give rise to superconductivity in the first place. How can these Majorana particles be stabilized through this remote proximitization effect? And can they be readily and controllably manipulated? To address this, we study the proximitization process in more detail. Our theoretical work (See Fig. 4) provides guidance for experimentalists to select materials with optimal properties to realize topological superconductors. Due to the ease of manufacturing, this recently realized topological superconductor holds exciting promise for a scalable topological quantum computing platform.

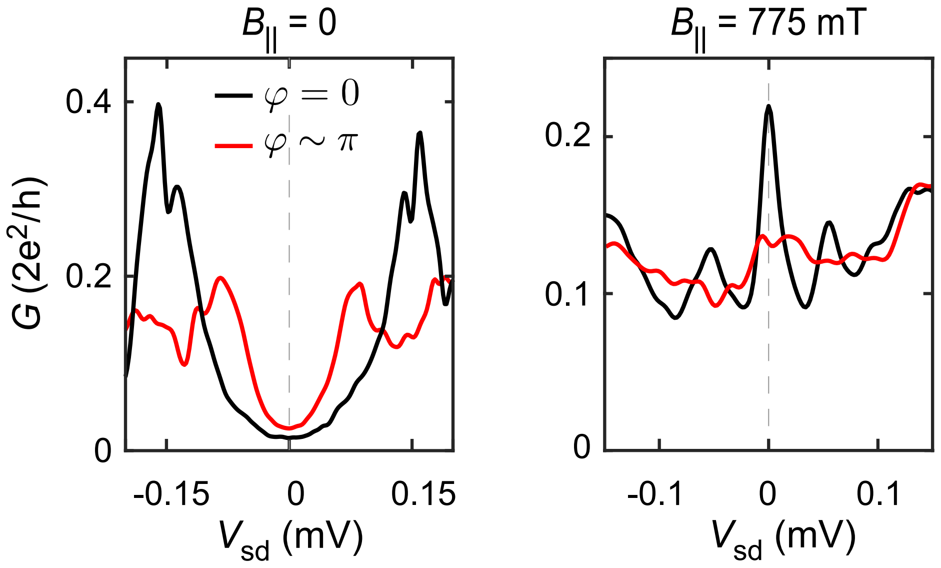


Figure 3

Differential conductance G as a function of voltage bias Vsd and magnetic flux for different magnetic field Bk parallel to the junction. Left and right panel show the conductance with and without a peak at zero voltage bias which corresponds respectively to the case without and with Majorana bound states. Picture taken from Fornieri et al., Nature 569, 89 (2019).

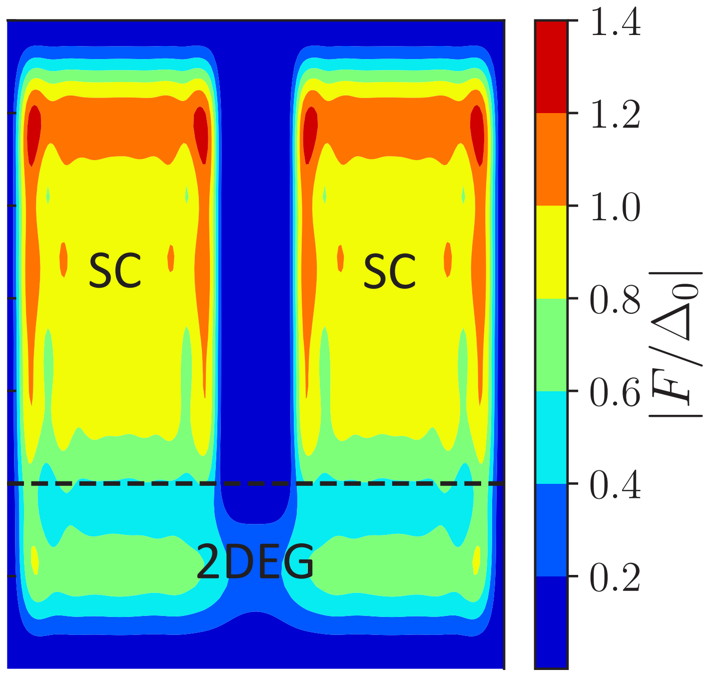
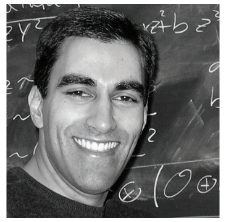


Figure 4

Pairing amplitude profile across the cross section of a proximitized Josephson junction. Picture taken from Setiawan et al., Phys. Rev. B 99, 174511 (2019).

The Mystery of Dark Energy

SAVDEEP SETHI



This is a story about dark energy and the quantum mechanics of gravity. It is an unfolding saga whose ending has yet to be revealed. The story begins in 1998 with the discovery that the universe is actually accelerating rather than decelerating. This observation is stunning because it implies that roughly 68% of the total energy density of our universe resides in something called dark energy. This mysterious dark energy produces a sufficiently repulsive force that it overwhelms the attractive pull of gravity, which would otherwise have led to a decelerating universe. By comparison, the particles that constitute us, which are studied at particle accelerators like the Large Hadron Collider at CERN, make up only approximately 5% of the energy density of the universe. Most of what comprises the energy density of our universe is a mystery!

For a theoretical physicist, this looks like a wonderful situation. What more could one desire than a mysterious universe awaiting explanation? The existence of dark energy, however, comes with a literally enormous problem. Observational data strongly suggests that dark energy is vacuum energy, or something with an equation of state very close to vacuum energy. It might sound strange to discuss the energy of the vacuum. We first learn in classical mechanics that the exact value of the potential energy is unobservable. Only gradients of the potential energy, which give rise to forces, are observable. Quantum mechanics adds a twist to this picture: even if the minimum of the potential energy is classically at zero energy, as shown in figure 1 for a simple harmonic oscillator, the actual vacuum energy is not vanishing because of quantum fluctuations. It is still, however, not directly measurable.

Only when we include gravity does the vacuum energy become physically important. All forms of energy gravitate, including vacuum energy. In this context, the value of the vacuum energy density is often called the cosmological constant. Now we arrive at the puzzle. Particles in nature come in two basic flavors: bosons and fermions. Each flavor contributes to the vacuum energy with opposite signs. The net vacuum energy can therefore be positive or negative. A back of the envelope estimate of the expected vacuum energy density, using well-understood and well-tested principles of quantum field theory, gives a number approximately 10^{120} times larger than the actual observed dark energy density. That's a ridiculously large discrepancy for any theory of quantum gravity to explain.

In string theory, which is our leading candidate for a theory of quantum gravity, there is a possible explanation for this enormous hierarchy. Non-perturbative string theory, which is usually called M-theory, lives in eleven space-time dimensions. To arrive at our four-dimensional universe, we need to curl up seven of those dimensions. Over the past two decades, we have come to understand that there are a huge number of possible ways of curling up, or compactifying, those extra dimensions. One recent rough estimate suggests more than $10^{272,000}$ such ways! We can think of string theory as possessing a very complicated potential, which I have depicted in figure 2, with an enormous number of metastable minima. For a sufficiently complex potential, fine-tuning 120 orders of magnitude or more is not so hard. This kind of picture for how dark energy might be explained in string theory was proposed by myself, Jonathan Feng, John March-Russell and Frank Wilczek, and separately by Raphael Bousso and Joe Polchinski, in 2000. It was later dubbed the "string landscape."

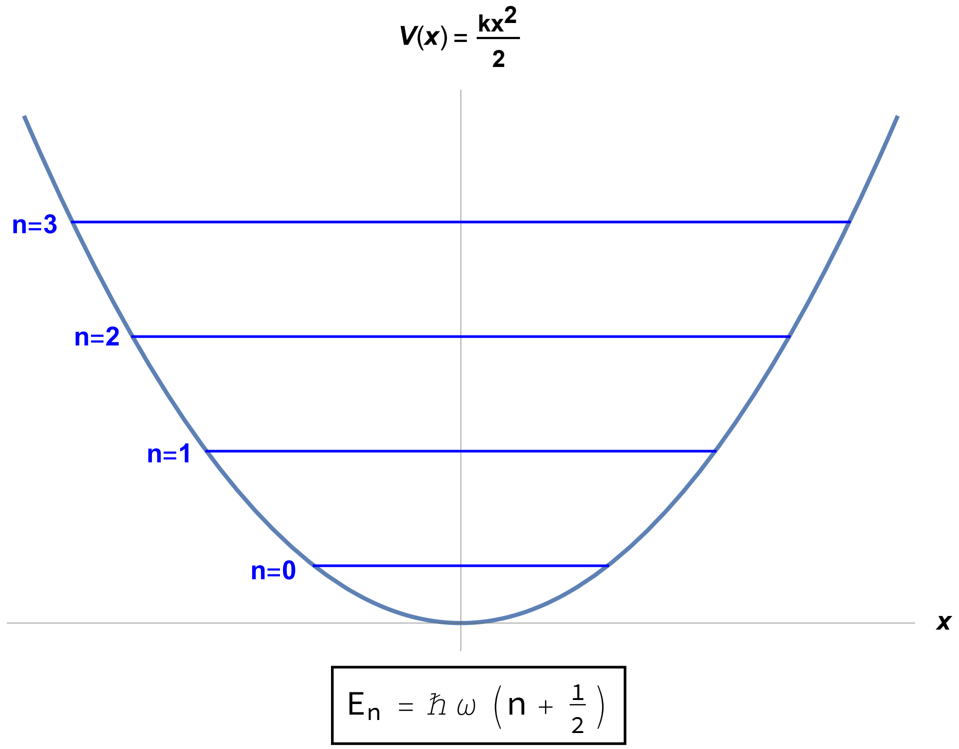


Figure 2
Energy levels for a simple harmonic oscillator.

Dedicated to my father Mohinder Singh Sethi (October 1, 1933 - August 17, 2019) for whom my work was always a mystery.

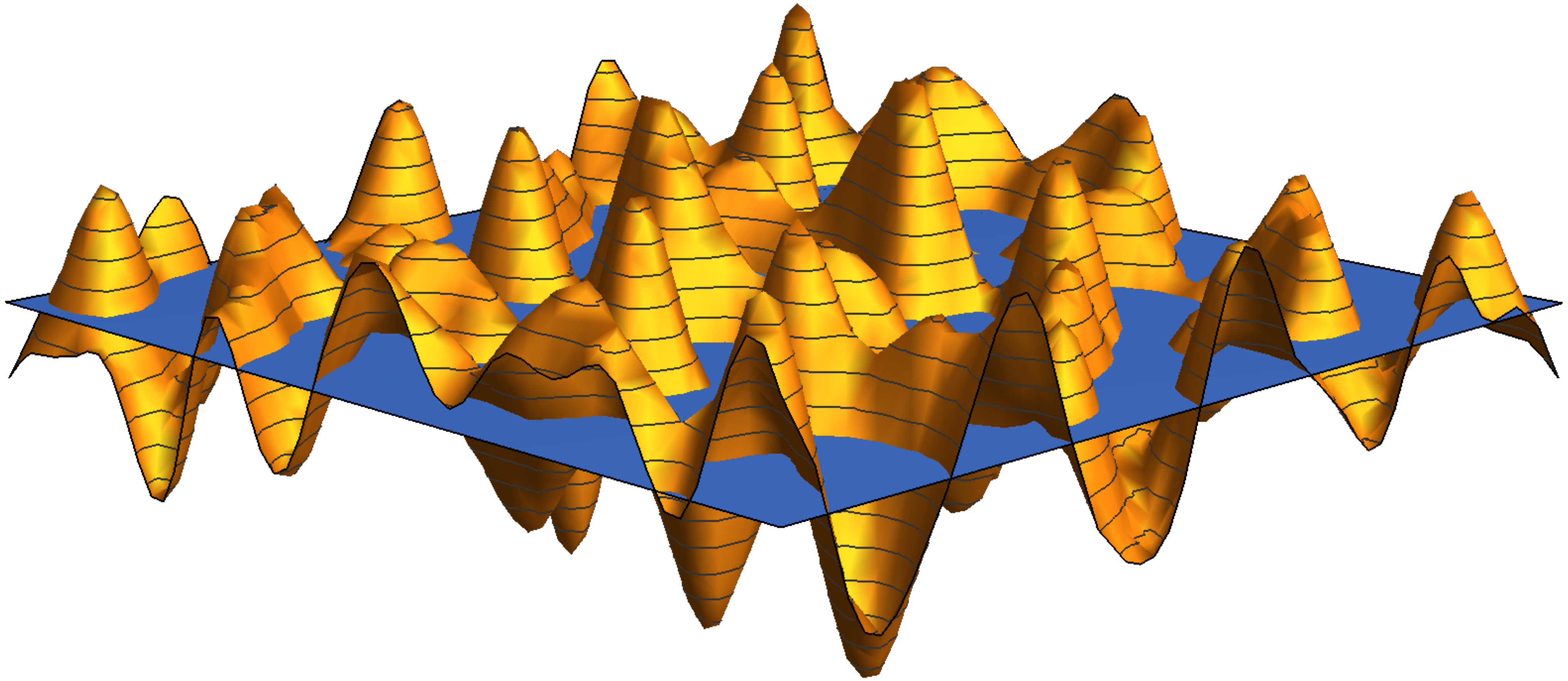


Figure 2

The string landscape involves a complicated potential, like the one depicted here, with many minima both above and below the zero energy surface designated by the blue plane.

There are two worries with this picture. The first is more philosophical: this kind of string landscape paradigm inevitably leads to anthropic reasoning as an explanation for some of the observed properties of the universe. Anthropic reasoning tends to blur the line between philosophy and physics, making it hard to determine which parameters of nature should be computable and which parameters of nature simply take values needed for us to exist. This leaves many physicists, including me, uneasy if not unhappy. The second problem is that the solutions that have been robustly constructed in string theory do not look like accelerating universes, but instead correspond to space-times with either negative or zero vacuum energy. There are numerous constructions that do claim to give accelerating universes, but they have quite serious issues, which I described in 2017.

This worry about whether positive vacuum energy universes can actually be realized in string theory has led to a fun and vibrant current debate in the string theory community. On the one hand are people who believe that the string landscape is the correct picture. On the other hand are people who believe that solutions of string theory with positive vacuum energy do not exist. Rather that such backgrounds belong to the “swampland” of models which are inherently inconsistent with quantum gravity. If this is the case then dark energy cannot be vacuum energy and must have a dynamical origin. If true, this is a striking prediction: while vacuum energy is constant and unchanging any alternative, like rolling on a very flat potential, must exhibit some degree of time-dependence.

We do not yet know with surety that the question of whether string theory admits solutions with positive vacuum energy can be solved. Any convincing construction will almost certainly require clever new theoretical insights. On the other hand, more precise cosmological observations will help pin down the equation of state of dark energy, which in turn will help us differentiate vacuum energy from alternative models of dark energy.

This set of questions has been a central theme of my research since the discovery of cosmic acceleration in 1998, and I look forward to a resolution of this debate: will the swampland or landscape paradigm prevail? Or will a new unexpected explanation for dark energy emerge? Stay tuned.

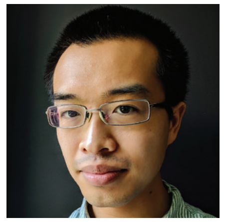
New Faces

The Department of Physics would like to welcome its newest faculty member, **CLAY CÓRDOVA**. Assistant Professor Córdova is a theoretical physicist working on foundational issues of quantum field theory and in string theory. He will also be a member of the Enrico Fermi Institute and the Kadanoff Center for Theoretical Physics.

ZOSIA KRUSBERG joined the Department of Physics as Senior Lecturer and Director of Graduate Studies in September 2019.

The Department of Physics welcomes the new Grainger Postdoctoral Fellows:

SEVERINE ATIS



JESSE LIU

DANIELLE NORCINI

The Department of Physics welcomes the 2019-2020 Graduate Students!

PAUL CHICHURA
DAINE DANIELSON
BRENNAN DIZDAR
KRISTIN DONA
TOKA TAREK EID
PETER FIELDS
CASEY FRANTZ
TANVI GANDHI
DAIKI GOTO
ALEXANDER (ALEC) HRYCIUK
RUNYU JIANG
TALI KHAIN
CARLY KLEINSTERN
SAMANTHA LAPP
ZIQIAN LI
ANDREW LINGENFELTER
WANQIANG LIU
ZHAONING LIU
JIANYU LONG
MORGAN LYNN
EDGAR MARRUFO VILLALPANDO
ANNA MOVSHEVA
SHU NAGATA
TONG OU
LUKAS PALM
SUGATA (JONTY) PAUL
JESSICA (LACEY) RAINBOLT
JOSEPH REDEKER
SERGEI SHMAKOV
GABRIEL ARTUR WEIDERPASS
ROBERT WEINBAUM
CHEYNE WEIS

Prizes & Awards

FACULTY AWARDS (SINCE 2018)

Congratulations to the Event Horizon Telescope (EHT) collaboration for being awarded the 2020 Breakthrough Prize in Fundamental Physics. The citation reads: "For the first image of a supermassive black hole, taken by means of an Earth-sized alliance of telescopes." The $3 million prize will be shared equally among the 347 co-authors.

Several UChicago researchers are involved in the EHT collaboration, and the 10 meter South Pole Telescope (SPT) is a critical component of the network of telescopes that make up the EHT. Chicagoland EHT collaboration members include **BRAD BENSON**, **JOHN CARLSTROM**, **TOM CRAWFORD**, **JASON HENNING**, **RYAN KEISLER**, **ERIK LEITCH**, **DANIEL MICHALIK**, **ANDREW NADOLSKI**, **STEVE PADIN**, and **SASHA RAHLIN**.
See breakthroughprize.org/News/54

Professor **YOUNG-KEE KIM** has been named the 2019 Scientist of the Year jointly by the Korean Scientists and Engineers Association (US) and the Korean Federation of Science and Technology Societies (Korea).

MICHAEL LEVIN, together with Xie Chen (Caltech), Lukasz Fidkowski (U of Washington), and Max Metlitski (MIT), will receive one of the 2020 New Horizons in Physics Breakthrough Prizes. They are cited for "incisive contributions to the understanding of topological states of matter and the relationships between them." More information is available at breakthroughprize.org/News/54

Congratulations to Professors **DAM T. SON** and **MICHAEL LEVIN** who have been awarded a Simons Foundation grant as part of the Foundation's program on ultra-quantum matter.

ABIGAIL VIEREGG is being honored with the Presidential Early Career Award for Scientists and Engineers (PECASE) and the UChicago Neubauer Faculty Development Fellowship for Innovative and Effective Teaching. The PECASE is the highest honor bestowed by the U.S. government on outstanding scientists and engineers who are beginning their independent research careers.

ROBERT WALD awarded First Prize in the 2019 Gravity Research Foundation competition this year for a paper written together with collaborators from Vienna (Alessio Belenchia, Flaminia Giacomini, Esteban Castro-Ruiz, Časlav Brukner, and Markus Aspelmeyer).

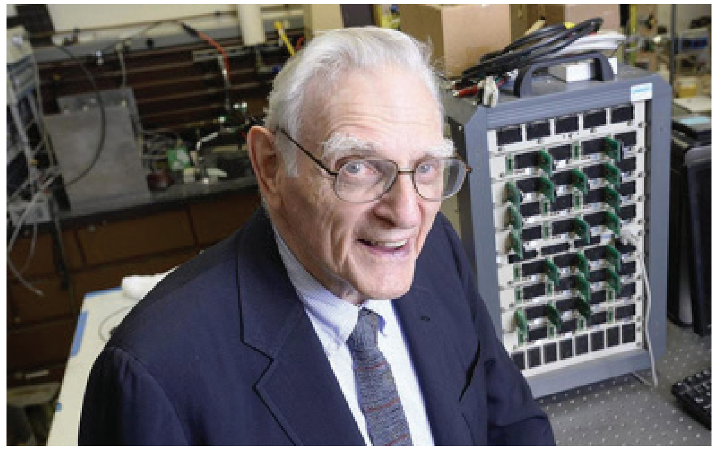
APPOINTMENTS & PROMOTIONS

LUCA GRANDI, **DAVID SCHMITZ** and **ABIGAIL VIEREGG** were recently promoted to Associate Professor.

WILLIAM IRVINE and **SHINSEI RYU** were recently promoted to full Professor.

Dam Thanh Son, University Professor at the University of Chicago, has been awarded the 2018 ICTP Dirac Medal for his contributions to revolutionizing human understanding of how quantum mechanics affects large groups of particles.

University of Chicago alumnus **John B. Goodenough** was awarded the 2019 Nobel Prize in Chemistry for his pioneering role in developing the lithium-ion batteries that now power our cell phones, laptop computers and electric cars.



2018 APS Medal for Exceptional Achievement in Research Awarded to **Eugene Parker**. The astrophysicist made fundamental contributions to solar and space plasma physics

Recent Happenings

The Women and Gender Minorities in Physics (WAGMIP) group at UChicago went on a first ever retreat at the Marina Grand Resort in New Buffalo, MI from May 4th to May 5th, 2019.

17 graduate students and postdocs from various subfields and years in the physics department gathered to discuss how to use our increased numbers to expand upon our activities and the events we hold.Overall, I found it most illuminating to hear others' perspectives on how we can make UChicago more welcoming to all. I personally believe this is a nontrivial feat, but we can begin by encouraging open communication between one another. As a result of this retreat, WAGMIP has created a list of concrete objectives that we hope will open conversations about our experiences in physics, both good and bad, so we can better understand one another and make UChicago physics a more welcoming place. We intend to implement objectives such as implicit bias workshops, improved diversity training, and discussion-based social events open to everyone in the coming quarters, so stay tuned and please send any feedback our way!

– Claire Baum

TOP: Women's Dinner for PSD faculty
BOTTOM: Women's Breakfast for Physics students

Nobel Lauriate Donna Strickland, University of Waterloo, gives the 2019 Maria Geoppert-Mayer Lecture: "Generating High-Intensity, Ultrashort Optical Pulses"

With the invention of lasers, the intensity of a light wave was increased by orders of magnitude over what had been achieved with a light bulb or sunlight. This much higher intensity led to new phenomena being observed, such as violet light coming out when red light went into the material. After Gérard Mourou and I developed chirped pulse amplification, also known as CPA, the intensity again increased by more than a factor of 1,000 and it once again made new types of interactions possible between light and matter. We developed a laser that could deliver short pulses of light that knocked the electrons off their atoms. This new understanding of laser-matter interactions, led to the development of new machining techniques that are used in laser eye surgery or micromachining of glass used in cell phones.

Special Colloquium to celebrate Cristina Marchetti, University of California, Santa Barbara, the first recipient of the American Physical Society's Leo Kadanoff Prize.

Leo Kadanoff was a Professor of Physics at the University of Chicago from 1978 until his death in 2015. He was one of the great formative thinkers in modern physics. The American Physics Society established the Kadanoff Prize to honor the memory and celebrate the remarkable legacy of Leo Kadanoff.

Karen Daniels, North Carolina State University gives the 2019 Inghram Lecture "Granular Materials: From Quotidian to Astronomical"

The purpose of the biennial Inghram Lecture is to present lucid experimental demonstrations of some of the laws and processes of nature and the theoretical interpretation of these results to a broad community. The level of presentation should be that of undergraduate students and/or advanced high school students. It should seek to interest, explain and excite individuals, as well as enhance the understanding of selected basic laws of physics."

2019 Equity, Diversity and Inclusion Colloquium presented by Ed Bertschinger, MIT: "Departments That Excel In Equity, Diversity, and Inclusion at Chicago and Across the Nation"

Women and people of color are severely underrepresented in many STEM departments, especially in physical sciences and engineering. Professional societies and universities have issued reports full of recommendations, but change is slow and difficult. This talk will identify departments that are most successful in diversifying bachelor's and doctoral degrees in STEM. Using data on student and faculty demographics, departmental practices where they are known, and interviews where they are available, I will present evidence as to how successful departments in physics, engineering, and other STEM departments at Chicago, MIT, and across the nation succeed in creating environments where all students can thrive.

2019 Zachariasen Lecture presented by David Saltzberg, UCLA: "How did Amy and Sheldon win their Nobel Prize?"

Since 2006, I worked with the writers and other crew of the television situation comedy, The Big Bang Theory which just aired its season finale. I will talk about my experiences putting my University of Chicago physics PhD to work helping the writers and others tell this story as their "science consultant." Along the way, I've learned that comedy is an empirical subject. I'll share a few of the other things I learned about working with creative and dedicated people in an industry seemingly far from my own.

Physics Faculty Retreat - May 2019, New Buffalo MI

On May 4 of this year, we traveled to New Buffalo, MI, on the eastern shore of Lake Michigan, in order to focus on two issues central to our Department, namely our undergraduate curriculum and its "delivery", e.g., our teaching. While the Teaching Activities and Curriculum Committees had already done much work identifying and discussing most of the issues we are facing, our chair, Young-Kee Kim, felt that a department-wide discussion, without the usual time constraints we face on campus, and taking place in a relaxed, informal setting, would facilitate reaching a consensus – and this is basically what occurred. (I also need to acknowledge our discussion leaders – Margaret Gardel, Daniel Holz, Vincenzo Vitelli and Bob Wald – who graciously agreed to my entreaties to help out!)

For two issues, we were able to reach a clear consensus fairly quickly, and thus are moving ahead to implementation. First, we agreed that the Physics Department should hire a Senior Lecturer with knowledge/experience in "active learning." This Senior Lecturer would teach courses in the 120s and 130s, and would be available to assist any faculty who want to incorporate active learning methods in their courses. There was also consensus that the search for such a Senior Lecturer should be national in scope. Second, we agreed to eliminating Physics 154, and to add an extra quarter to the QM sequence, as recommended by the Curriculum and the Teaching Activities Committee (TAC).

In four other areas, it was evident that further discussion would be required:

The Curriculum Committee had recommended that all physics majors be strongly encouraged to take the 140s, whereas the TAC had felt that there are physics majors for whom the 130s would be more appropriate and the two tracks should be kept for majors. There was a suggestion that the 130s and 140s be kept as they are for the first two quarters, but that all physics majors take 143, the idea being that merging the 2 tracks should occur as early as is feasible. This idea gained some support in the discussion but clearly needs further study. In addition, there was support for starting the QM sequence in the winter quarter of the second year (as opposed to starting it in the autumn quarter).

There were suggestions that TAs might be deployed differently (e.g., eliminating office hours in favor of group problem solving sessions), the motivation being both to reduce wasted time (since office hours tended to be poorly attended) and to gain efficiencies (we have some evidence that group problem solving sessions are welcomed by the students).

It was suggested that we should make a serious effort to determine the degree to which our "service" teaching of the 120s and 130s is meeting the needs of non-major students, such as pre-meds, biology majors, IME undergraduates, etc.

There was some support for reducing the number of compulsory courses – this needs further discussion, especially in the context of considering an alternative concentration that does not lead to graduate school in physics.

My sense was that the retreat was a success: The discussions were lively and productive, and I think to the surprise of many of us, far more enjoyable than the faculty meetings we've gotten used to in Hyde Park. Indeed, it was fun!

REU Summer Program BBQ

The University of Chicago Summer Research Experiences for Undergraduates (REU) Program in Physics, supported by the National Science Foundation offers undergraduate members of underrepresented minority groups (African-Americans, Hispanics, Native Americans and women) the opportunity to gain research experience working in the laboratory or research group of a Physics Department faculty member.

Students attend the 2019 Society for Advancement of Chicanos/Hispanics and Native Americans in Science Conference in Hawaii.

Students attend the 2019 Society for Advancement of Chicanos/Hispanics and Native Americans in ScienceConference in Hawaii. SACNAS is an inclusive organization dedicated to fostering the success of Chicanos/Hispanics and Native Americans, from college students to professionals, in attaining advanced degrees, careers, and positions of leadership in STEM.

Physics Department BBQ

Physics with a Bang!

Nathan Mueggenburg

Lisa Nash

Sophia C. Vojta

The 3rd Annual Physics Career Day was held on January 11, 2019.

Students learn about the exciting and rewarding career opportunities from our physics alumni with a variety of career paths. Speakers this year included Nathan Mueggenburg (PhD, 2004) Associate Professor, Lake Forest College; Lisa Nash (PhD, 2017) Data Scientist, IDEO; Sophia C. Vojta (BA, 2018) BA/BS Assistant Director of the UChicago Careers in STEM team.

Events

For full and future event listings, please visit:
physics.uchicago.edu/events/

UPCOMING

JANUARY 17, 2020
Physics Career Day

JANUARY 17-19, 2020
Conference for Undergraduate Women in Physics (CUWiP)

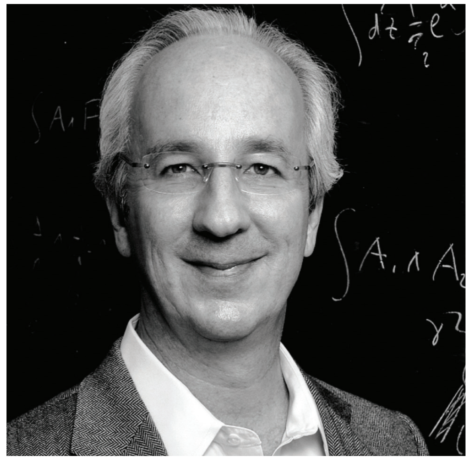
MARCH 13, 2020
Department of Physics Open House

MAY 1-3, 2020
Changes of State: a symposium in honor of Thomas F. Rosenbaum

MAY 15-17, 2020
Jeff Harvey's 65th birthday Celebration

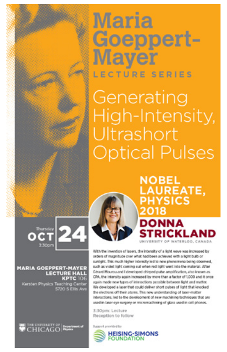
JUNE 12, 2020
Department of Physics Graduation Reception

Changes of State: a symposium in honor of Thomas F. Rosenbaum to be held May 1-3, 2020



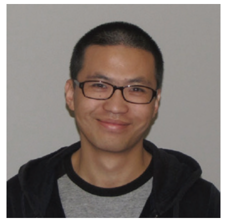
A celebration in honor of Jeff Harvey's 65th birthday, to be held May 15-17, 2020

Development



HEISING-SIMONS FOUNDATION TO SUPPORT LECTURES BY WOMEN IN PHYSICS

The Heising-Simons Foundation has granted $300,000 for an endowment to support the Maria Goeppert-Mayer Lecture Series at the University of Chicago. The annual lectures are given by outstanding women physicists in honor of Maria Goeppert-Mayer, who won the 1963 Nobel Prize in physics for developing the nuclear shell model while at UChicago and Argonne National Laboratory.



THE SIDNEY NAGEL PRIZE FOR CREATIVITY IN RESEARCH THAT WAS ESTABLISHED BY COLLEAGUES AND FRIENDS, IN HONOR OF PHYSICIST SIDNEY NAGEL

This prize is awarded annually by the Physics Department to a graduate student whose original research includes beguiling imagery and the 2019 prize was awarded to Lei Feng.

UCHICAGO NAMES BUILDING AFTER PIONEERING PHYSICIST ALBERT MICHELSON

The University of Chicago has named its Physics Research Center in honor of former faculty member and founding physics department chair Albert A. Michelson, a pioneering scientist who was the first American to win a Nobel Prize in the sciences for his field-defining work, including taking the first accurate measurement of the speed of light.

So many of the accomplishments associated with Physics at the University of Chicago have been made possible by the generous support of alumni, families, and friends through direct contributions and estate gifts. If you would like to support programs and places at the Department of Physics that are particularly meaningful to you, please visit our webpage: **physics.uchicago.edu/give**

In Fond Memory...

RICCARDO LEVI-SETTI

1927–2018

Professor Emeritus Riccardo Levi-Setti, a pioneering physicist and Holocaust survivor whose wide-ranging interests spanned cosmic rays to microscopy to trilobite fossils, died Nov. 8 in Chicago at age 91.

Referred to as a “Renaissance man” by his colleagues, Levi-Setti was active in exploring subatomic particles called strange quarks before pioneering new techniques in taking scientific images that revealed details about everything from superconductors to bones and kidneys.

“He was a brilliant and broad leader, making important contributions from particle physics to evolution,” said Angela Olinto, dean of the Division of the Physical Sciences at the University of Chicago. “What’s more, he was a wonderfully curious and open-minded person.”

[Source: https://news.uchicago.edu/story/riccardo-levi-setti-physicist-and-trilobite-collector-1927-2018]

CLEMENS C.J. ROOTHAAN

1918–2019

Clemens C.J. Roothaan was in a Nazi concentration camp when he made his first theoretical quantum calculations—work that later would be accepted as his master’s thesis in physics. After the war, he pursued his PhD at the University of Chicago, where he became a professor who created groundbreaking models of the electronic structure of molecules that are still used today.

Roothaan, the Louis Block Professor Emeritus of Physics and Chemistry, died June 17 at age 100.

“He was a pioneer in the development and application of rigorous theory to the electronic structure of atoms and molecules,” said Paul Bagus, PhD’66, a professor of chemistry at the University of North Texas and a former student of Roothaan’s. “He was a true giant in our discipline.”

[Source: https://news.uchicago.edu/story/clemens-cj-roothaan-eminent-quantum-chemist-and-concentration-camp-survivor-1918-2019]

COURTENAY WRIGHT

1923–2018

Professor Emeritus Courtenay Wright, a gifted teacher, World War II veteran and particle physicist who changed our understanding of the structure of protons and neutrons, died Nov. 22 in Chicago. He was 95.

During a career that spanned more than 50 years at the University of Chicago, Wright worked with scientists including Nobel laureate Enrico Fermi on particle accelerator research that provided some of the foundational measurements of the properties of quarks—the fundamental building blocks of matter.

“Wright made an incredible impact on the field of high-energy physics,” said Young-Kee Kim, the Louis Block Distinguished Service Professor and chair of the Department of Physics. “Modern experiments involving proton and neutron collisions rely on the knowledge of quark structure function that Wright and his contemporaries first established.”

[Source: https://news.uchicago.edu/story/courtenay-wright-particle-physicist-and-d-day-witness-1923-2018]

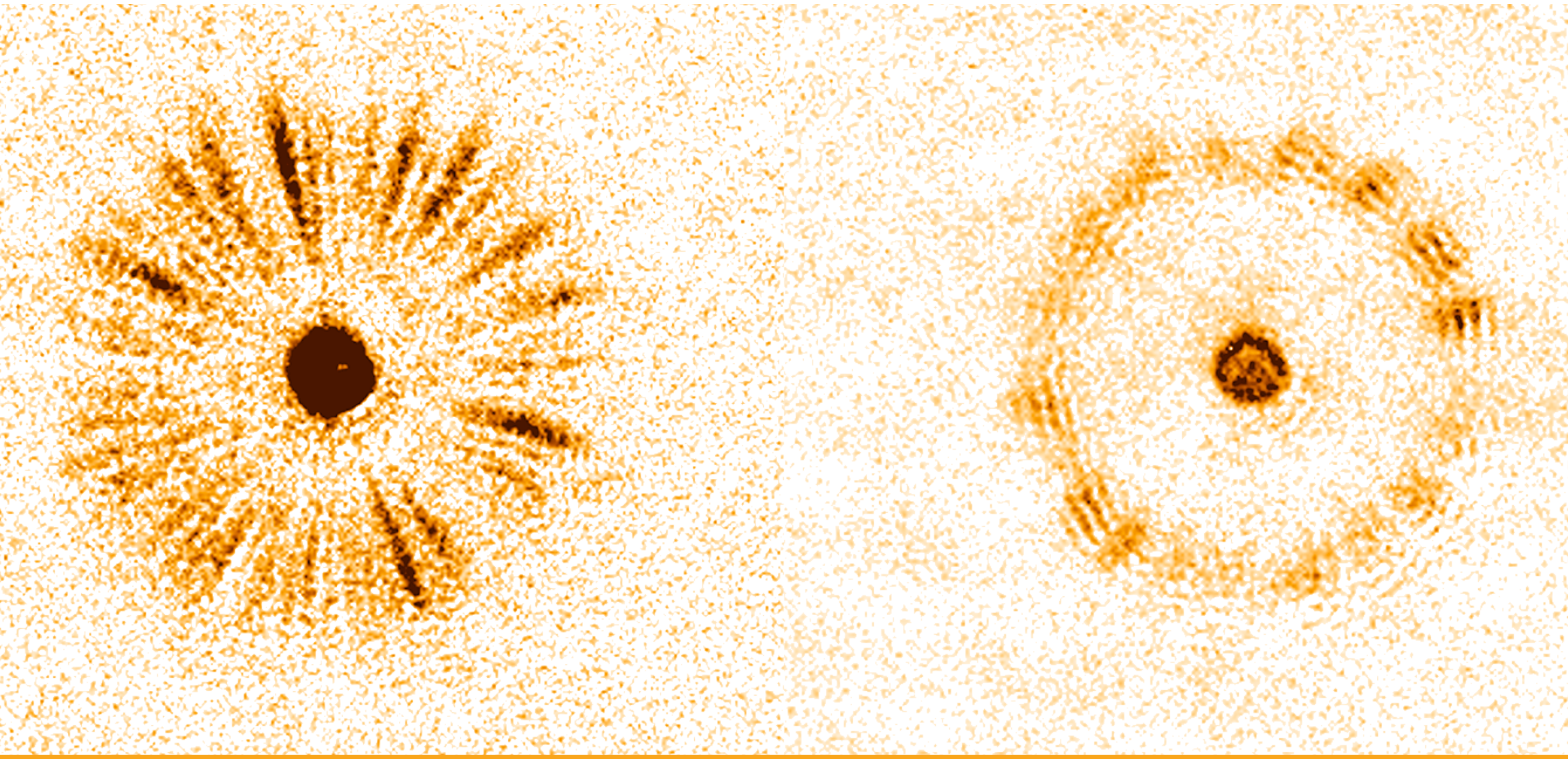
TOP: (left to right) Sidmey Nagel, Sara Paretsky, and Young-Kee Kim

BOTTOM (2) : Memorial reception for Courtenay Wright hosted by the Department of Physics

THE UNIVERSITY OF
CHICAGO

Department of Physics

Kersten Physics Teaching Center
5720 South Ellis Avenue
Chicago, Illinois 60637-1434



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