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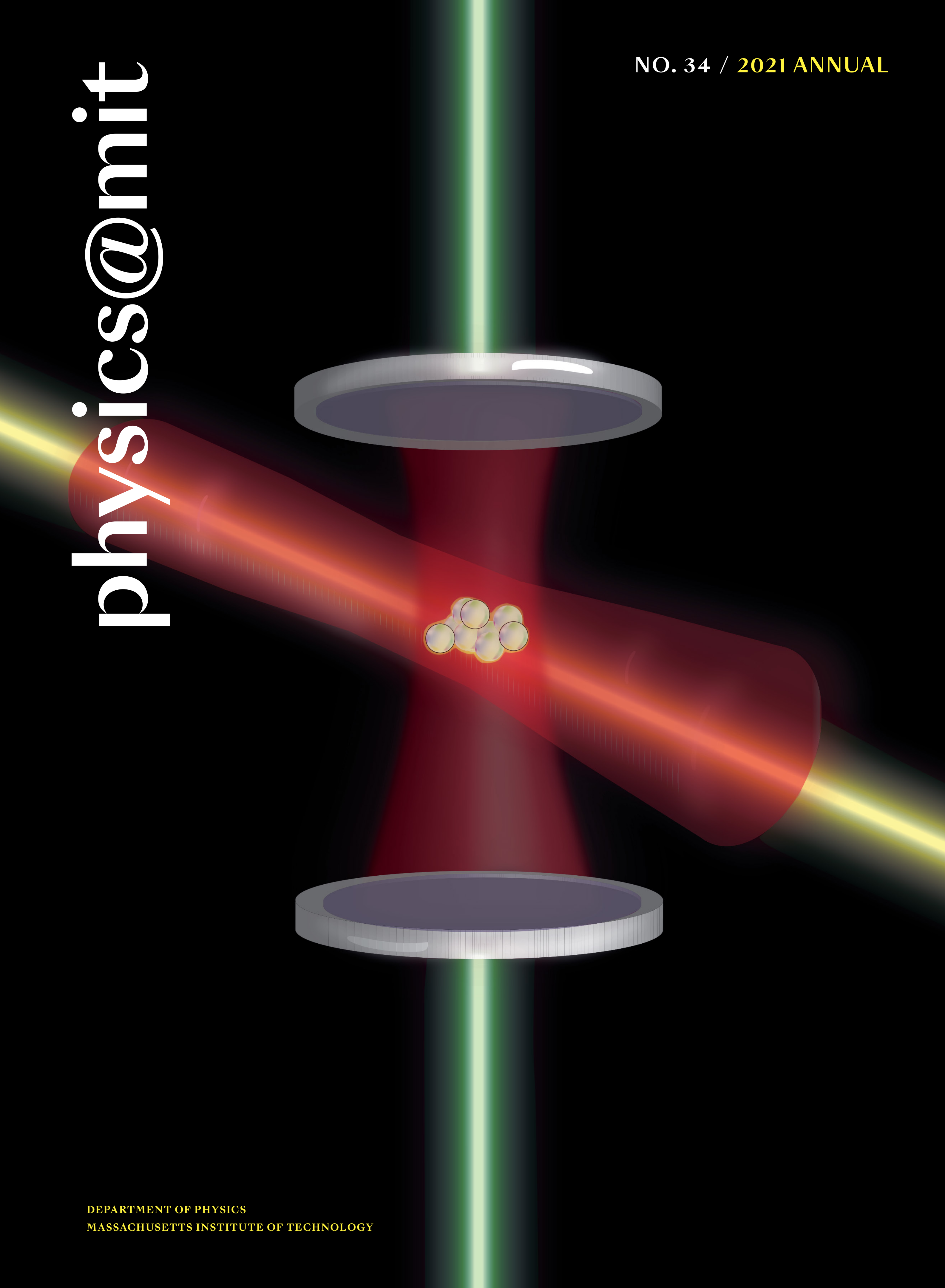
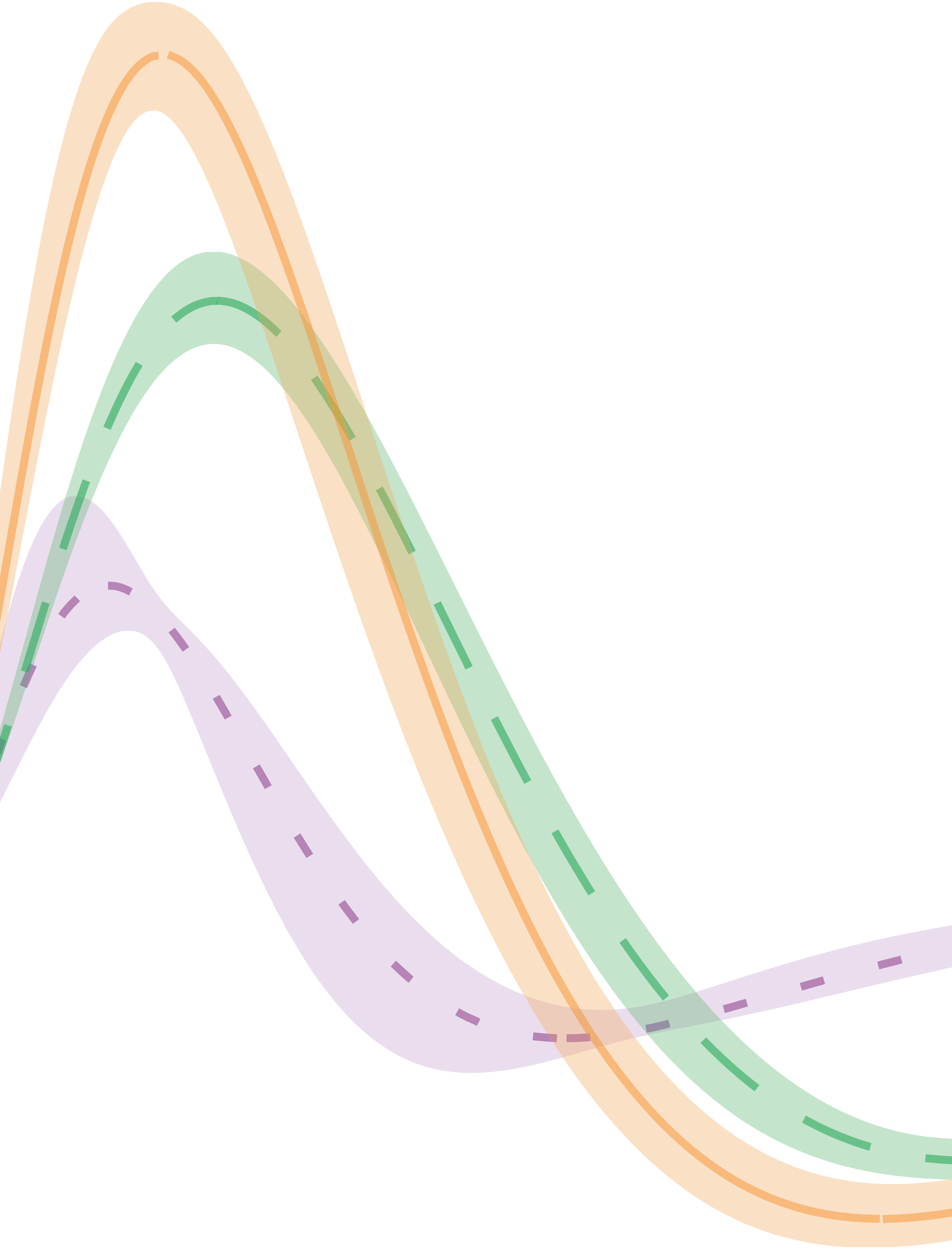


DEPARTMENT OF PHYSICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



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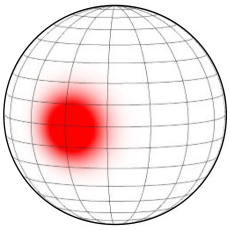
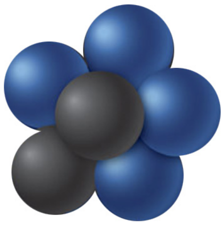




Cover designs adapted from figures in Prof. Vladan Vuletić's (front) and Prof. Phiala Shanahan's (inside cover) feature articles on pages 34 and 44, respectively.

Message from the Department Head

DEAR MEMBERS OF THE PHYSICS COMMUNITY,

This Spring, we celebrated the achievements of our seniors and doctoral students, and we are now well into the summer. Many of the Covid-19 restrictions around Cambridge have ended; we can now go around without masks, eat together indoors, and even go to ball games. We just celebrated Independence Day and families were able to gather for fireworks and cookouts for the first time in many months.

After 480 chaotic days, our part of the world seems to have begun recovering from the pandemic. I am writing today to acknowledge and celebrate our achievement in completing AY2021. The pandemic rages in many parts of the world, and I hope the U.S. can more widely distribute the vaccines quickly to help their recovery. The pandemic and series of horrible murders, some racially motivated, and other inequalities have revealed that many do not view others as human in this country.

There is much with which to reckon.

As summer passes, my invitation to you is to reckon. Reckon is an old word that means "...to give an account of, recount, tell or describe." The past 16 months have left us with an enormous psychic bolus of experiences and feelings that need reckoning–time and space for us to recount first to ourselves, then to each other, and finally, as a world, *what just happened*. Our humanity demands we reckon, and I hope fundamental changes come from our collective reckoning, which will occur over the following months and years.

Completing the academic year will form a big part of the reckoning for our students, faculty and staff. For some, the work over the past months may have seemed easy, while others found their work took almost all of their reserves. Their achievements are outstanding from where I sit; I myself feel I barely survived as a simple administrator. At the same time, many created new knowledge and all solved problems we had not conceived of before March 2020: delivered and attended lectures, went to office hours, and supported our students and faculty. Over Zoom. During the fear and uncertainty of a pandemic. Time will teach what a remarkable achievement this was.

My doctoral supervisor, Felix Boehm, passed away a few days ago at the age of 96. As a Swiss, Felix had a particular kindness and decency bred into him and, after my thesis defense, told me to take time off, at least a week. He was telling me to reckon. I protested that I had a paper to write, a conference to prepare for, a new experiment to start. He said, in a slightly peevish Swiss way, "Nooo, you cannot mistreat yourself so. You need some time."

In my own reckoning over the last 16 months, I have been struck, in retrospect, by how difficult everything at MIT has been. We did a lot of hard things because we had to and perhaps did not notice them at the time. While Zoom enabled us to continue to teach, learn and do research, Zoom did not replace daily human contact, which I came to crave and then be wary of as time passed. Now, as I spend more time at MIT, I'm finding I have to "relearn" being with others in a closed space.

Through the pandemic, our alumni and friends continued to support us; many worried about us and reached out to see how MIT Physics was doing. We had our annual Patrons Dinner via Zoom with high attendance. And their support has allowed us to admit 64 new graduate students for the fall—perhaps our most interesting incoming class ever.

Looking back, I am also struck by how well we did and at the same time how awful (really the right word: awe-inspiring in an unpleasant way) the last 16 months have been. I feel as if we all gave and gave and gave until we ran out at the end of May with the end of the term. Despite the awfulness, we endured and overcame together, and I feel great gratitude for that.

I'll close with that: take some time and reckon. My deepest thanks to all of you.

With best regards,

Peter Fisher

PETER FISHER
Thomas A. Frank (1977) Professor of Physics
Head, Department of Physics

Credit: Justin Knight Photography

New Faculty

July 2021

Soonwon Choi

Assistant Professor of Physics,
The Center for Theoretical Physics

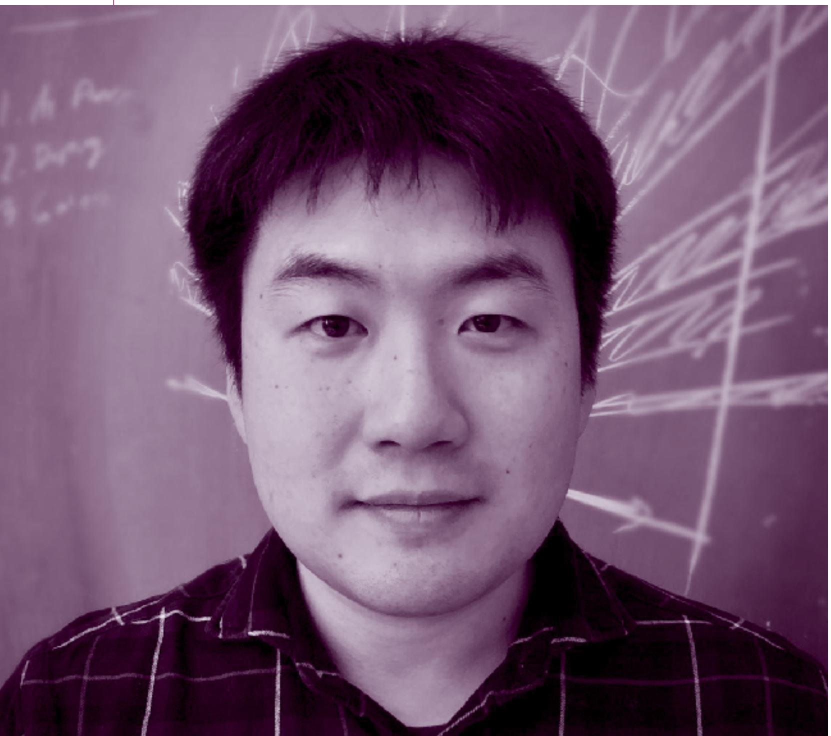
Research Interests

Professor Soonwon Choi is interested in exploring dynamical phenomena that occur in strongly-interacting quantum many-body systems, and designing their novel applications in quantum information science.

This research topic often involves a wide variety of interdisciplinary approaches to study, from analytic theory and numerical computation to collaborations on experiments with controlled quantum degrees of freedom. For example, Choi's past contributions include developing a simple method to engineer the dynamics of a strongly-interacting spin ensemble. The method was swiftly adopted in an experiment involving solid-state spin defects and enabled the observations of exotic quantum many-body phenomena, such as anomalously slow thermalization, or discrete time crystalline order. Later, the technique was further improved, leading to a novel sensing protocol to detect an oscillating magnetic field with an unprecedentedly high sensitivity.

More recently, Choi's research is focused on understanding the dynamics of quantum entanglement in chaotic systems. He showed that for a wide range of quantum systems evolving under unitary or non-unitary dynamics, many properties of quantum entanglement and information flow can be well described by using classical statistical mechanics models. This connection between information dynamics and classical statistical mechanics models may provide fresh insights to both fundamental physics problems, such as quantum chaos and thermalization, and practical applications such as designing quantum error correction schemes. At MIT, Choi aims to continue his research on the interaction of quantum many-body physics and information science.

Credit: S. Choi



Biographical Sketch

Soonwon Choi was born in Seoul, South Korea, and grew up in Daejeon in that country. He completed his undergraduate study in physics at Caltech in 2012, then earned his PhD in physics from Harvard University under the supervision of Prof. Mikhail Lukin in 2018. Choi was a Miller Postdoctoral Fellow at the University of California, Berkeley before joining MIT as an Assistant Professor of Physics in July 2021.

For a list of Prof. Choi's selected publications, please visit his faculty web page at *physics.mit.edu/faculty/soonwon-choi/*.

Credit: David Sella

Lina Necib PhD ’17

Assistant Professor of Physics,
MIT Kavli Institute for Astrophysics
and Space Research

Research Interests

As a theoretical astroparticle physicist, Prof. Lina Necib works on using galactic dynamics to understand properties of dark matter. She uses cosmological simulations, stellar catalogs, machine learning techniques and a background of particle physics to build the first map of dark matter in the Milky Way.

Using the space telescope Gaia, she modeled the kinematics of accreted stars, some of which originate from particular merger events such as the Gaia Sausage/ Enceladus. With cosmological simulations, Necib has shown that such accreted stars are excellent trackers for the kinematics of dark matter, and are a great resource in mapping out the local dark matter, and subsequently studying the expected dark matter signal in terrestrial detection experiments. In the process, Necib discovered a new stellar structure, called Nyx, after the Greek goddess of the night. Such studies can be extended to dark matter with non-standard interactions, as well as other dense dark matter sources in the Milky Way such as dwarf galaxies and the galactic center.

Biographical Sketch

Lina Necib is originally from Tunisia. She moved to the United States in 2008 to attend Boston University, where she earned a BA in mathematics and physics in 2012, followed by a PhD in theoretical physics from MIT, under the supervision of Prof. Jesse Thaler. Necib next relocated to the west coast, where she was a Sherman Fairchild Fellow at Caltech from 2017–2020 and a Presidential Fellow at the University of California, Irvine in 2020. This was followed by a Fellowship in Theoretical Astrophysics at The Carnegie Observatories from 2020–2021. In July 2021, Necib joined the MIT Physics faculty as an assistant professor in the Kavli Institute for Astrophysics and Space Research.

For a list of Prof. Necib’s selected publications, please visit her faculty web page at *physics.mit.edu/faculty/lina-necib/*.

Andrew Vanderburg

Assistant Professor of Physics,
MIT Kavli Institute for Astrophysics
and Space Research

Research Interests

Professor Andrew Vanderburg's research focuses on studying exoplanets, or planets which orbit stars other than the Sun. He is interested in developing cutting-edge techniques and methods to discover new planets outside of our solar system, and studying the planets we find to learn their detailed properties. In recent years, astronomers have found that planets the size of Earth are common in our galaxy, but little is known about their characteristics. Are these planets mostly rocky like the Earth, or do they have thick gaseous atmospheres like Uranus and Neptune? From which elements and materials are these planets built, and are their geologies similar to that of our own planet?

Vanderburg and his team tackle these problems by conducting astronomical observations using facilities on Earth like the Magellan Telescopes in Chile, as well as space-based observatories such as the Transiting Exoplanet Survey Satellite and the James Webb Space Telescope. Once the data from these telescopes are in hand, the Vanderburg team specializes in developing new analysis methods that help extract as much scientific value as possible. Currently, his group is exploring the use of machine learning–especially deep neural networks–in exoplanet detection to both increase the sensitivity and efficiency of planet searches. Eventually, through this work, Vanderburg hopes to help answer questions such as, "Are the planets orbiting other stars throughout the galaxy anything like the worlds in our Solar system?" and "Could any of these planets be hospitable to life, like Earth?".

Biographical Sketch

Andrew Vanderburg is originally from Austin, Texas. He received his BA in physics and astrophysics from the University of California, Berkeley, in 2013 and his PhD in astronomy from Harvard University in 2017. He then moved to the University of Texas at Austin with a NASA Sagan postdoctoral fellowship. In 2020, he joined the Astronomy faculty at the University of Wisconsin-Madison before moving to MIT in July 2021.

For a list of Prof. Vanderburg's selected publications, please visit his faculty web page at *physics.mit.edu/faculty/andrew-vanderburg/*.

Faculty & Staff Notes

Honors + Awards

Adi Ashkenazi, Postdoctoral Associate, Hen Group, received the 2020 Tollestrup Award of the Universities Research Association for "substantial improvements to the modeling of neutrino interactions using electron scattering data and widespread contributions to data acquisition, background modeling and systematics on MicroBooNE."

William A. Barletta, Adjunct Professor of Physics, received the 2020 Exceptional Service Award, Division of Physics of Beams, American Physical Society.

Credit: Justin Knight Photography

↑ **Edmund Bertschinger**, Professor of Physics, received MIT's 2021 Everett Moore Baker Award for Excellence in Undergraduate Teaching. The award is given annually to a faculty member in recognition of exceptional interest and ability in the instruction of undergraduates, and is the only teaching award whereby the nomination and selection of recipients are exclusive to students.

Credit: Justin Knight Photography

↑ **Arup K. Chakraborty**, Professor of Physics and Chemistry, and Robert T. Haslam Professor of Chemical Engineering, was named an Institute Professor, the highest honor MIT bestows upon its faculty members.

↑ **Ibrahim Cissé**, Class of 1922 Career Development Associate Professor of Physics, was awarded a 2021 Vilcek Foundation Prize for Creative Promise in Biomedical Science for "using super-resolution biological imaging to directly visualize the dynamic nature of gene expression in living cells."

Credit: Justin Knight Photography

↑ **Riccardo Comin**, Class of 1947 Career Development Assistant Professor of Physics, received a 2021 U.S. Department of Energy Early Career Research Program Award; and the MIT Frank E. Perkins Award for Excellence in Graduate Advising (2020), given annually to a faculty member from each school who has served as an excellent advisor and mentor for graduate students.

Dan Craik, Postdoctoral Associate, Williams Group, was awarded a 2020 Ambizione Fellowship of the Swiss National Science Foundation.

↑ **Emma Dunn**, Undergraduate Advising and Program Coordinator, Physics Department Academic Services, received a 2021 Infinite Mile Award from the MIT School of Science.

Credit: Justin Knight Photography

↑ **Netta Engelhardt**, Biedenharn Career Development Assistant Professor of Physics, received a 2021 U.S. Department of Energy Early Career Research Program Award; and awarded a 2021 New Horizons in Physics Prize for Early-Career Achievements in Physics and Math (Breakthrough Prizes) for “calculating the quantum information content of a black hole and its radiation.”

↑ **Peter H. Fisher**, Physics Department Head, was named the inaugural Thomas A. Frank (1977) Professor of Physics; and elected a Fellow of the American Association for the Advancement of Science.

Anna Frebel, Associate Professor of Physics, was named a 2020–2021 Fellow of the Wissenschaftskolleg zu Berlin (Institute for Advanced Studies), Germany.

Daniel Freedman, Professor of Applied Mathematics and Physics Emeritus, was elected to the National Academy of Sciences (2021).

Jeff Gore, Associate Professor of Physics, was named a Schmidt Science Polymath (2020), a new program which invests in recently-tenured faculty who demonstrate "remarkable track records, promising futures, and a desire to explore interdisciplinary research."

Philip Harris, Assistant Professor of Physics, received a 2021 U.S. Department of Energy Early Career Research Program Award.

Chhayfou Hong, Financial Assistant, Laboratory for Nuclear Science, received a 2021 Infinite Mile Award from the MIT School of Science.

Pablo Jarillo-Herrero, Cecil and Ida Green Professor of Physics, received the 2021 National Academy of Sciences Award for Scientific Discovery for his "pioneering developments in nanoscience and nanotechnology"; the 2021 Lise Meitner Distinguished Lecture and Medal of The Royal Swedish Academy of Sciences for his groundbreaking work on "twistronics," a technique that adjusts the electronic properties of graphene by rotating adjacent layers of the material; and the 2020 Spanish Royal Physics Society Medal for his pioneering experimental work on twistronics.

David Kaiser, Professor of Physics; Germeshausen Professor of the History of Science; and Associate Dean for Social and Ethical Responsibilities of Computing, Schwarzman College of Computing, had his latest book, *Quantum Legacies: Dispatches from an Uncertain World* (University of Chicago Press, 2020), named to the "Best of the Year" lists of *Physics Today* and *Physics World* magazines.

↑ **Erin Kara**, Assistant Professor of Physics, was awarded an MIT-Israel Zuckerman STEM Fund by the MIT International Science and Technology Initiatives (MISTI) program; and received an MIT Solomon Buchsbaum Research Fund award "for launching new research initiatives that cut across disciplinary lines."

Beverly LaMarr, Sponsored Research Technical Staff, MIT Kavli Institute for Astrophysics and Space Research, received a 2021 Infinite Mile Award from the MIT School of Science.

Dien Nguyen, Postdoctoral Fellow, Hen Group, was awarded a 2020 Nathan Isgur Fellowship of the U.S. Department of Energy's Jefferson Laboratory.

Nathaly Santiesteban, Postdoctoral Fellow, Hen Group, was named a School of Science Fellow (2020).

Katelin Schutz, Pappalardo Fellow, received the American Physical Society's 2020 J.J. and Noriko Sakurai Dissertation Award in Theoretical Particle Physics.

↑ **Sara Seager**, Class of 1941 Professor of Physics and Planetary Science, was awarded the 2021 Magellanic Premium Medal of the American Philosophical Society, the oldest medal recognizing scientific achievements given by a North American institution; and was invested as an Officer into the Order of Canada (2020) for her "multidisciplinary research that has contributed to transforming the study of extrasolar planets into a full-fledged planetary science."

Credit: Justin Knight Photography

↑ **Phiala Shanahan**, Class of 1957 Career Development Assistant Professor of Physics, received the Maria Goeppert Mayer Award of the American Physical Society (2021) for "key insights into the structure and interactions of hadrons and nuclei using numerical and analytical methods and pioneering the use of machine learning techniques in lattice quantum field theory calculations in particle and nuclear physics"; received the Kenneth G. Wilson Award for Excellence in Lattice Field Theory (2020) for "excellence in the study of hadrons and nuclei in lattice QCD and for pioneering the application of machine learning and artificial intelligence techniques to lattice field theory"; was included in "SN 10: Scientists to Watch" (Science News, 2020); and received MIT's Teaching with Digital Technology Award (2020).

Tracy Slatyer, Jerrold R. Zacharias Career Development Associate Professor of Physics, was awarded a 2021 New Horizons in Physics Prize for Early-Career Achievements in Physics and Math (Breakthrough Prizes) for "major contributions to particle astrophysics, from models of dark matter to the discovery of the 'Fermi Bubbles.'"

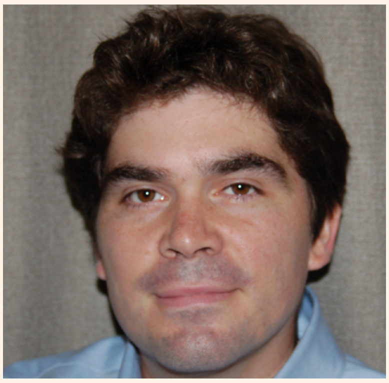
Marin Soljačić, Professor of Physics, was named a Highly-Cited Researcher by Web of Science (2020).

Credit: Justin Knight Photography

↑ **Salvatore Vitale**, Assistant Professor of Physics, received a Faculty Early Career Development Program (CAREER) Award from the National Science Foundation.

Joshua Wolfe, Technical Instructor, Physics Department, received a 2021 Infinite Mile Award from the MIT School of Science.

Promotions



↑ **Joseph Checkelsky** to Associate Professor of Physics with tenure.

Riccardo Comin to Associate Professor of Physics without tenure.

Jeff Gore to Full Professor of Physics.

Daniel Harlow to Associate Professor of Physics without tenure.

Or Hen to Associate Professor of Physics without tenure.

Credit: Justin Knight Photography

↑ **Kerstin Perez** to Associate Professor of Physics with tenure.

Jesse Thaler to Full Professor of Physics.

Retirement

John W. Belcher [1971–2021]

Class of 1922 Professor of Physics, Emeritus

In research, John Belcher concentrated on the plasma physics of the solar system and the local interstellar medium, and in education he helped introduce an active learning version of *8.02: Electromagnetism I*, together with Dr. Peter Dourmashkin '76 and Prof. David Litster.

Following in the footsteps of his mentor, Prof. Herbert Bridge, he was heavily involved in the Voyager Outer Planets and Interstellar Mission, which investigated the magnetospheres of the outer planets and of the local interstellar medium.

Belcher was twice awarded the NASA Exceptional Scientific Achievement Medal, and received the 2016 Oersted Medal of the American Association of Physics Teachers. The Oersted Medal recognizes those who have had an outstanding, broad and lasting impact on the teaching of physics.

Credit: Paul Rivenberg

Credit: Diana Bailey

Robert L. Jaffe [1974–2021]

Otto (1939) and Jane Morningstar Professor of Science, Post-Tenure

Robert Jaffe, Otto (1939) and Jane Morningstar Professor of Science, Post-Tenure, is a theoretical physicist known best for his research on the quark substructure of matter and the quantum structure of the vacuum. With MIT colleagues, he formulated the first consistent description of quark confinement. Jaffe also initiated the study of exotic hadrons and the spin substructure of protons and neutrons.

He chaired the MIT Faculty from 1993–1995, led the Center for Theoretical Physics (CTP), and co-founded the Symposium at MIT, an interdisciplinary effort to build bridges amongst MIT's five Schools.

Jaffe won many prizes in recognition of his teaching, initiated several courses in the physics curriculum, and together with CTP colleague Prof. Washington Taylor developed, taught, and wrote the groundbreaking textbook *The Physics of Energy*, a first-of-its-kind course on the physical foundations of energy sources, uses and systems.

Robert Redwine [1979–2021]

Professor of Physics, Emeritus

Robert Redwine retired in early 2021 after 42 years on the MIT faculty. He is an experimental nuclear physicist who used a number of particle accelerator facilities around the world to investigate issues related to nuclear reactions, and to searches for physics beyond the so-called Standard Model.

Redwine has also throughout his career sustained a strong interest in education. He served as Academic Officer in the Physics Department and later as MIT Dean for Undergraduate Education. This latter role was a wonderful opportunity to support students and to connect with colleagues around the Institute.

He is greatly appreciative of the opportunities that MIT has provided him and looks forward to continuing his many connections with his MIT colleagues.

Credit: Darren Stahlman Photography

News & Events in Physics

Q&A with Dean Nergis Mavalvala: First-year Update

Credit: Bryce Vickmark

With nearly a year's experience under her signature baseball cap in leading the School of Science as its first new Dean in six years (and the first woman to hold that position), Nergis Mavalvala, the Curtis and Kathleen Marble Professor of Astrophysics, generously shares a few highlights of her first year with the physics@mit community.

physics@mit: Dean Mavalvala, it must have been an extraordinary first year of your deanship, balancing the demands and unique responsibilities of MIT's extended lockdown, while coming up-to-speed on the critical details of leading one of the world's renowned Schools of Science.

Can you share one or two highlights of your experience branching out from your home base of LIGO physics to the myriad departments, labs and centers within the School of Science, under these uniquely challenging conditions?

Dean Nergis Mavalvala: When I stepped into the role of dean of the School of Science, perhaps the most important goal I set for myself was to not break anything that was working well. I have been delighted by how many, many things in the School do work really, really well. This is due to incredible staff across the School, and also a remarkable group of departmental leaders. Starting during the pandemic should have made it harder to get to know people in the dean's office, on Science Council, Dean's Council, Academic Council, and across MIT. But the warm welcome, generous support, and new friendships have blown me away. I have really loved getting to know many new colleagues in other departments. I have also loved the challenge of learning science that is far afield of my own expertise. The School of Science is also blessed with many generous donors, and it has been a real highlight to get to know them.

I knew I was taking the helm of one of the very best Schools in the world, but this pandemic year has revealed strengths I never would have known were possible.

p@m: For five years as the Physics Department's associate head overseeing academic programming and student well-being, you led initiatives in doctoral requirements and exams, digital learning, student advising and mentoring. Are there plans to expand these initiatives throughout the School's other departments, and would the approach differ in response to the distinct needs of each of the School's academic disciplines?

NM: This has been one of the benefits of serving as dean after being associate head in Physics—seeing the multiple opportunities to expand what worked well in Physics, but also learning of the numerous other practices across the School that really are best practices that are more widely applicable.

I'm proud that the leadership of every department in the School is strongly committed to finding a good balance between the challenges and demands of the rigorous academic programs at MIT and the well-being of students.

Issues of student well-being, social and racial justice, diversity and inclusion should not be seen as counter to our educational and research objectives. We cannot be good educators or researchers in the absence of these wider social imperatives. I am really pleased and grateful that many of my colleagues see this the same way and are committed to making MIT and the world a better place.

p@m: In the Physics Department, you were recognized for seeking to address stress and workload issues amongst the student and faculty community. As a spouse and parent of two children with significant professional responsibilities, can you offer any key takeaways for coping and thriving in the MIT environment?

NM: I am blessed with boundless energy, so happy to exist in a whirlwind of activity. That said, I am thoughtful and deliberate about carving out family time—most evenings that I'm not traveling, and weekend days. I work late into the night when needed, but am pretty religious about exercising regularly and bouncing about with my kids when they are awake.

For those who wish for a healthy and balanced life, which is most of us, I can't emphasize enough the importance of carving out time away from work. In most cases, we do better work if we allow ourselves some time away from it, doing other things we enjoy.

p@m: Bonus question! Those of us on campus well know your dedication to commuting by bike. Any plans to install the first-ever bike rack within the Dean's suite in Building 6?

NM: So far I've just been leaning my bike against a wall in the office. But I think you are right. Deanly decorum would dictate an elegant rack for my trusty two-wheeler. *(C.A. Breen / J. Keller)*

> “We do better work if we allow ourselves some time away from it, doing other things we enjoy.”
>
> DEAN NERGIS MAVALVALA

Andrea Ghez '87 wins a share of the 2020 Nobel Prize in Physics

by Jennifer Chu | MIT News Office

Astrophysicist **Andrea Ghez '87** has been awarded the 2020 Nobel Prize in Physics, by the Royal Swedish Academy of Sciences in Stockholm. She shares half of the prize with Reinhard Genzel, "for the discovery of a supermassive compact object at the center of our galaxy." The other half of the prize was awarded to Roger Penrose, "for the discovery that black hole formation is a robust prediction of the general theory of relativity."

Credit: Kyle Alexander

Ghez received a BS in physics at MIT in 1987, where she started out majoring in mathematics before changing to physics. She received her PhD at Caltech in 1992, and is currently a professor of physics and astronomy at the University of California at Los Angeles.

She is known for her pioneering work in using high spatial-resolution imaging techniques to study star-forming regions and the supermassive black hole known as Sagittarius A* at the center of the Milky Way Galaxy. In particular, she studies the kinematics, or interactions between stars, in order to characterize the extremely dynamic region at the galaxy's center.

Ghez shares half of this year's Nobel Prize in Physics with Genzel, who is professor emeritus of physics at the University of California at Berkeley. Ghez and Genzel each lead a team of astronomers that has focused on mapping the brightest stars at the Milky Way's center, with increasing precision. The two groups have used some of the world's largest and most powerful telescopes to peer through many light years of interstellar gas and dust, to focus on the orbits of stars at the galaxy's center.

Their independent measurements have revealed an incredibly massive, invisible object that appears to be pulling on the stars and flinging them around the galaxy's center at enormous speeds. Their work, according to the Royal Swedish Academy of Sciences, "has given us the most convincing evidence yet of a supermassive black hole at the center of the Milky Way."

"What Andrea Ghez and Reinhard Genzel did was one of the coolest things ever—revealing stars in the center of our galaxy orbiting a black hole too small to see with a telescope," says Peter Fisher, professor and head of MIT's Department of Physics. "I always showed their video visualizing this process when I taught relativity—it is a great way to think about a black hole and it shows the incredible patience needed to do great science."

"Indeed we now have understood that these behemoths live at the center of most galaxies," adds Nergis Mavalvala, dean of MIT's School of Science and the Curtis and Kathleen Marble Professor of Astrophysics. "All of her career, Andrea has been an awe-inspiring scientist and educator, and role model for women and girls. And now, as a Nobel laureate, her groundbreaking science and her story are sure to reach even farther and inspire a generation of young women to pursue careers in science."

"I hope I can inspire other young women into the field," Ghez said at the press conference. "It's a field that has so many pleasures, and if you are passionate about the science, there's so much that can be done."

Ghez is the 14th MIT Physics Department graduate to win a Nobel Prize in Physics, and the Department's first woman to do so.

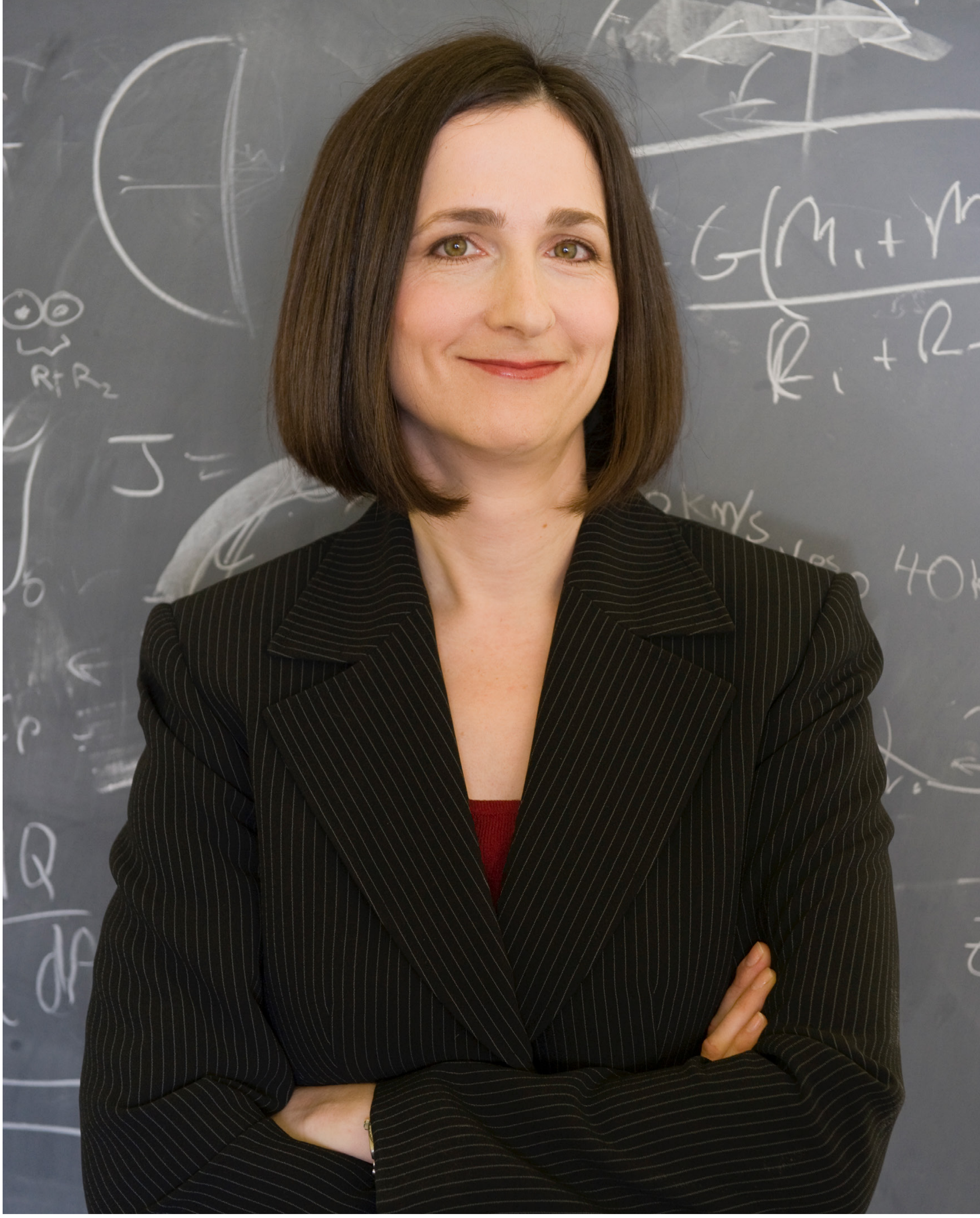
Article adapted from MIT News Office Online: *news.mit.edu/2020/andrea-ghez-shares-2020-nobel-prize-physics-1006*, with kind permission.

MIT PHYSICS DEPARTMENT GRADUATES

Nobel Laureates

1. William Shockley '36 – 1956
2. Richard Feynman '39 – 1965
3. Murray Gell-Mann PhD '51 – 1969
4. John Schrieffer '53 – 1972
5. Burton Richter '52, PhD '56 – 1976
6. Henry W. Kendall PhD '55 – 1990
7. William D. Phillips PhD '76 – 1997
8. Robert Laughlin PhD '79 – 1998
9. Eric Cornell PhD '90 – 2001
10. Carl Wieman '73 – 2001
11. George Smoot '66, PhD '70 – 2006
12. Adam Riess '92 – 2011
13. Rainer Weiss '55, PhD '62 – 2017
14. Andrea M. Ghez '87 – 2020

(*S. Miller*)



Pappalardo Distinguished Lecture: Sara Seager

On October 22, 2020, the Department held the annual Pappalardo Distinguished Lecture featuring exoplanets research pioneer **Sara Seager**, MIT Class of 1941 Professor of Physics and Planetary Science. Seager spoke on “The Search for Signs of Life Beyond Earth by Way of Atmospheric Biosignature Gases” to a virtual ‘sell-out’ crowd via the Zoom platform. She enhanced the virtual lecture by inserting herself as a speaker within the talk’s slides, sharing her research on exoplanets and atmospheric gases across our universe. Department Head and host **Peter Fisher** thanked **Neil and Jane Pappalardo** for their generous support of the Department’s annual lectureship series. (*Danielle Forde*)

2021-2024 Pappalardo Fellowships in Physics Competition


Kevin Burdge

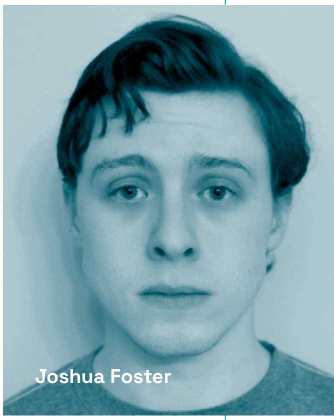
The Department's premier postdoctoral fellowship program, the Pappalardo Fellowships in Physics, wrapped up its 22st annual competition in early January 2021 with the appointment of three new Fellows: astrophysicist **Kevin B. Burdge '15**; nuclear and particle theorist **Joshua Foster**; and string theorist **Manki Kim**.

Kevin B. Burdge '15, is a 2021 PhD from the California Institute of Technology whose interests lie in discovering and characterizing astrophysical sources of both gravitational and electromagnetic radiation, especially those detectable by the upcoming space-based gravitational wave detector, the Laser Interferometer Space Antenna (LISA).

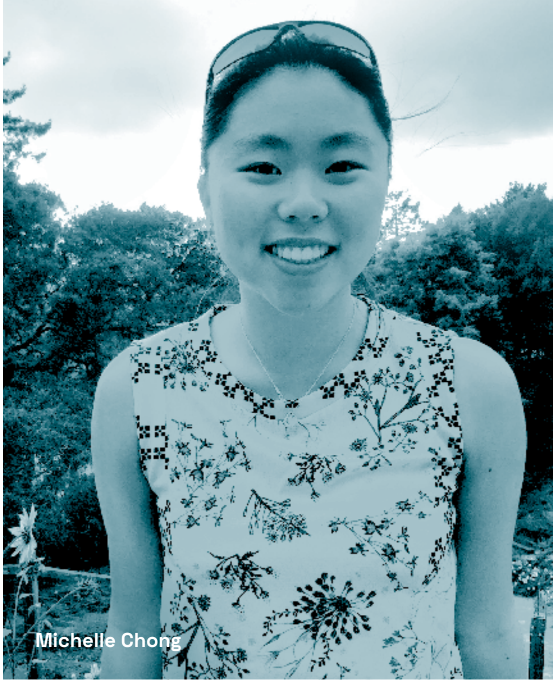
Joshua Foster, earned his 2021 PhD under the supervision of former Pappalardo Fellow Professor Benjamin Safdi at the University of Michigan, Ann Arbor. His work is focused on the identification of dark matter and dark sectors by determining how signals of new physics may manifest in astrophysical systems and the laboratory. A theorist by training, he is particularly interested in searches for new physics in real data and the application of high-performance computing to phenomenology.

Manki Kim is a 2021 PhD from Cornell University, whose research is centered on string theory and its applications in the physics of the early universe. His long-term goal is to experimentally test string theory through the physics of the early universe, such as inflation, which is highly sensitive to the Planck-scale physics.

Detailed biographies, including research descriptions and selected publications for all Pappalardo Fellows, are available on *physics.mit.edu/research/pappalardo-fellowships-in-physics/*. The MIT Pappalardo Fellowships in Physics program was initiated, and is sustained, by funds generously provided by **A. Neil (1964) and Jane Pappalardo**. (*C.A. Breen*)


Joshua Foster


Manki Kim


Michelle Chong

Patrons of Physics Fellows

The Department celebrated its 16th annual Patrons of Physics Fellows event on April 7, 2021, with 76 guests gathered via Zoom, allowing our community to come together across the U.S. and beyond.

Among those joining were Art and Fran Peskoff, Ping Huang, Howard and Colleen Messing, Paul Swartz, Earl Epstein, Bill Ladd, Curt Marble, George Elbaum and Mimi Jensen, Jose Alonso, Neil Constable, Phyllis Buschsbaum, Riccardo Di Capua, Thomas and Renate Cardello, Jim and Sylvia Earl, Michael Bos and Majika Shephard, F. Scott McDermott, Samuel Gasster, and Walid Fakhry.

Physics Department Head Professor Peter Fisher opened the event by sharing some Department updates, including the virtual graduate student open house and other struggles and triumphs of living, working and learning during this past unprecedented year.

"Lighting talks"—brief, five-minute updates—were given by **Michelle Chong**, **Whiteman Fellow**; **Elba Alonso Monsalve, Peskoff Fellow**; and **Jasmine Kalia**, **Frank Fellow**. Michelle discussed her work on laser cooling and trapping in Professor Vladan Vuletić's group; Elba spoke on researching black holes; and Jasmine gave updates on lab work in condensed matter and atomic physics and using a lithium apparatus.

Donors, students and faculty then connected in Zoom breakout rooms to exchange stories about their time at MIT and share further details on the fascinating research being done.

Tom Frank, Champion of the Patrons Society, gave a closing speech, congratulating all the students on overcoming the hardships that this year has put forth and thanking everyone for their continued support of the fellowships. (*Danielle Forde*)


Jasmine Kalia

Elba Alonso Monsalve

19th Annual Pappalardo Fellowships in Physics Symposium

Five members of the Department's leading postdoctoral fellowship program, the Pappalardo Fellowships in Physics, adapted to virtual world circumstances and hosted the program's annual spring symposium celebration with a five-part series of talks via Zoom.

Over the five-week period, each speaker showcased new results and future ambitions on one or more innovative research projects, with introductory remarks given by members of the MIT Physics faculty.

Tracy Slatyer, Jerrold R. Zacharias Career Development Associate Professor of Physics, launched the series on April 21, 2021, sharing observations from mentoring theoretical particle and astrophysicist **Katelin Schutz**. Schutz, who followed her Pappalardo term with a NASA Einstein Fellowship, joins the Physics faculty at McGill University in Fall 2021; she shared the secrets of "Making Dark Matter Out of Light." On April 28, astrophysicist and astronomer **Anna-Christina Eilers** was introduced by MIT Kavli Institute Director and Francis L. Friedman Professor **Rob Simcoe**. Eilers, completing a NASA Hubble Fellowship prior to her Pappalardo appointment, discussed "The Formation and Growth of Supermassive Black Holes." Following on May 5, leading neutrino physicist Professor **Janet Conrad** presented experimental particle physicist **Rachel Carr**, who described "Chasing Anomalies with Reactor Neutrinos." Carr, a former Stanton Fellow with the MIT Laboratory for Nuclear Security and Policy, begins a Physics faculty position at the United States Naval Academy in Fall 2021. Next up on May 12, astronomer and astrophysicist **Nicholas Kern** was introduced by former MIT Kavli Institute Director and Julius A. Stratton Professor **Jacqueline Hewitt**. Nick, who adroitly managed the dual challenges of launching his MIT Pappalardo career within the virtual bubble of remote research, alongside welcoming his first child, shared myriad details of his plans for "Ushering in a New Era for High Redshift Astrophysics and Cosmology with the 21 cm Line." Wrapping up the online series on May 19, the multiple accomplishments of theoretical condensed matter physicist **Hoi Chun "Adrian" Po** were enthusiastically outlined in extemporaneous remarks by senior colleague **Liang Fu**, Lawrence C. and Sarah W. Biedenharn Associate Professor of Physics. Po, with his faculty career well underway at The Hong Kong University of Science and Technology, logged in from across the globe to reveal in "Topology at the Corner of the Table," the startling, revolutionary physics of...table salt, or, sodium chloride.

Leading the series' virtual audience each week was Pappalardo Fellowships founder and benefactor, **A. Neil Pappalardo '64**, joined variously by Department Head **Peter Fisher**, Dean of Digital Learning **Krishna Rajagopal**, longstanding friends and supporters **Howard Messing** and **Curt Marble**, and faculty, postdocs, students and staff from all subfields of the Department. (*C.A. Breen*)

Student Honors & Awards

Undergraduate

2021 Malcolm Cotton Brown Award

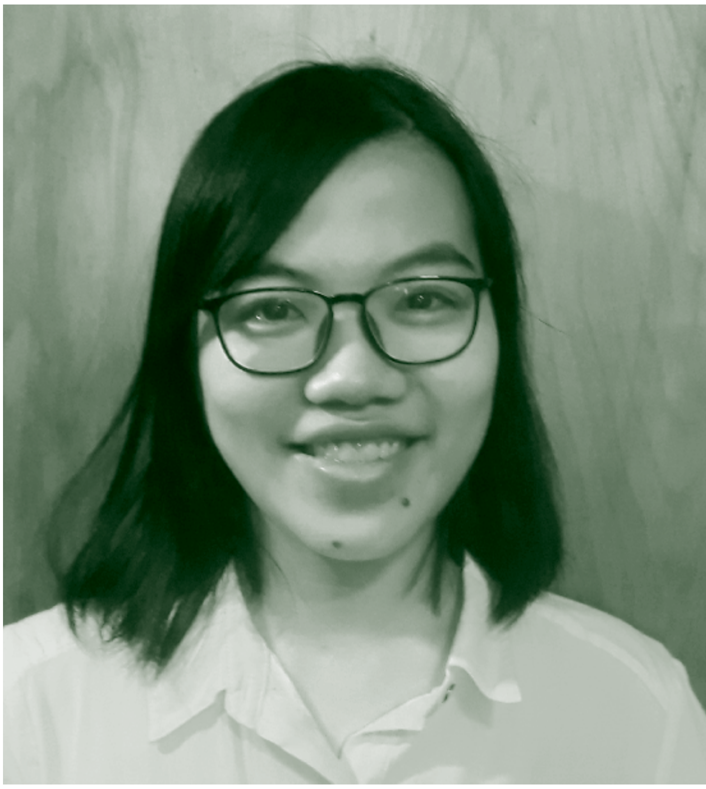
Given in memory of Lt. Malcolm Cotton Brown, Royal Air Force, who was killed in service on July 23, 1918. One thousand dollars is awarded to one or more seniors of high academic standing in physics and outstanding research in experimental physics.

Thao H. Dinh SB ’21

Thesis supervisor: William D. Oliver

Anjali Nambrath SB ’21

Thesis supervisor: Or Hen



2021 Malcolm Cotton Brown Award winners **ABOVE:** Thao H. Dinh and **LEFT:** Anjali Nambrath.

2021 Burchard Scholars

The Burchard Scholars Program brings together distinguished members of the faculty and promising sophomores and juniors who have demonstrated excellence in some aspect of the humanities, arts, and social sciences, as well as in science and engineering. The Program is sponsored by the Dean's Office, School of Humanities, Arts, and Social Sciences.

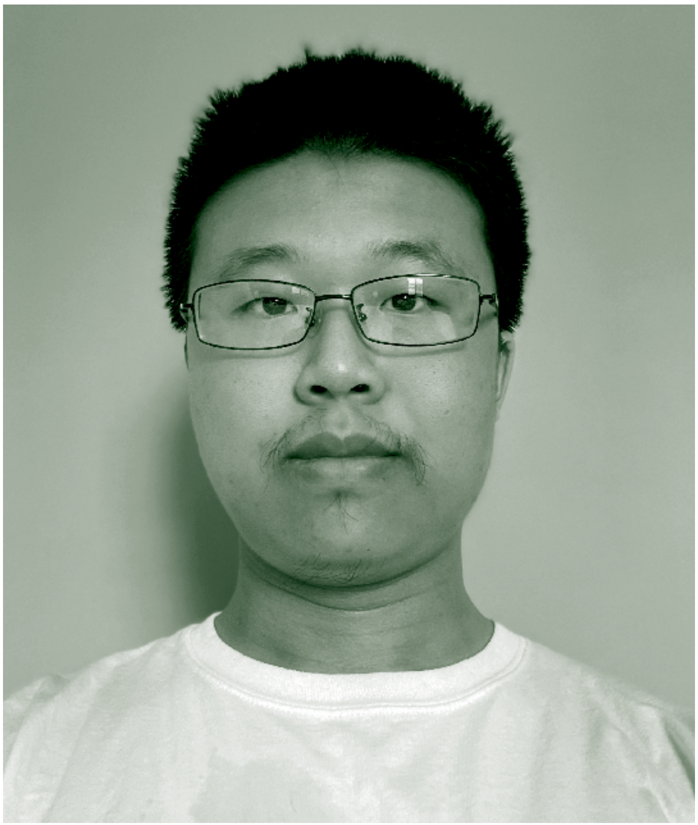
Hillary Diane Andales SB '23
Karna Morey SB '22
Jeffery Yu SB '22

The 2021 Morse/Orloff Award for Research

Given in memory of the late MIT Professor of Physics Philip Morse, one of the renowned physicists of the twentieth century, whose contributions spanned basic physics to engineering. Funds are generously provided by Dr. and Mrs. Daniel Orloff in memory of their son Joel, a Physics major, who died in an automobile accident shortly after graduation from MIT in 1978. One thousand dollars is awarded to a senior student in high academic standing who plans to pursue graduate study in physics.

Haoyang Gao SB '21

Thesis supervisor: Leonid Levitov



LEFT: 2021 Morse/Orloff Award for Research winner Haoyang Gao.

The 2021 Joel Matthew Orloff Awards

Established by Dr. and Mrs. Daniel Orloff in memory of their son Joel, a Physics major, who died in an automobile accident shortly after graduation from MIT in 1978. One thousand dollars is awarded to award winners in three categories.

SERVICE

Given to the student(s) with the most outstanding service to the Department, Institute, or community.

Grecia Castelazo SB ’21–22

Academic Advisor: Barton Zwiebach

Rian Flynn SB ’21

Academic Advisor: Nergis Mavalvala

Sujay S. Kazi SB ’21

Academic Advisor: Matthew Evans

Rachel C. Zhang SB ’21

Academic Advisor: Philip Harris

CLOCKWISE FROM TOP LEFT:
2021 Joel Matthew Orloff Award for Service co-winners Grecia Castelazo, Rian Flynn, Sujay S. Kazi, and Rachel C. Zhang.

SCHOLARSHIP

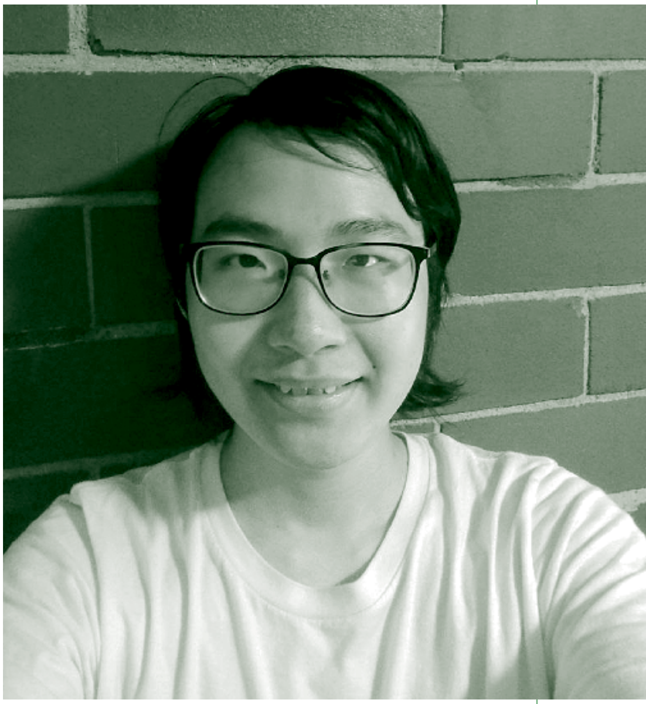
Given to the student(s) with outstanding scholastic achievement in physics.

Srijon Mukherjee SB '21

Academic Advisor: Christoph Paus

LEFT: 2021 Joel Matthew Orloff Award for Scholarship winner Srijon Mukherjee.

BELOW: 2021 Joel Matthew Orloff Award for Research winner Qiantan Hong.



RESEARCH

Given to the student(s) with the most outstanding research in Physics.

Qiantan Hong SB '21

Research Supervisor: Leonid Levitov

The 2021 Order of the Lepton Award

Awarded to a graduating senior who best exemplifies the spirit and characteristics of MIT's Physics students. Established with gifts from alumni and friends of the Department, the Order of the Lepton embodies the community spirit and collaboration that are hallmarks of the MIT Physics Department. The fund provides a prize of $1,000.

Anjali Nambrath SB '21

Academic advisor: Raymond Ashoori

ABOVE: 2021 Order of the Lepton Award winner Anjali Nambrath.

2021 Sigma Pi Sigma Inductees

Election to Sigma Pi Sigma is based upon a student's strong academic record. With over 90,000 members throughout its history, its purpose is to be of service to the broader physics community. It encourages scholarship in physics by admitting a student to the fellowship of others with similar interests and accomplishments. This year, MIT's Physics Department inducts 15 new members.

Thiago R. Bergamaschi
Thao H. Dinh
Haoyang Gao
Uriel Guajardo
Qiantan Hong
Sujay S. Kazi
Anna Khoroshilov
Yuan Lee
Srijon Mukherjee
Debaditya Pramanik
Luke Qi
Yogeshwar A. Velingker
Charles Wang
Fan Francis Wang
Jennifer J. Yu

2021 Phi Beta Kappa Inductees

Phi Beta Kappa is the oldest honor society in the United States of America. Less than 10% of the graduating class is invited, and selection is based upon academic record, dedication to the liberal arts and language skills. This year, MIT's Chapter (Xi) of Phi Beta Kappa voted to invite 149 members of the Class of 2021, 29 of whom are physics majors, to membership in the Society.

Ghadah M. Alshalan
Sheila J. Baber
Thiago R. Bergamaschi
Abhijatmedhi Chotrattanapituk
Thao H. Dinh
Aidan Faustina
Rian Flynn
Haoyang Gao
Uriel Guajardo
Qiantan Hong
Sami Kaya
Sujay S. Kazi
Anna Khoroshilov
Yuan Lee
Yong Hui Lim
Alex Miller
Gabriel L. Mintzer
Srijon Mukherjee
Anjali Nambrath
Erik J. Porter
Luke Qi
Nicholas R. Venanzi
Charles Wang
Fan Francis Wang
Harrison K. Wang
Deborah H. Wen
Jennifer J. Yu
Mikaeel M. Yunus
Rachel C. Zhang

Other Undergraduate Awards & Honors

Aidan Driscoll (SB '21. Thesis advisor: Barton Zwiebach) was awarded MIT's Alan Brody Prize in Theater Arts, given to "a senior who has demonstrated artistic excellence in the theater with an emphasis on playwriting."

Rian Flynn (SB '21. Academic advisor: Nergis Mavalvala) received the 2021 Laya and Jerome B. Wiesner Student Art Award for outstanding achievement in, and contributions to, the arts at MIT; and the 2021 Joseph D. Everingham Award in recognition of notable creative accomplishments in theater arts.

Kylie Hansen (SB '22. Academic advisor: Tracy Slatyer) was named a 2021 Margarita Ribas Groeger Distinguished Scholar for "achievement of proficiency in language, cultural understanding and enthusiasm in language learning."

Anjali Nambrath (SB '21. Thesis advisor: Or Hen) received a National Science Foundation Graduate Research Fellowship; a Fulbright India Student Research Award; First Prize in the Global Languages Awards for Excellence; and MIT's Laya W. Wiesner Award for "an undergraduate woman student who has most enhanced MIT community life."

Audrey Saltzman (SB '21. Academic advisor: Yen-Jie Lee) was awarded a National Science Foundation Graduate Research Fellowship; and received the Ida M. Green Fellowship from the MIT Office of Graduate Education.

Graduate

2021 Alan H. Barrett Prize

The prize honors the late Professor Alan H. Barrett's outstanding influence in the education of physicists and his fundamental contribution to the science and technology of astrophysics. One thousand dollars is awarded to a graduate student with outstanding research in astrophysics.

Andrea Biscoveanu
Astrophysics
Thesis supervisor: Salvatore Vitale

2021 Buechner Student Teaching Prize

Awarded to a graduate student for outstanding contributions to the educational program of the Department during the past academic year. The $1,000 prize was established in 1987 by the late Mrs. Christina Buechner in memory of her husband Prof. William Buechner, who served as Physics department head from 1962–1967.

Emily Crabb
Theoretical Condensed Matter
Thesis supervisor: Jeffrey Grossman

2021 Martin Deutsch Student Award for Excellence in Experimental Physics

Created in 1987 in honor of Professor Martin Deutsch's outstanding career as an experimentalist and for his influence as an educator. $1,000 is awarded annually to a graduate student mid-way through his or her thesis research in any field, with preference for an experimentalist.

Thomas Hartke
Atomic, Molecular and Optical Physics
Thesis supervisor: Martin Zwierlein

Christopher Whittle
Astrophysics
Thesis supervisor: Matthew Evans

2021 Graduate Student Prizes for Service to the Physics Department

These prizes were established in 2020–2021, a tumultuous year which saw the closing of the campus for much of the year and where social justice issues had great importance for students, staff and faculty. Department Head Peter Fisher created the Graduate Student Prize for Service to the Physics Department in recognition of a great outpouring of service by the graduate student body to address Departmental diversity, equity and inclusion issues.

Dominika Durovcikova
Astrophysics
Thesis supervisor: Vivishek Sudhir

Rahul Jayaraman
Astrophysics
Thesis supervisor: George Ricker

Mason Ng
Astrophysics
Thesis supervisor: Deepto Chakrabarty

Olumakinde Ogunnaike
Theoretical Condensed Matter Physics
Thesis supervisor: Leonid Levitov

Wenzer Qin
Theoretical Nuclear and Particle Physics
Thesis supervisor: Tracy Slatyer

Stella Schindler
Theoretical Nuclear and Particle Physics
Thesis supervisor: Iain Stewart

Cedric Wilson
Atomic, Molecular, and Optical Physics
Thesis supervisor: Martin Zwierlein

2021 Andrew M. Lockett III Memorial Fund Award

Awarded to a graduate student in theoretical physics, with preference given to students from Los Alamos, NM, and New Orleans, LA. The award currently carries a prize of $1,000. The award was established by Mrs. Lucille Lockett Stone in memory of her husband, Dr. Andrew M. Lockett, who received his PhD in physics from MIT in 1954.

Gurtej Kanwar
Theoretical Nuclear and Particle Physics
Thesis supervisor: William Detmold

Sergio Vazquez Prize

Established in memory of Sergio Vazquez, a graduate student in the Center for Theoretical Physics who was killed in an automobile accident on April 1, 1990. One thousand dollars to be awarded annually to a graduate student, with preference for a student from an underrepresented sector of the population who had to overcome racial, physical or financial barriers.

Cedric Wilson
Atomic, Molecular, and Optical Physics
Thesis supervisor: Martin Zwierlein

Other Graduate Awards & Honors

Sylvia Biscoveanu (Astrophysics. Thesis supervisor: Salvatore Vitale) received the 2021 Ragnar and Margaret Naess Award of MIT's Music and Theater Arts Section, for recognition of creative accomplishments in music.

Robert Johnston (Experimental Nuclear and Particle Physics. Thesis supervisor: Richard Milner) was awarded a 2020–2021 JSA/Jefferson Lab Graduate Fellowship.

Sangbaek Lee (Experimental Nuclear and Particle Physics. Thesis supervisor: Richard Milner) was awarded a 2020–2021 JSA/Jefferson Lab Graduate Fellowship.

Chiara Salemi (Experimental Nuclear and Particle Physics. Thesis supervisor: Lindley Winslow) was awarded the Dr. Pliny A. and Margaret H. Price Prize from The Ohio State University's Center for Cosmology and Astroparticle Physics in recognition of "research excellence and exceptional scientific promise in all areas of cosmology and astroparticle physics."

Zhaozhong Shi (Experimental Nuclear and Particle Physics. Thesis supervisor: Yen-Jie Lee) received the Office of Science Graduate Student Research Award of the U.S. Department of Energy (2020).

Graduate Degree Recipients 2020–21

The Physics Department's virtual Graduate Commencement celebration was held on Thursday, June 3, 2021. The event, organized and led by Graduate Student Coordinator Sydney Miller, included students, their families and faculty supervisors. Graduates shared words of wisdom and gratitude, alongside location photos of their remote thesis defenses and research, as well as a surprising number of outstanding hiking vistas.

September 2020

Ran Bi, PhD
Jasmine Therese Brewer, PhD
Jennifer Renee Crawford, SM
Wenjie Ji, PhD
Eric Mario Metodiev, PhD
Jarrett S. Moon, PhD
James Francis Pelletier, PhD
Ryuji Takagi, PhD
Tzer Han Tan, PhD
Kaya Tatar, PhD
Elizabeth Ann Tolman, PhD
Furkan Cagri Top, PhD
Andrew Patrick Turner, PhD
Gherardo Vita, PhD
Linda Ye, PhD
Haocun Yu, PhD
Guo "Alfred" Zong, PhD

February 2021

James Owen Andrews, PhD
Alexandru "Alex" Bacanu, PhD
Thomas Julian Boettcher, PhD
Sergio Hiram Cantu, PhD
Sungjoon Hong, PhD
Gwang-Jun Kim, SM

June 2021

Daniel Robert Abercrombie, PhD
Anirudh (Ani) Chiti, PhD
Woo Chang Chung, PhD
Joseph Patrick Johnston, PhD
Gurtej (Tej) S. Kanwar, PhD
Dahlia Rivka Klein, PhD
Patrick T. Komiske, PhD
Rolando Luis La Placa Massa, PhD
Bola Malek, SM
Kevin Joseph Montes, PhD
Marjon H. Moulai, PhD
John Christopher Napp, PhD
Hamed Pakatchi Shotorbannejad, PhD
Melis Tekant, PhD
Constantin Weisser, PhD with SDS
Chih-Liang Wu, PhD
Yunjie Yang, PhD

Student Profile: Cedric Wilson

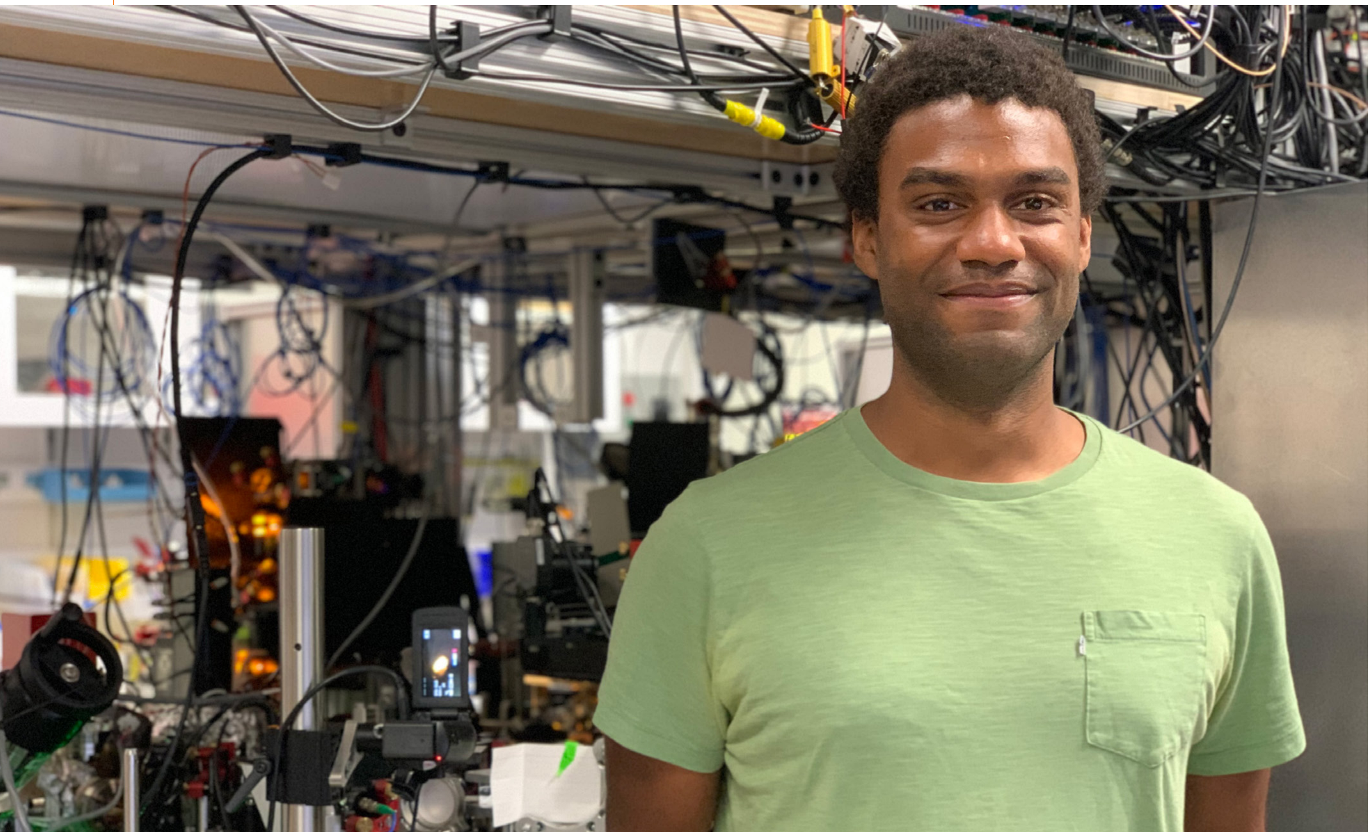
by Sandi Miller

PhD Candidate, Experimental Atomic Physics (Zwierlein Group)

Cedric Wilson is a fifth-year PhD student in the Ultracold Quantum Gases Group within the MIT-Harvard Center for Ultracold Atoms (CUA), led by Thomas A. Frank (1977) Professor of Physics Martin Zwierlein. There, Cedric is playing a key role in a groundbreaking experiment studying fast-rotating Fermi gases.

Cedric was nominated for a Hugh Hampton Young Fellowship, sponsored by the MIT Office of Graduate Education (OGE), for his academic and scientific accomplishments and service to others. Cedric also worked with the OGE to overhaul the MIT Summer Research Program (MSRP), improving research opportunities for underrepresented students. The MSRP gives students from underrepresented backgrounds a chance to come to MIT to do summer research. Cedric was an application reviewer for the MSRP and knew it was a great program with potential for improving diversity in physics. In fact, this year the MSRP tripled the number of incoming students.

Cedric has also helped to improve diversity and inclusion efforts within the CUA, and in December 2020 he was active in



Credit: Airlia Shaffer

launching the Harvard-MIT National Society of Black Physicists (NSBP) chapter. The CUA's NSBP members are exploring what kinds of outreach they're interested in and some have been mentoring students from a local high school. Initially, Cedric was the NSBP's only graduate student member, but now there are four. He notes that for underrepresented physicists, it's really important to have support, networking, and to be able to think of yourself as a physicist.

Cedric, what attracted you to physics and MIT?

As a kid I didn't think science was a job you could have. After high school, I didn't plan to go to college. I worked jobs that weren't the most exciting, like construction and restaurant work, but I learned the value of a good work ethic in getting things done.

My grandmother always encouraged me to give college a try. She was a nurse, and she inspired me to study medicine. I took classes in community college and then at the University of Utah. My pre-med chemistry class was awesome. That was my first experience with the world of physics. If you have an idea of how nature works, you can use that to figure out how to do things. For example, molecular structure tells you why alcohol is better than water at cleaning oil stains. Learning about a way to describe nature gave structure to my life. I thought, "This is the most fun I have had in a class and I'd rather do physics."

I didn't expect to get into MIT and almost didn't apply. I had a positive interaction with my advisor when choosing schools so that was what drew me here. I also like the style of MIT. It's not flashy; most of the effort goes toward research.

Ten years ago, if you asked me what I'd be doing, I wouldn't have guessed I'd be here. It's comforting to think you aren't stuck somewhere if you change your focus as an adult.

Can you explain a bit more about your research?

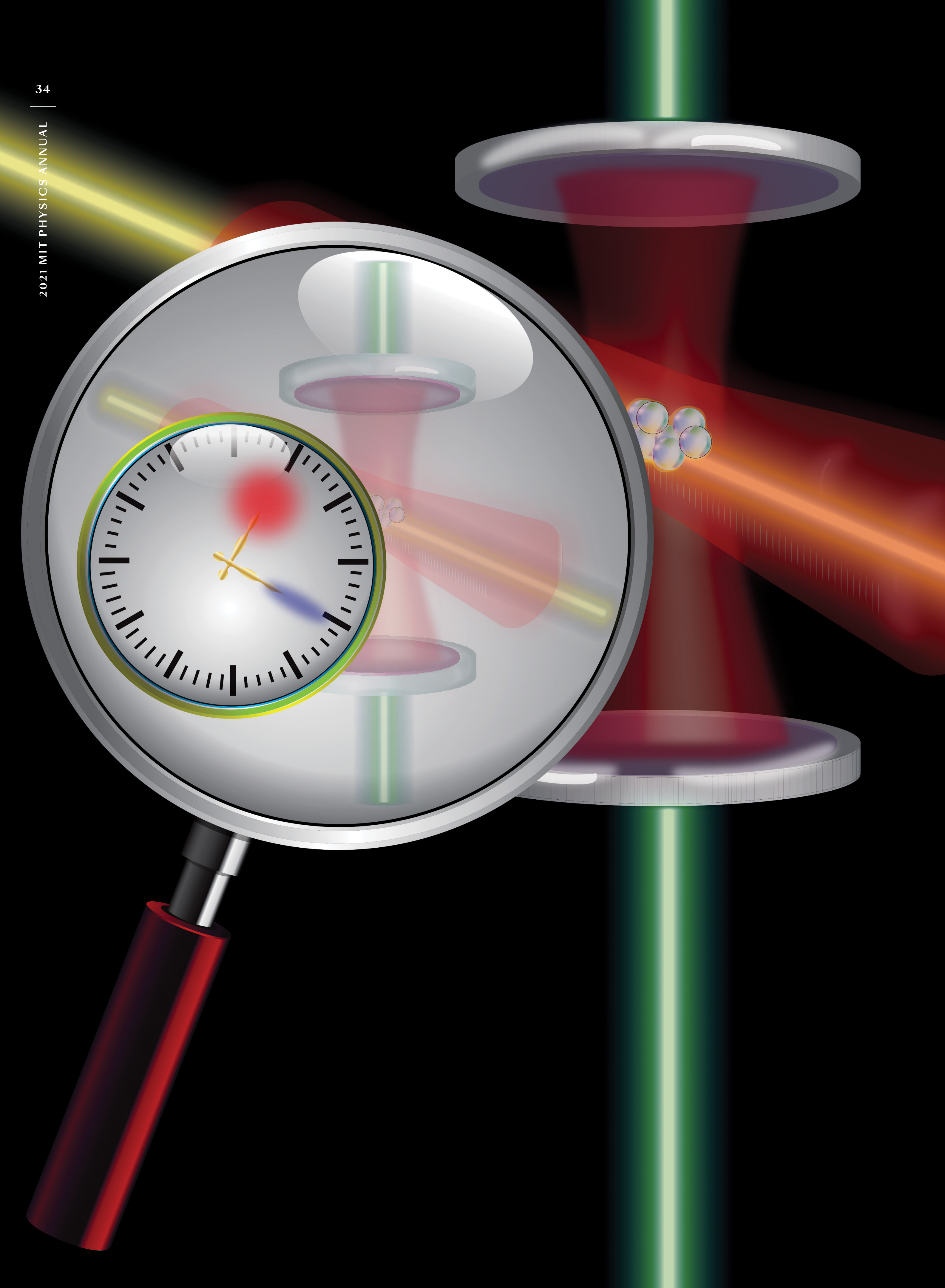
We're interested in rotating quantum gases. Quantum gases are made up of atoms that have been cooled to very low temperatures and have reached a temperature low enough that the atoms actually begin to "overlap." At this point there is a transition to unusual states of matter. We rotate the gases, which are electrically neutral, to create an artificial magnetic field for the atoms. The physics of rotating neutral particles is exactly analogous to the physics of charged particles in a magnetic field. We then have a window into the physics of unusual quantum states in magnetic fields, which we can image directly with a high-resolution microscope.

We get to work at extremes—weird states of matter that only show up a millionth of a degree above absolute zero. That's pretty amazing already. Then we get to manipulate those states and use them to answer fundamental questions. I also enjoy working with my hands, so working with optics and electronics is fun for me.

What are some key 'take-aways' from your MIT experience, thus far?

I think the most valuable lesson I learned in grad school is not about physics, but how to deal with situations where something goes wrong. Being able to trust in my reasoning and stick with an idea even when it doesn't work the first time is very important. On the other side, you have to know when to move on, so you don't waste time. There's a delicate balancing act between those two extremes.

In future, I could see myself enjoying teaching. I have also thought a lot about working in industry with research and development of quantum materials, quantum computing, optical technologies.



Keeping Better Time through Entanglement

by Vladan Vuletić, Simone Colombo and Edwin Pedrozo-Peñafiel

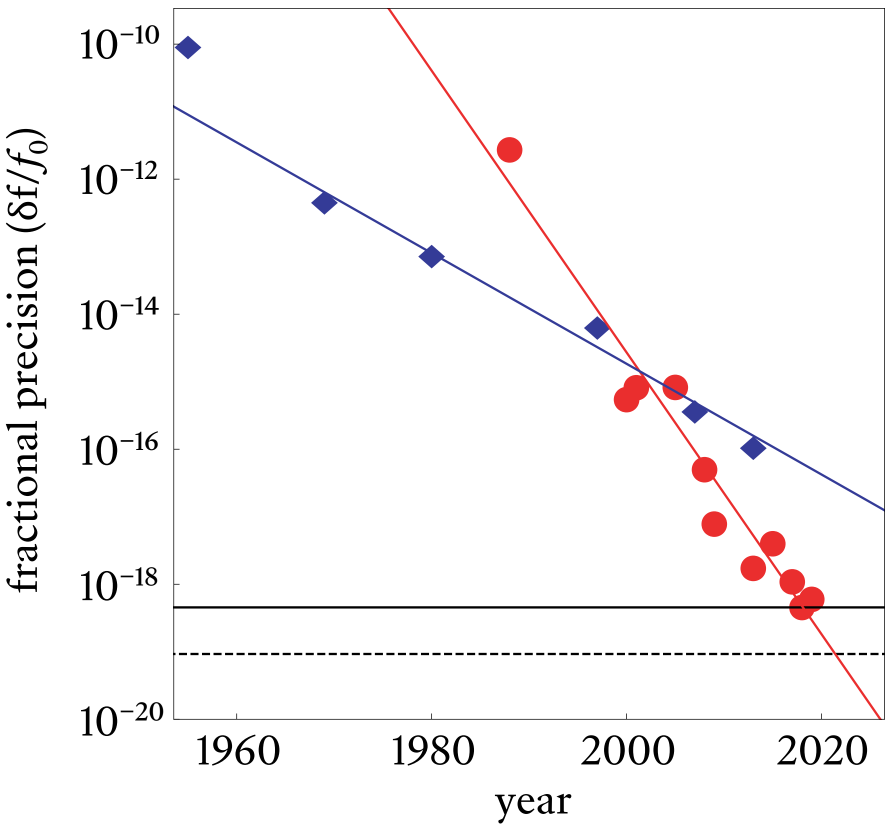
How to accurately measure time? Since time immemorial, humans have tried to keep track of the passing of time. How can one measure time? In a somewhat circular definition, time is measured through a periodic or repetitive process where each period takes a constant time.

For millennia, the best time standard that humanity had was the motion of celestial bodies, as evidenced by the length of the day, the lunar calendar or the solar year. In fact, until 1960 the standard of time was based on the Earth's motion around the Sun, *i.e.*, the astronomical year. However, by the middle of the last century it had been experimentally found that certain internal oscillations in atoms can be more stable than the motion of the Earth around the Sun, which is being influenced by the constellation of other planets. Hence, for the last 60 years time has been defined through the oscillation of a cesium atom between the hyperfine levels of its electronic ground state, with exactly 9,192,631,770 oscillations constituting 1 second.

Figure 1 shows the progress in accuracy made by cesium clocks over the past decades (blue data points). The improvement of cesium clocks follows an exponential Moore's law with about one order of magnitude in precision gain every decade. After 2000, a new type of clock was introduced, enabled by breakthroughs in laser and atom cooling and trapping technologies. These new devices are optical clocks that measure not the oscillations between hyperfine states at microwave frequencies (in the 10^{10} Hz range) like the cesium clock, but instead keep track of oscillations at the 10^5 times higher optical transition frequencies of 10^{15} Hz. Due to their much higher oscillation frequency, such clocks quickly started

FIGURE 1:

Progress in atomic clock precision over the last decades. The blue data points represent microwave clocks using cesium atoms, while the red data points represent clocks that operate on an optical transition. The solid black line represents the Standard Quantum Limit of an ytterbium optical-transition clock operated with five seconds of repeated interrogation time for one hour using 1,000 atoms. The Standard Quantum Limit is the best performance that can be achieved with independent, *i.e.*, not entangled, atoms. Credit: Vuletić Group



outperforming microwave clocks (red data points in *Fig. 1*). Today, optical-transition clocks are approaching a mindboggling fractional stability below 10^{-19}, equivalent to an error of only a few milliseconds for a hypothetical clock running since the Big Bang. This precision also means that one needs to be very careful about controlling the gravitational environment when measuring time: According to Einstein's general theory of relativity, time passes more slowly in a more negative gravitational potential, and current clocks are already sensitive to centimeter-scale differences in the clock height in the Earth's gravitational field.

How do atomic clocks achieve such exquisite performance? The working principle of atomic clocks is the conversion of an energy difference E between two atomic levels into a frequency f or oscillation period $T = 1/f$ via Planck's quantum h, $f = E/h$. To achieve high precision, atomic clocks use a long-lived electronically excited state with a typical lifetime τ of 10 seconds or more, corresponding to a high quality factor of the oscillation $Q = f\tau > 10^{16}$. Furthermore, as described by the Fourier theorem, high frequency or time resolution can only be achieved if the interrogation time is long: a precision of 1 Hz in one atom requires an interrogation time of one second. Atoms exhibiting random motion at room temperature would be leaving the interrogation laser beam far too quickly, but by laser cooling them and holding them in a trap, long clock interrogation times up to several seconds can be achieved. The trap, however, needs to have quite special properties, since it must affect exactly equally the energies of the two atomic states so that the energy difference E is not changed by the trap. This is accomplished by using a laser beam trap that is tuned to a 'magic wavelength' such that the optical polarizabilities for the ground state and the electronic excited state are exactly the same (*Fig. 2*). Finally, most optical-transition atomic clocks use many atoms, typically between 10^3 and 10^5, to improve the signal-to-noise ratio.

Quantum limitations of atomic clocks and entanglement

Atomic clocks operate by creating a quantum mechanical superposition of the ground state $|g\rangle$ and an excited state $|e\rangle$, and measuring the evolution frequency $f = E/h$ of the quantum mechanical phase between the two levels. The two-level system consisting of $|g\rangle$ and $|e\rangle$ can be represented formally as a (pseudo-) spin-½ system. A collection of N identical atoms constituting a clock can then be considered as a large spin $S = N/2$ that can be visualized as a vector $\vec{S}$ on a sphere of radius $\sqrt{S(S+1)}$, the so-called Bloch sphere (*Fig. 2*). The clock oscillation of the quantum phase $|g\rangle + e^{-iEt/\hbar}|e\rangle$ then corresponds to a rotation of the effective spin vector $\vec{S}$ around the equator of the Bloch sphere. To measure this rotation, the accumulated phase, or equivalently, the direction of the angular-momentum vector in the equatorial plane, is compared to the oscillation phase of a laser that operates at very nearly the same frequency. For a probing time of 1 second, $\vec{S}$ has performed as many as 10^{15} rotations, and the electric field of the laser beam has also oscillated the same number of times. The atomic phase, or equivalently, the direction of $\vec{S}$ in the equatorial plane, is then used as feedback to stabilize the laser phase.

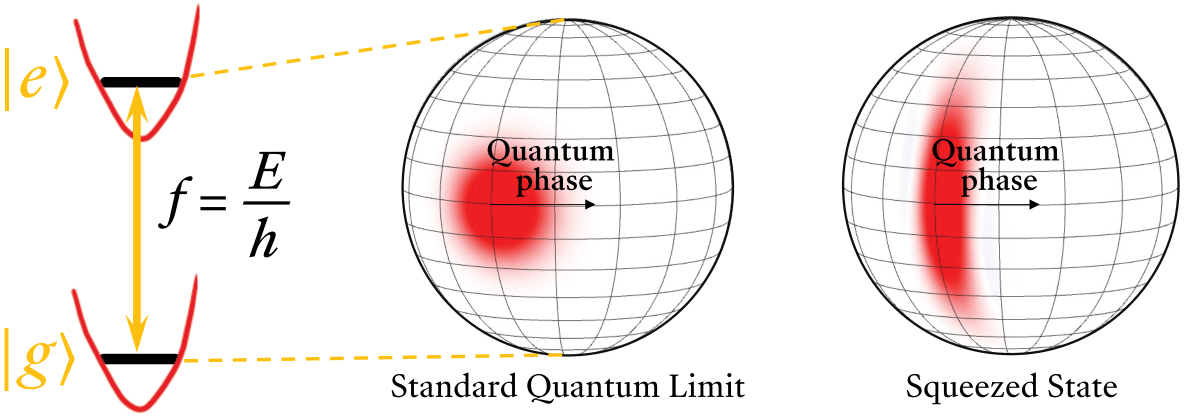
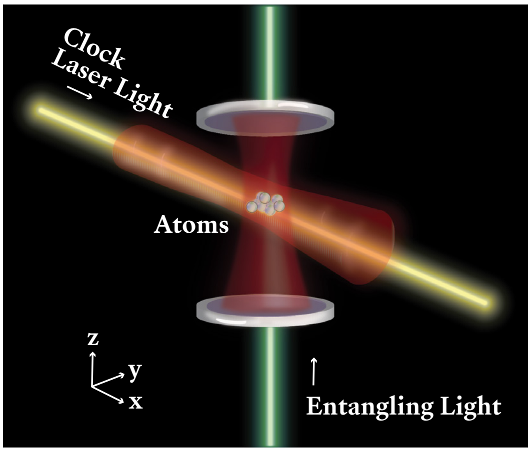


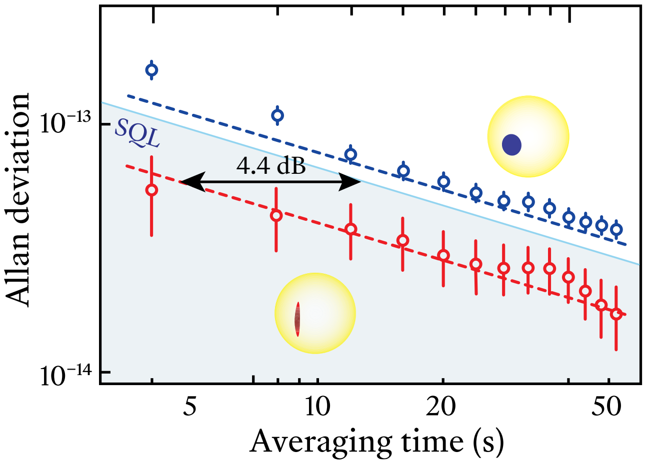
FIGURE 2:
Two-dimensional magic wavelength optical-lattice trap holding ytterbium atoms at micro-Kelvin temperature for the realization of the entanglement-enhanced optical atomic clock. (p. 38) The two atomic levels are $|g\rangle$ and $|e\rangle$, and the N two-level systems are represented on the generalized Bloch sphere as an effective total spin $\vec{S}$. The top-middle and top-right distributions on the Bloch spheres represent an unentangled state of independent atoms and a squeezed spin state, respectively. The projection noise of the final measurement, or equivalently, the Heisenberg uncertainty rules for angular momentum, impose an uncertainty in the direction of the total spin $\vec{S}$. The squeezed spin state using entangled atoms has a lower quantum noise in the phase direction, *i.e.*, enables better frequency resolution. (p. 39, on left) Experimental setup. (page 39, on right, adapted from [7]) Clock uncertainty (Allan variance) vs. averaging time, comparing a clock using as input states an unentangled state (blue) and a squeezed spin state (red), respectively. The entangled state outperforms the Standard Quantum Limit by 4.4 dB. Credit: Vuletić Group

While the direction of a classical angular momentum can in principle be measured perfectly, the quantum mechanical spin $\vec{S}$ is subject to Heisenberg uncertainty rules, which impose a non-zero uncertainty in its direction, or equivalently, a fundamental uncertainty in the measurement of the quantum mechanical phase (*Fig. 2*). This can be traced to the discrete nature of measurements in quantum mechanics. Measuring a component of a spin ½ in a superposition state $|g\rangle + |e\rangle$ is like a coin toss where only after many repetitions of the toss it is possible to access the probabilities for head or tail with some accuracy. The corresponding binomial distribution for N coin tosses (or measurements on N spin-½ particles) gives rise to the so-called Standard Quantum Limit where the precision of the experiment improves with the number of coin tosses (or particles) as $N^{-1/2}$. This is a fundamental limit on measurements with independent particles that exists even after all noise of a technical nature has been eliminated. State-of-the-art optical clocks typically operate near the Standard Quantum Limit.

However, the Standard Quantum Limit is not an absolute limit in a many-particle system if one allows for the possibility to establish quantum correlations (entanglement) between the particles. The simplest states with metrologically useful entanglement are so-called squeezed spin states [1], where the quantum noise of the spin is reduced (squeezed) in one quadrature at the expense of another quadrature that is not directly relevant to the measurement. In particular, as shown in Figure 2, one can redistribute the quantum noise from the phase quadrature (that measures time) into the S_z quadrature that to lowest order does not affect the measurement of phase or time.

Squeezed spin states had been proposed in the 1990s as a possibility to improve over the Standard Quantum Limit [1,2], but it was not until twenty years later that it became possible to entangle the quantum states





of many atoms with each other. The breakthrough was provided by laser and optical-resonator technology, when we realized that light circulating inside a resonator can be used as a messenger between atoms that can induce many-body quantum correlations in the atomic system [3]. In 2010, a group led by Eugene Polzik in Copenhagen [4] and our group at MIT [3,5] independently demonstrated the first atomic spin squeezing using light. (A method using atomic collisions in a Bose-Einstein condensate had been demonstrated a little earlier by a group in Heidelberg led by Markus Oberthaler [6], but that method is not suitable for precision experiments due to large uncontrolled collision-induced clock shifts.) We were also able to show in 2010 that a microwave clock could indeed be improved by spin squeezing, when we achieved an improvement by a factor of three over the Standard Quantum Limit.

However, those results were mainly first proof-of-principle experiments with microwave clocks that were operating far from the precision that can be achieved with state-of-the-art clocks. We then proceeded to build an apparatus that enables spin squeezing and performance beyond the Standard Quantum Limit in an optical-transition clock using ^{171}Yb atoms, one of the two frontrunner clock types in the field. In 2020 we demonstrated for the first time that an optical-transition clock can be spin squeezed and operated beyond the Standard Quantum Limit (*Fig. 2*) [7]. The step from microwave to optical clocks took almost a decade in part because, due to the 10^5 times larger energy difference between atomic levels and associated phase evolution rate $E/\hbar$, it is much more difficult to maintain entanglement in the optical domain than in the microwave domain.

Reversing time

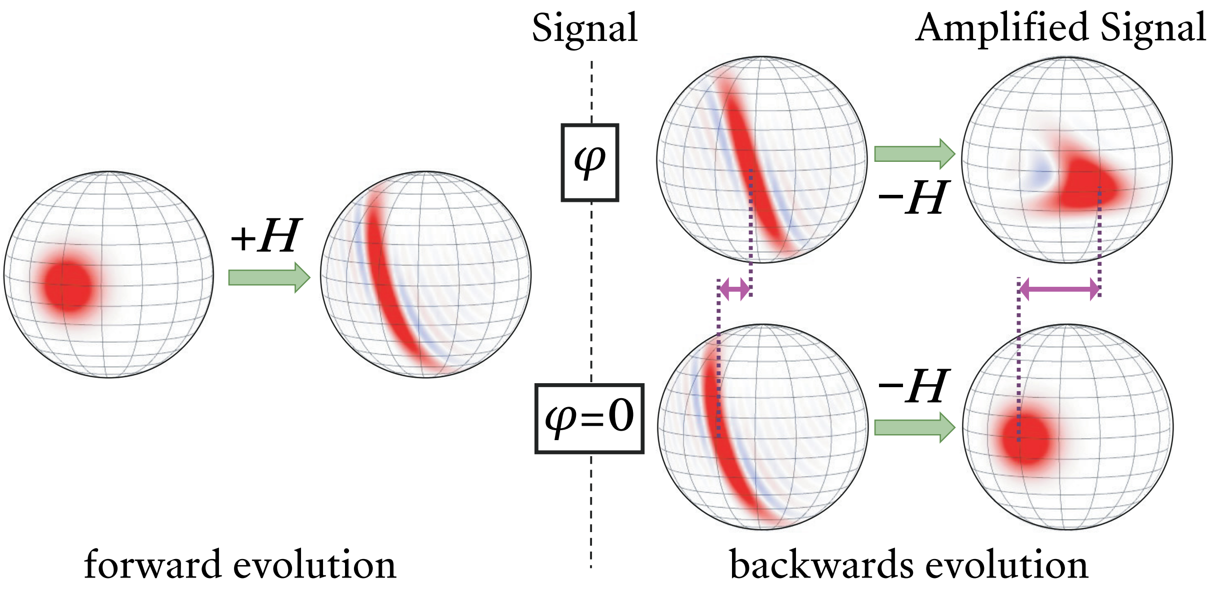
It is possible to create more complex many-body entangled states than the squeezed spin state, and such states can also potentially offer even more improvement over the Standard Quantum Limit. A particularly interesting possibility is the generation of an evolution effectively backwards in time by switching the sign of a many-body Hamiltonian H. Since the evolution of a quantum state is governed by the operator $U = exp(-iHt/\hbar)$, such a sign change from H to $-H$ is equivalent to an evolution backward in time under the original Hamiltonian H.

It turns out that this type of time-reversal process can be used for quantum metrology well beyond the Standard Quantum Limit. Furthermore, this process may potentially allow one to operate a clock close to the truly fundamental Heisenberg Limit. The latter is determined by the Heisenberg uncertainty rules for angular momentum, and sets a limit N^{-1} to the improvement of the clock precision with atom number N, as opposed to the $N^{-1/2}$ Standard Quantum Limit. For 10^4 atoms, a clock at the Heisenberg limit could outperform the Standard Quantum Limit by a factor of 100.

We have recently demonstrated such a scheme where a strongly entangled state is generated by a many-body Hamiltonian (*Fig. 3*). This state is highly sensitive to small displacements, and if such a displacement occurs, it can be made directly visible after an evolution "backwards in time" with the negative Hamiltonian. This effectively leads to an entanglement-induced signal amplification that enables operation of a quantum sensor or clock well beyond the Standard Quantum Limit, and at fixed distance from the Heisenberg Limit as we vary the atom number (*Fig. 4*). We achieve a precision improvement that is linear in the atom number, rather than improving only as the square root of the atom number. This system also yields the highest gain, by a factor of 15, beyond the Standard Quantum Limit that has been demonstrated by any interferometric device demonstrated so far.

Over the last two decades, many-body entanglement has developed from a pure basic research area to a useful tool to improve atomic clocks and other quantum sensors. Interestingly, precision clock that use entanglement have much in common with quantum simulators and quantum computers: the need to preserve quantum mechanical superposition states for long times, to perform controlled

FIGURE 3:
Quantum metrology with many-body entangled states based on time reversal. An entangled state with a strongly non-Gaussian envelope is generated by the action of a many-body Hamiltonian (*+H*). This state is then first subjected to a small displacement, and then to a negative Hamiltonian (*-H*), which generates an evolution effectively backwards in time. This results in a strong amplification of the small signal. The time-reversal protocol enables the use of highly entangled states for quantum metrology while performing a simple final measurement, removing the need for high measurement resolution.
Credit: Vuletić Group



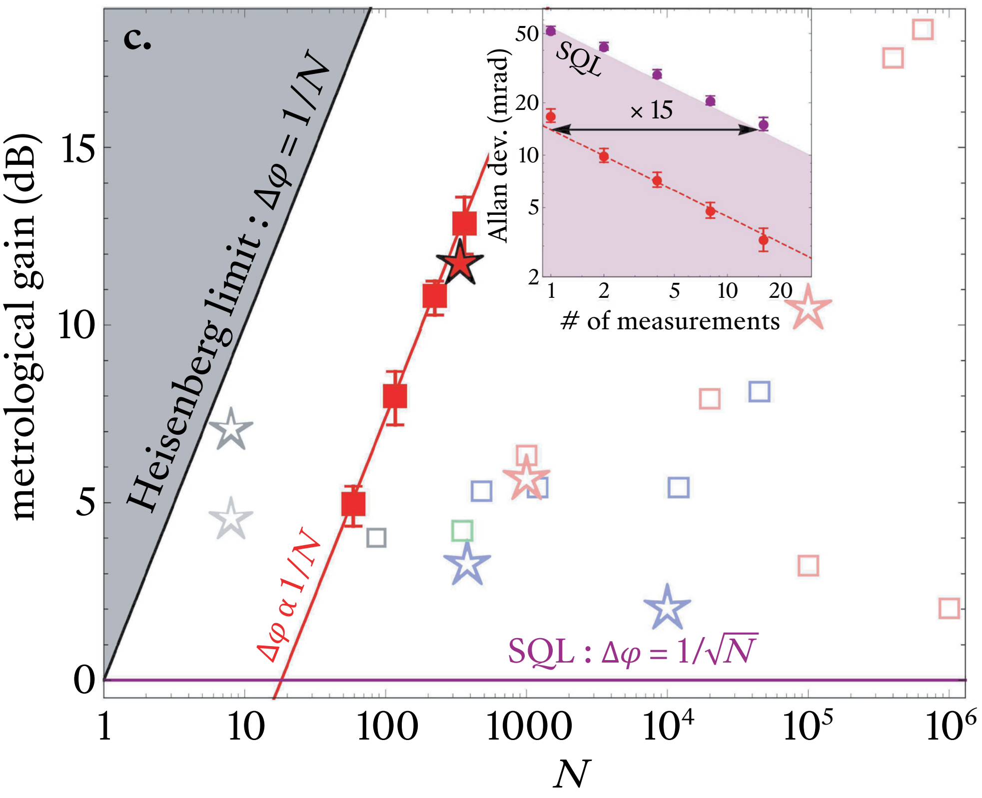


FIGURE 4:

Heisenberg scaling of sensitivity with atom number. The Heisenberg limit for phase detection, scaling with atom number as N^{-1} is shown. Filled red squares represents our experimental data showing N^{-1} Heisenberg scaling in precision, and being 12.6 dB away from the Heisenberg limit. For comparison, results from previous experiments using Bose-Einstein condensates (blue empty squares), thermal atoms (red squares), ions (black squares), and Rydberg atoms in tweezer arrays (grey squares) are shown. The stars correspond to phase measurements in a full interferometric sequence following the same color code. Our measurement (filled red star) shows the best phase sensitive beyond the Standard Quantum Limit, (11.8 ± 0.8) dB. The inset shows the clock instability (Allan variance) for phase measurement where we observe an improvement by a factor of 15 in sensitivity when compared to the Allan variance of an unentangled state. Credit: Vuletić Group

state transformations, and to utilize entanglement to achieve system properties that cannot be attained by classical systems. Compared to quantum simulators, entangled atomic clocks typically use less complicated many-body quantum states but (many) more atoms. In the past, there has been significant cross-fertilization between the fields, with ideas from quantum information science strongly influencing the development of quantum metrology.

Finally, as clocks start breaking the 10^{-20} barrier of fractional stability, gravitational effects on time need to be seriously considered: A difference in clock height of 1 mm corresponds to a gravitational red shift of 10^{-19}. Thus to compare two clocks at the 10^{-20} level, one needs to establish their relative height difference in the Earth's gravitational potential to better than 100 µm. How does one compare clocks across the United States, let alone across continents, at this level? On the other hand, with such a high precision, there may be new fundamental effects influencing the passing of time awaiting to be discovered. These include new unknown physics such as the possibility that our fundamental constants, *e.g.*, the speed of light or the fine structure constant, are changing as the Universe is expanding. Atomic clocks and quantum entanglement may thus, through a new precision window, open a glimpse into the inner workings of our world.

REFERENCES

[1] M. Kitagawa and M. Ueda, “Squeezed spin states,” Phys. Rev. A **47**, 5138 (1993).

[2] D. J. Wineland, J. J. Bollinger, W. M. Itano, D. J. Heinzen, “Squeezed atomic states and projection noise in spectroscopy,” Phys. Rev. A **50**, 67 (1994).

[3] I.D. Leroux, M.H. Schleier-Smith, and V. Vuletić, “Implementation of Cavity Squeezing of a Collective Atomic Spin,” Phys. Rev. Lett. **104**, 073602 (2010).

[4] J. Appel, P. J. Windpassinger, D. Oblak, U. B. Hoff, N. Kjærgaard, and E. S. Polzik, “Mesoscopic atomic entanglement for precision measurements beyond the standard quantum limit,” Proc. Natl. Acad. Sci. U.S.A. **106**, 10960–10965 (2009).

[5] M.H. Schleier-Smith, I.D. Leroux, and V. Vuletić, “States of an Ensemble of Two-Level Atoms with Reduced Quantum Uncertainty.” Phys. Rev. Lett. **104**, 073604 (2010).

[6] J. Estève, C. Gross, A. Weller, S. Giovanazzi, and M. K. Oberthaler, “Squeezing and entanglement in a Bose-Einstein condensate,” Nature **455**, 1216–1219 (2008).

[7] E. Pedrozo-Peñafiel, S. Colombo, C. Shu, A. Adiyatullin, Z. Li, E. Mendez, B. Braverman, A. Kawasaki, D. Akamatsu, Y. Xiao, and V. Vuletić, “Entanglement on an Optical Atomic-Clock Transition,” Nature **588**, 414–418 (2020).

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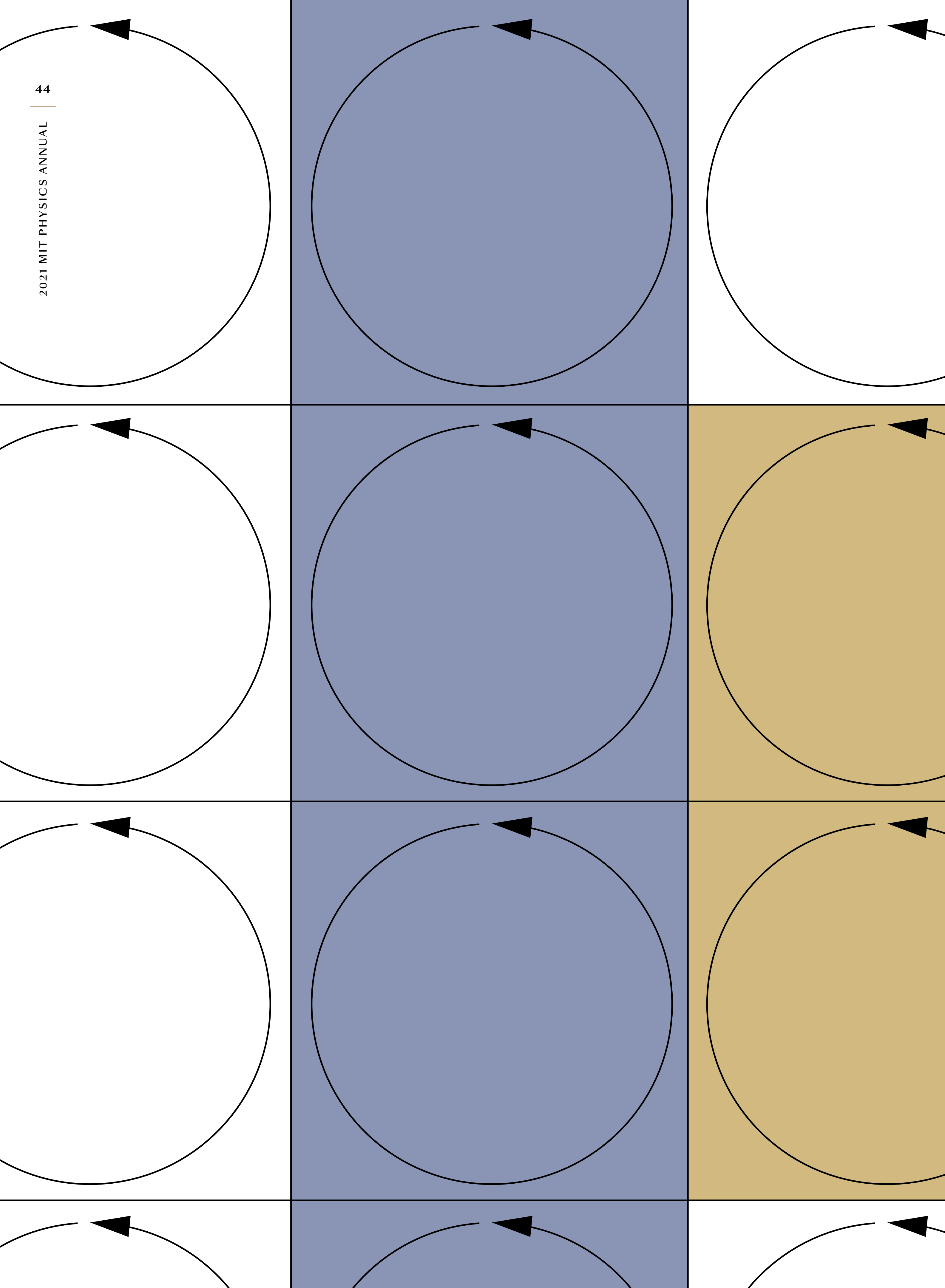
DR. EDWIN PEDROZO-PEÑAFIEL is a Postdoctoral Associate at the Research Laboratory of Electronics (RLE) and the MIT-Harvard Center for Ultracold Atoms (CUA). He combines cavity QED and atomic, molecular and optical techniques with atomic ensembles at ultra-cold temperatures for applications to quantum metrology. Pedrozo's primary goal is to create exotic quantum states to reach the ultimate limit imposed by quantum physics—the Heisenberg Limit. He is also interested in applying quantum-enhanced devices to search for new physics and the development of new quantum technologies. Pedrozo earned his undergraduate degree in Physics at the University of Atlántico in Colombia, his home country, and his PhD at the University of Sao Paulo, Brazil, where he worked with Bose-Einstein condensation to study fundamental physics.



From Quarks to Nuclei

The Building Blocks of Matter

by Phiala Shanahan

Since the 1970s, we have understood three of the four fundamental forces of nature in terms of a unified whole: the Standard Model of particle physics. This theory is elegant, symmetric and compact, and it is inarguably a triumph of modern physics.

Encoding the strong, electromagnetic and weak interactions of the 17 fundamental particles, we believe that the Standard Model describes the structure and interactions of matter at all distance and energy scales we can access, from high energy particle collisions at the Large Hadron Collider, to the decays of heavy nuclei, to the properties of matter under extreme conditions, such as in the core of a neutron star. It is also clear, however, that this theory does not describe everything that we observe about the universe; there has not yet been a successful unification of gravity (which is described by the separate theory of general relativity) into the framework, and the Standard Model does not explain other "beyond-Standard-Model" phenomena, from the masses of neutrinos to the abundant gravitational evidence for dark matter and dark energy.

In this context, direct studies of our fundamental theory serve two purposes, both complementary and entwined. First, they give us a window on the complexity of nature: Can we truly reveal the emergence of the structure of matter, explaining observations from the mass of a single proton through to nuclear reactions, neutron stars and supernovae, all from the simple rules of the underlying theory? Can we learn how sensitive the existence of atomic structure, and ultimately life, is to the free parameters of the theory, such as the masses of the fundamental particles like electrons and quarks?

Second, terrestrial experiments searching to constrain beyond-Standard-Model physics are built from protons, neutrons, and nuclei, themselves composed of fundamental particles. Understanding their structure and interactions is thus crucial to determine the necessary backgrounds and benchmarks for our searches for new physics beyond that which we understand. These questions, and their answers, reach across particle physics, nuclear physics and cosmology, and their pursuit drives a rich program of theory investigations that leverages high-performance computing at the most extreme scales.

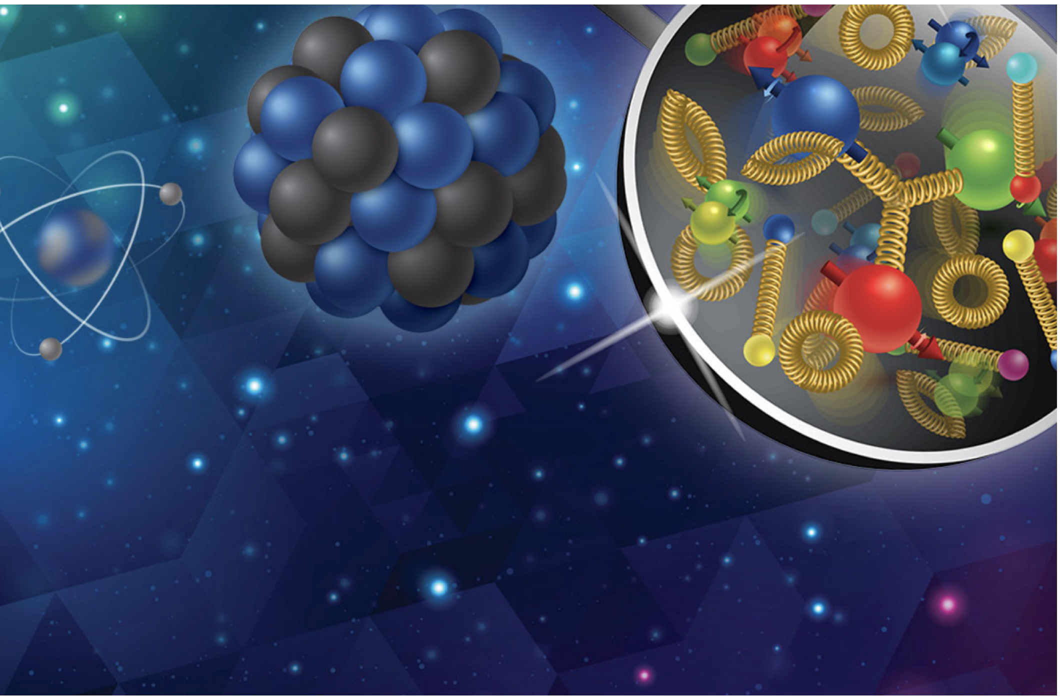


FIGURE 1:
At the core of atoms (left) are atomic nuclei made of protons and neutrons (center). The protons and neutrons are themselves composed of fundamental particles called quarks and gluons (right).
Credit: Brookhaven National Laboratory and Thomas Jefferson National Accelerator Facility

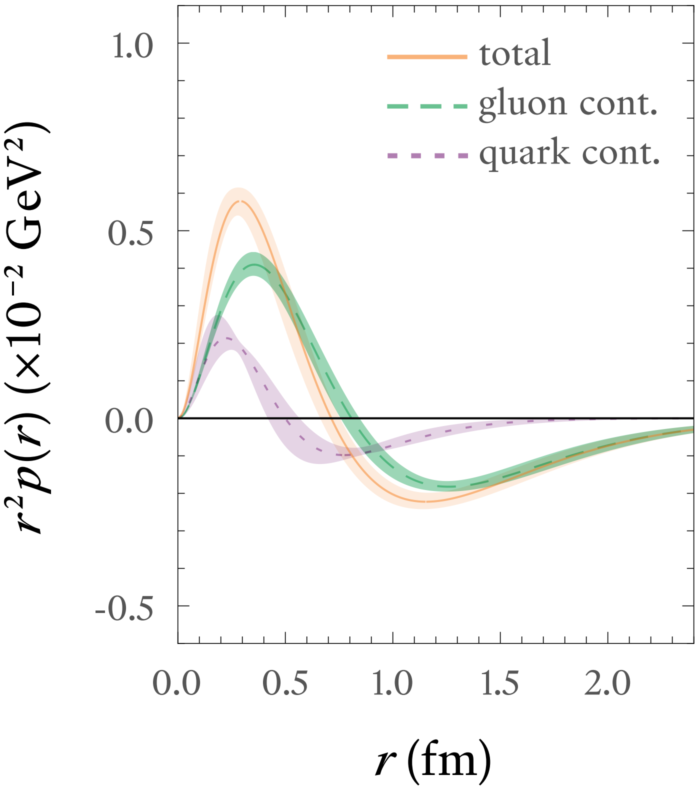


FIGURE 2:
Quark and gluon contributions to the radial pressure distribution in the proton, calculated using lattice field theory. The horizontal axis shows the radial distance from the center of the proton, while the vertical axis shows that distance squared times the pressure. This quantity must integrate to zero for the stability of the proton. Credit: Shanahan Group; Copyright: American Physical Society

Computing the strong interactions

Within the Standard Model, the strong nuclear force, responsible for binding fundamental particles called quarks and gluons together into protons and neutrons, and for binding the protons and neutrons together into nuclei, presents a particular obstacle to theory calculations. At the low energy-scales relevant, for example, to nuclei at rest in a detector, the only known systematically-improvable approach to calculation is a numerical method named "lattice field theory." Over the last 20 years, lattice field theory computations, which proceed by discretizing space and time onto a four-dimensional grid (a lattice), have become an extraordinarily powerful and versatile tool. They can accurately describe how the masses of the proton and neutron arise (and importantly for the stability of atoms, how they differ), and have been used to make predictions of the masses of new composite particles later discovered by experiments at CERN. More complicated quantities are also accessible: calculations I have undertaken with my colleague Will Detmold have revealed that the pressure generated by the quarks and gluons inside a proton is larger than that inside neutron stars, and have shown for the first time how nuclear reactions, such as the proton-proton fusion process that initiates the chain reaction that powers the sun, emerges from our most fundamental understanding of particle physics.

> “Can we truly reveal the emergence of the structure of matter, explaining observations from the mass of a single proton through to nuclear reactions, neutron stars and supernovae, all from the simple rules of the underlying theory?”

Nevertheless, there are significant limitations imposed on the lattice field theory approach by its computational demands. Even with approximately 10% of open-science supercomputing in the United States devoted to such studies, many calculations that would elucidate new details about the structure and formation of the matter in our universe remain quite simply too expensive to pursue. In particular for nuclei, the computational challenge presented by such calculations is daunting; naively, there are compounding factorial and exponential growths in computational cost with the atomic number of the nucleus under study. As a result, while direct calculations of the structure of the proton are now extremely precise, with theory calculations in some cases competitive with or better than the best experimental measurements, for nuclear physics the era of controlled calculations through this framework is only now beginning.

One concrete example of the computational challenge posed by lattice field theory for nuclear physics is offered by a recent calculation that my collaborators and I undertook, which revealed unexpectedly large nuclear effects in the scattering cross-sections of a class of dark matter candidates with the Helium-3 nucleus. While the calculation was performed with values of the quark masses larger than they are in nature (given the limitation of computing resources), it revealed that there are important corrections to the standard "Born approximation," which models the nucleus as a collection of free protons and neutrons and neglects any correlations between them. If similar effects exist in the larger nuclei, such as Xenon, used as detectors in experiments searching for direct evidence of dark matter, these corrections will have important impact on the interpretation of the experimental results. However, while we in principle know how, there is not enough computing capacity in the world to calculate predictions for the scattering of dark matter from such large nuclei directly. Matching lattice field theory calculations to models of nuclear physics, which involve protons and neutrons as the effective degrees of freedom—so-called "nuclear effective theories"—provides some information, but clearly there are compelling reasons to develop new methods that circumvent the computational limitations of lattice field theory to enable an understanding of larger nuclei directly from the Standard Model.

Faced by computational challenges of this extreme scale, the only solution is to develop novel approaches in the form of new types of computing hardware or more efficient algorithms. From custom silicon devices to quantum computing, all avenues are being pursued at MIT, but the fantastic success of machine learning (ML) and artificial intelligence (AI) in recent years across applications from the game of Go to image recognition presents a tantalizing new possibility on the algorithmic side. Can we use AI not as a black box to achieve tasks that typically require human intelligence, but in a provably-exact way to accelerate the algorithms we use in first-principles physics calculations?

New possibilities with *ab-initio* artificial intelligence

For more than 70 years, since Turing's 1950 paper, "Computing Machinery and Intelligence," asked the question: *Can machines think?*, the branch of computer science described as AI has sought to design algorithms which mimic human intelligence and learning. Whether we can use similar algorithms in a different context, to enable theoretical physics calculations that are currently computationally intractable, is one of the questions that motivates the new National Science Foundation Institute for Artificial Intelligence and Fundamental Interactions (*iaifi.org*), launched this year as a collaboration between physics and AI researchers at MIT, Harvard, Northeastern and Tufts Universities. The interdisciplinary team, which includes 12 MIT physics faculty, is developing the new field of "*ab-initio* AI": approaches to artificial intelligence

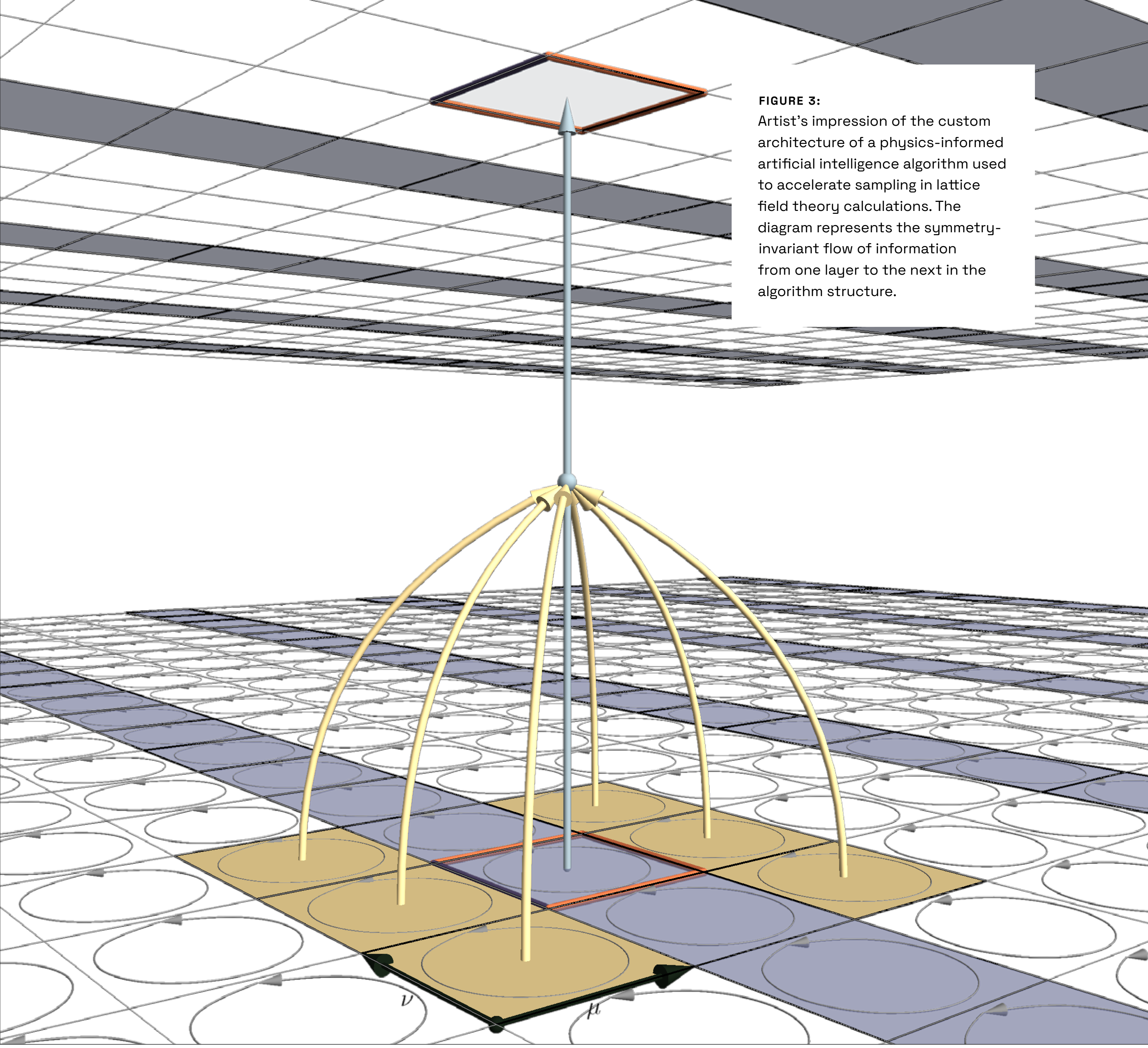


FIGURE 3:
Artist’s impression of the custom architecture of a physics-informed artificial intelligence algorithm used to accelerate sampling in lattice field theory calculations. The diagram represents the symmetry-invariant flow of information from one layer to the next in the algorithm structure.

that build in and incorporate the fundamental physics principles that underpin our understanding of the universe.

The development of *ab-initio* AI addresses the unique challenges that arise in the application of AI or ML to fundamental physics, including within lattice field theory calculations. We require calculations or analyses to obey precise principles, for example symmetries, conservation laws, scaling relations, limiting behaviors, locality or causality. We demand rigor in the computation of systematic uncertainties, as well as reproducibility, verifiability, and crucially, guarantees of exactness for applications which require them. In some cases, there might be no “training data” available with which to optimize the algorithms; generating that data might in fact be the task at hand, requiring the development of self-training approaches. All of these challenges arise in the application of AI to lattice field theory calculations of nuclei, where it is crucial to the integrity of the approach (as a direct first-principles theoretical study of our underlying theory), to maintain mathematical rigor.

Over the last few years, my group has developed provably-exact algorithms exploiting *ab-initio* AI for first-principles nuclear physics. Exciting progress has been made to address one computational challenge in lattice field theory calculations in particular: Studying physical quantities in the theory requires sampling over contributions to extremely high-dimensional integrals (over up to 10^{12} variables in state-of-the-art calculations). Developing an efficient, provably-exact, self-training approach to generate these samples that precisely incorporates all of the symmetries of the underlying strong interactions has led my group to an intense interdisciplinary collaboration with researchers at Google DeepMind. The result has been a number of groundbreaking ML algorithms that achieve results orders of magnitude faster than traditional algorithms when applied to simplified versions of the Standard Model. To impact state-of-the-art particle and nuclear physics studies, the approach must be scaled to the first exascale supercomputing systems in the United States, which are currently under construction. The new machines, named Aurora (*alcf.anl.gov/aurora*) and Frontier (*olcf.ornl.gov/frontier/*), will compute a billion billion (*i.e.*, a quintillion) operations each second, making them many thousands of times faster than a high-end desktop computer.

With exascale computing under development, the ultimate impact of AI on state-of-the-art lattice field theory calculations remains to be seen, but the novel algorithm developments that the challenge of AI for first-principles nuclear theory has inspired have already found broad interdisciplinary applications. The same work that enables ML architectures to be defined for the mathematical group structures needed in lattice field theory enables architectures to work with the angles that define the positions of a multi-jointed robot arm. The same algorithmic approaches that provide guarantees of exactness in the relevant limits of the theory are being applied to studies of molecular design and protein folding in computational chemistry. Already it is clear that the nascent field of *ab-initio* AI is only beginning to reveal its full potential.

Nuclear physics calculations at the exascale and beyond

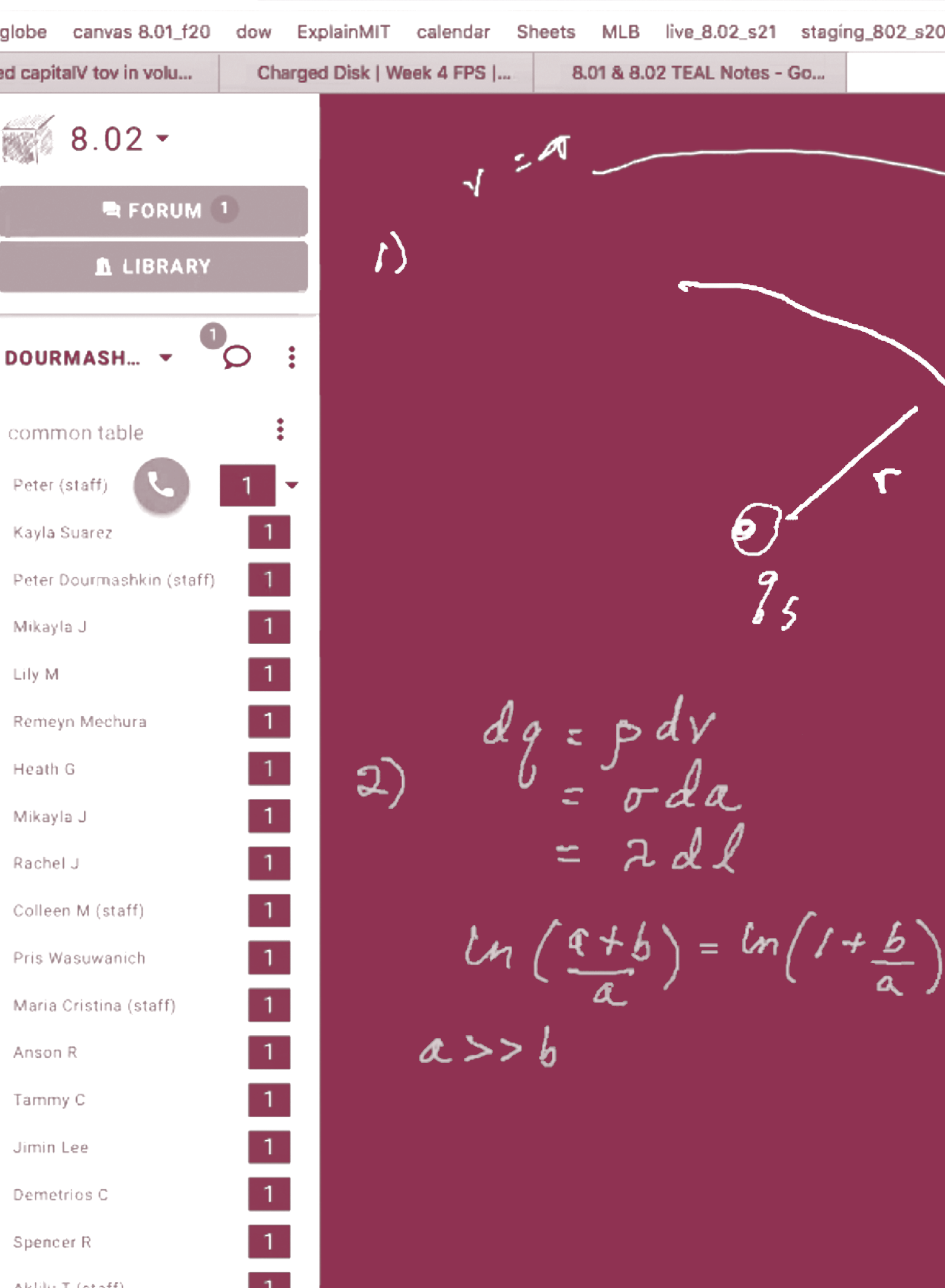
As we consider the history and future of first-principles Standard Model calculations, it is apparent that we are at a turning point: We have begun to connect the Standard Model to nuclear physics in a robust and systematically controlled way, through calculations that we are only now beginning to have the algorithmic technology, and the supercomputers, to undertake. We have recently demonstrated this potential by accomplishing the very first first-principles calculations of simple nuclear reactions, and beautiful examples of the critical role that theory input plays in searches for new physics beyond the Standard Model. Over the next decades we can expect that first-principles theory calculations will allow us to answer questions about the fine-tunings in nuclear physics that are deeply important for our existence. We will be able to see, from the underlying Standard Model, how sensitive the production of carbon in the universe via the triple-α process is to the free parameters of the theory, and to answer why we see clustering in nuclei. We will be able to compute not just the first step, but the entire chain of Big Bang nucleosynthesis reactions to understand how the elements formed in the first minutes of the universe's existence. As we continue to push the physics frontier, a new generation of provably-exact physics-informed ML algorithms promises to enable calculations that were previously intractable and to usher-in the grounding of nuclear physics in the Standard Model, as we continue our ages-old quest to understand the universe from its most fundamental building blocks.

FIGURE 4:
Aurora, currently under construction, will be the first exascale computing system in the United States. It will compute a billion billion (*i.e.*, a quintillion) operations each second. Credit: Argonne Leadership Computing Facility

PHIALA SHANAHAN is the Class of 1957 Career Development Assistant Professor of Physics in MIT's Center for Theoretical Physics. Her research is focused on particle and nuclear theory, as well as on the development of novel computational and algorithmic tools for theoretical physics.

In particular, Shanahan works to understand the structure and interactions of hadrons and nuclei from the fundamental (quark and gluon) degrees of freedom encoded in the Standard Model of particle physics. Her recent work has focused in particular on the role of gluons, the force carriers of the strong interactions described by Quantum Chromodynamics (QCD). Using analytic tools and high-performance supercomputing, Shanahan recently achieved the first calculation of the gluon structure of light nuclei, making predictions which will be testable in new experiments proposed at Jefferson National Accelerator Facility and at the planned Electron-Ion Collider. She has also undertaken extensive studies of the role of strange quarks in the proton and light nuclei, which sharpen theory predictions for dark matter cross-sections in direct detection experiments. To overcome computational limitations in QCD calculations for hadrons and in particular for nuclei, Shanahan is pursuing a program to integrate modern machine learning techniques in computational nuclear physics studies.

A native of Adelaide, Australia, Phiala Shanahan earned her BSc from the University of Adelaide in 2012, and her PhD from the same institution in 2015. In 2015–2017 she held a postdoctoral position within the MIT Center for Theoretical Physics, followed by joint appointments at The College of William & Mary (faculty) and the Thomas Jefferson National Accelerator Facility (senior staff scientist). In July 2018, Shanahan returned to MIT Physics as an Assistant Professor. Her research has been recognized with numerous awards and fellowships including Early Career Awards from both the National Science Foundation and the Department of Energy, the 2021 Maria Goeppert Mayer Award from the American Physical Society, a Simons Foundation Emmy Noether fellowship, and she was listed in Forbes Magazine's "30 Under 30 in Science" in 2017.



$V = A$

1)

r

q_s

2) $dq = \rho\, dV$

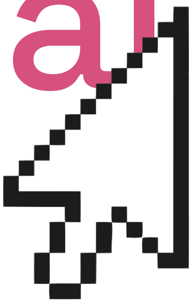
$= \sigma\, da$

$= \lambda\, dl$

$\ln\left(\frac{a+b}{a}\right) = \ln\left(1+\frac{b}{a}\right)$

$a >> b$

Remotely Educational



Teaching physics in the age of Zoom.

by Sandi Miller

In March 2020 as a campus shutdown loomed, the MIT Physics Department focused on its students. "We invited seniors outside to Killian, where staff and faculty saluted the graduates," recalls Academic Administrator Cathy Modica. "[Department Head] Peter Fisher gave a toast, [Undergraduate Coordinator] Emma Dunn created diploma-like certificates, and we laughed and cried. One senior approached me, instinctively reaching out for a hug, then remembered... but we hugged anyway. We didn't know if we would ever see each other again." Days later, students, staff, and faculty were told to pack up and leave campus.

Then-Associate Department Head Nergis Mavalvala first focused on logistics. "Initially I worried about the mechanics of online instruction. But we had tremendous expertise on those things, after years of delivering classes through MITx." Faculty with digital teaching experience set up workshops for peers. Instructors created lab kits to mail to students' homes.

With classes underway, Mavalvala then took a more holistic approach. "A bigger gap was how to support students' well-being, as well as their learning," she recalls. "We had no experience with the upheaval everyone faced, leaving campus with little notice, and regrouping online with differing personal circumstances and resources. A huge effort went into supporting struggling students. I kept pinging students to see if they were okay, to let them know, 'I care about you, I need to know you're okay.'"

The Physics Academic Programs Office located students who weren't showing up for classes; connected students to academic and personal support; and with the help of Krishna Rajagopal, MIT Dean for Digital Learning and the William A.M. Burden Professor of Physics, guided those students needing technology support.

Professor of Physics and former Department Head Edmund Bertschinger created a mentorship program for students in 8.02 (Electricity and Magnetism), focusing on at-risk students. Associate Professor Kerstin Perez later expanded it to the fall 2020 sophomores. "Ed spun it up on very short notice," says Deepto Chakrabarty, Professor of Physics and Associate Department Head. "It became a critical need during the pandemic to help students struggling with uncertainty. Kerstin laid a lot of the groundwork to train peer mentors, particularly targeting women and minority students."

Students lost summer 2020 internships, research work and full-time jobs; the Department responded by soliciting over 75 remote UROP positions to fill the gaps. Professor of Physics Marin Soljačić offered

FIGURE 1:
Physics Department leadership and staff created an *en plein air* celebration to honor its graduating seniors in Killian Court—MIT's traditional location for the annual spring Commencement. Credit: Deepto Chakrabarty

one-year research assistantships to three graduating seniors. “A simple action just at the right time can have such a large positive impact on people’s lives,” says Soljačić.

> “A simple action just at the right time can have such a large positive impact on people’s lives.”
>
> MARIN SOLJAČIĆ

With spring over, planning for fall 2020 began. The Department had to ensure an MIT-quality curriculum while demonstrating ongoing flexibility. “We were able to focus on the fall, we had time to think about it, to make MIT physics work educationally in an all-remote environment,” says Chakrabarty.

As the Department prepares to return, it may keep some of its on-the-fly solutions. “The 8.02 mentoring program and the summer UROP programs were quite successful, and I hope we will continue those,” said Mavalvala. “Asynchronous classes also had distinct advantages.”

Of course, not all the changes were keepers. “We should be honest with the challenges,” says Chakrabarty. “There are some things we simply cannot do effectively. Luckily, these things are very few. We were fortunate.”

As the new School of Science Dean, Mavalvala looks forward to ongoing debate about future online learning. “Engaging students in online learning is evolving,” she says. “I don’t think we’ve figured that out. And not having access to labs really detracted from the *manus* part of our *mens et manus* approach to education. But I’m optimistic that many of the lessons we learned will serve us well beyond this time of pandemic-driven remote learning.”

So, how did the Physics Department retool its classes for remote learning? Here were some of the approaches taken.

TEAL (Technology-enabled Active Learning)

Pre-lockdown, hundreds of first-years attended classes 8.01 (Classical Mechanics) and 8.02 (Electricity and Magnetism) at tables of nine in Building 26’s TEAL (technology-enabled active learning) classroom. These classes took a high-tech leap in 2001 (for 8.02), and 2003 (for 8.01) when John Belcher, Class of 1922 Professor of Physics, introduced the TEAL format. TEAL merged lectures, simulations, concept questions and group problems, and hands-on desktop experiments to create a collaborative learning experience. Students accessed online visualizations and simulations, lectures, problem sets, experiments and concept questions on MITx, much of which is on OpenCourseWare (OCW).

TEAL’s teaching team—eight section leaders plus lecturers, postdocs, a course manager, technical instructors and TAs—were primed to go fully remote. But it wasn’t easy.

“I remember talking with Peter [Dourmaskhin] every day to strategize, and working non-stop to get asynchronous content in place for the students,” says Physics lecturer Michelle Tomasik, who, along with senior lecturer Peter Dourmashkin, led the content review for spring 2020, fall 2020 and spring 2021 classes. Spring 2021 courses also were online. “I remember being pretty overwhelmed, but also pretty confident that we could provide a quality education to our students asynchronously and remotely.”

They were already using MITx, Dropbox, Piazza and Canvas, so quizzes were hosted on MITx. “This seemed like a perfect use of that content, mixed in with live Zoom support for students and hand grading of p-sets,” says Tomasik.

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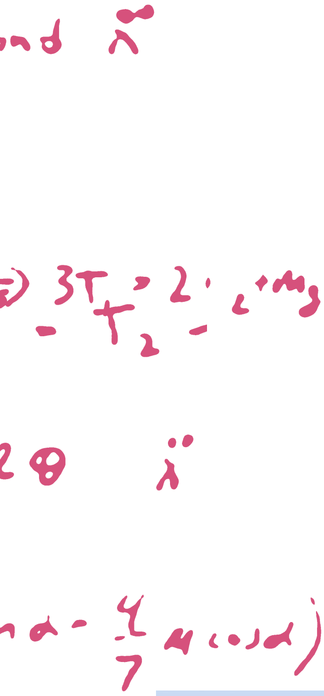
> “I’m optimistic that many of the lessons we learned will serve us well beyond this time of pandemic-driven remote learning.”
>
> NERGIS MAVALVALA



While many other classes slogged through long videos, TEAL’s were streamlined. “We were able to present a lot of short videos with short problems immediately following that helped the students practice the concept they just watched,” says Tomasik. “It was mimicking our TEAL classroom experience. We had deadlines for all those video/problem sequences to make sure people kept up to date. Starting in fall 2020, we made those problems due before the class, so that in-class problem discussion could be a review, going into greater depth for everyone. It’s more of a flipped classroom than it was before.”

FIGURE 2:
Like most, Physics lecturer Michelle Tomasik experienced Zoom overload during the extended lockdown. However, one unlooked for upside was the platform’s usefulness in hiding bouts of morning sickness during meetings, via an easy activation of Zoom’s stop-video feature. Tomasik with her second child, son Felix Cheng. Credit: Andrew Cheng

But the real gamechanger was adding the website platform *explain.mit.edu*, developed by Elton Lin ’20, hosted by MIT and serving about 1,000 active users, including 8.01/8.02 students. Akin to Zoom on steroids, it’s designed to consolidate the learning process with uploaded materials and archived Q&As. An online blackboard with audio and video offers collaborative workspaces for small groups; p-set lounges for quick meetings with the teaching team; and problem set collaborations with peers.

During a typical Friday problem-solving workshop, Dourmashkin starts with slides, and then sends students into breakout rooms per group assignments. He and TAs visited rooms to comment on p-sets, pulling up a digital whiteboard to illustrate a point. For whole-class announcements, he pulls everyone back. Dourmashkin says the hands-on teaching is key to generating excitement about physics.

“There are three important things that teachers generally do: You can deliver information; be a motivator; and be someone who can bring closure to any discussion,” says Dourmashkin. “A lot of the work today is to motivate the students that they can successfully learn physics.”

Because 8.02 students aren’t sitting at tables with equipment, postdoc Alex Shvonski and technical instructor Joshua Wolfe led a team to assemble a kit for electricity and magnetism take-home design experiments, funded by a J-Wel grant.

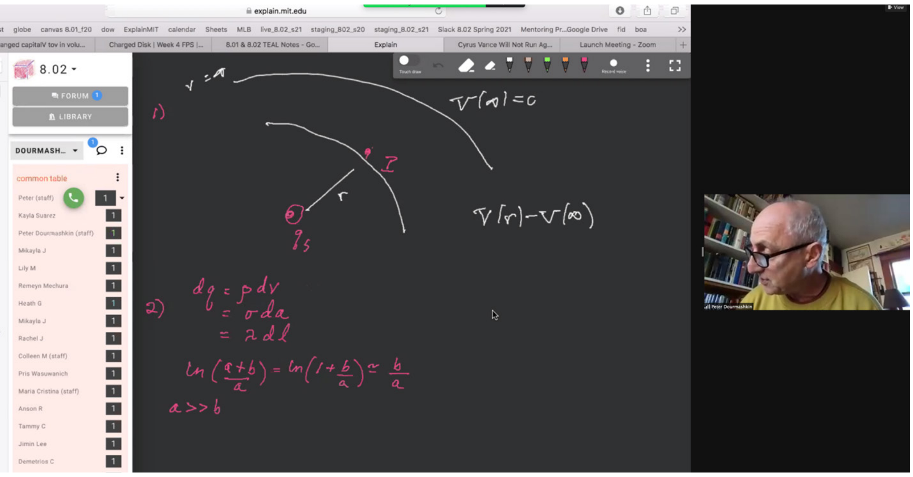


FIGURE 3 (LEFT): Physics Senior Lecturer Peter Dourmashkin teaching 8.01 and 8.02 (TEAL) on website platform *explain.mit.edu*. Developed by Elton Lin '20, the platform hosts an online blackboard with audio and video, and offers collaborative workspaces for small groups, as well as p-set lounges for meetings with the teaching team and problem set collaborations with peers.

FIGURE 4 (BELOW): Junior Lab's home lab kit includes (a) two pocket-sized "CosmicWatch" cosmic ray muon detectors, developed by student (now LNS postdoc) Spencer Axani, and (b) a Red Pitaya STEMLab board—a programmable signal generator and digitizer. Credit: Sean Robinson

Designed to build four basic experiments that test fundamental physics concepts, each kit includes wires, LEDs, magnets, 3D-printed LEGO pieces and a microprocessor used as a multimeter among other functions.

For fall and spring 2021, TEAL began grading attendance because participation in concept questions and group problems is essential. Says Tomasik, "There are several students who don't turn on their camera, but at least they do interact with each other because they are collectively working on a problem on an online whiteboard."

Junior Lab

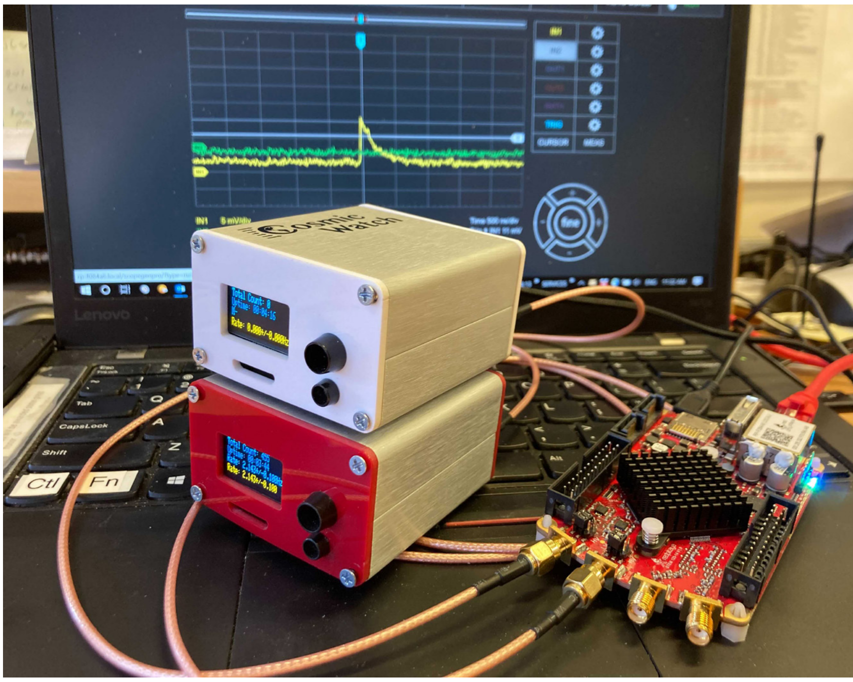
On March 13, 2020, Professor of Physics Gunther Roland was on his way to Taiwan, and Dr. Sean Robinson '99, PhD '05, Junior Lab Manager and Physics Lecturer, was at home rigging a workstation on a card table with equipment borrowed from the lab. Several students retreated to rural cabins; others reoriented themselves in various global time zones.

Roland and Robinson reinvented 8.13: Experimental Physics I ("Junior Lab") on the fly, and arranged for Cambridge-area staff to maintain lab equipment. Most 8.13 students were halfway through their first experiment before leaving campus, so they were told to just write up whatever data they had. Several planned projects were scrapped because they required hands-on access to the lab. The staff considered installing small robot arms to remotely rotate knobs, but quickly deemed it impractical. A few projects continued as planned with remote operation.

"There was lot of good will from the students, especially once they knew it was pass/fail grading," says Robinson.

But Junior Lab is not just about awesome experiments, it's about turning a physics student into a physicist. And they discovered that remote learning actually worked well for them.

"Collaboration is a really important part, and that can be practiced in a purer form



when practiced remotely," says Roland. "It was, of course, a very confusing time in terms of my personal life, but in terms of Junior Lab I saw it as an exciting challenge."

In July 2020, they learned few students would be on campus in the fall, so they brainstormed ideas for a shippable lab kit. It would include a Red Pitaya STEMLab board (a programmable signal generator and digitizer) and two pocket-sized "CosmicWatch" cosmic ray muon detectors, developed by graduate student Spencer Axani (now an MIT Laboratory for Nuclear Science postdoc). "These are very cute home-built things," says Robinson. But they are also professional-quality particle detectors, that needed to be assembled quickly. "We're building the resistors and the capacitors and the scintillators. We're drilling the holes. This is all in August [2020]. We needed to get these kits out before the September 15 exercises. Spencer is working full-time helping us build the kits. He's one of the heroes here."

Some kits were distributed to on-campus students in Killian Court, while MIT helped figure out how to ship others across the U.S. and to several countries with varying legal restrictions. It turns out you can't send nuclear particle detectors to certain parts of the world, so some student experiments needed customization. Shipping lags shifted lesson plans.

Another strategy was remote-controlled experiments. The lab's two-qubit NMR quantum computer could be run online. The Green Building's rooftop radio dish could

remotely make a radio map of the Milky Way (when either the VPN was working, or MIT Radio Society members made it past campus Covid-19 protocols to maintain the dish).

Other experiments could be performed in the actual lab, via "zombie" staffers. "At first, we started joking that we could be in the lab and turn things on, being controlled by the students remotely while wearing Go Pros, like robots," says Robinson. But then they developed procedures to go into the lab for their students to make small changes, record responses and offer feedback. "On Slack, students could ask, 'Can you turn the amplifier to 7?'"

Another longtime back burner item finally went live: pure computational projects, where pairs of students would analyze "big data" sets and computational models. Using publicly available data, instructors would help students replicate Nobel-level discoveries, from LIGO's detection of two black holes colliding, to the Higgs boson observation at the LHC. "These are billion-dollar experiments, much more complex than what we can do in the lab," says Roland.

For spring 2021, 8.13 remained a remote class as it was in fall 2020, but 8.14 would be taught as an in-person lab subject—reopening after 356 days without students. There is social distancing between lab partners and lab staff standing nearby, checking in via Slack. Most communication is from a distance, but when physical intervention is needed, "They back up from the bench, I go up to the bench," Robinson says. "It's a ballet."

FIGURE 5 (LEFT):
Junior Lab students returning in March 2021, 356 days post-lockdown. Credit: Sean Robinson

By now, most of the lab experiments can be operated remotely, in addition to the take-home kits and data analysis projects. "It's running pretty smoothly," says Roland. "We have settled into a bit of a routine operation."

With the switch to remote learning, Roland and Robinson saw improved communication, especially using Slack channels set up for different functions within the class, Zoom for group and class discussions and Dropbox Paper for online notebooks.

"You kind of forget you're typing in a chatroom; it feels like a conversation," says Robinson. "There are tone changes. The shy ones, when they are in the Slack channels to discuss tech issues, are writing like Dickens."

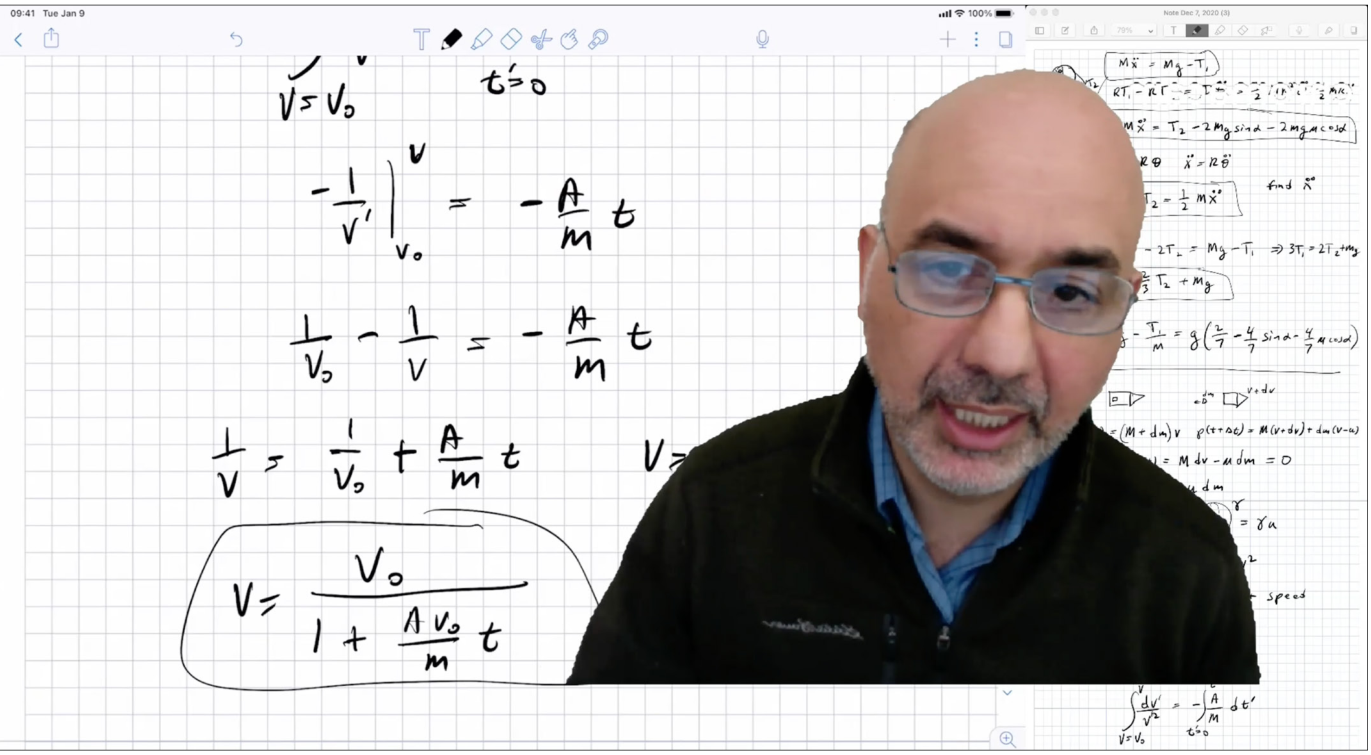
Adds Roland, "Before, there were lab sessions twice a week and the students were pretty busy doing their experiments. Now, the actual performance of the experiment is decoupled from the discussion time. I think it's a very nice change, but it's not so clear how we're going to preserve that when we go back."

Upper-Level Classes

When Professor of Physics Ray Ashoori, Division Head for Atomic, Biophysical and Condensed Matter Physics, and Professor of Physics Iain Stewart, Director of the Center for Theoretical Physics, were faced with shifting to online teaching, they tapped into their primary physics skills: innovation and curiosity.

Ashoori was lecturer for 8.022 (Electricity and Magnetism) in spring 2020. To quickly transition, he found YouTube videos to replace the in-class demonstrations, including some from the Department's in-house lecture demo group, the TSG (Technical Services Group, led by Andrew Neely).

On Zoom, he was frustrated when he ran out of virtual chalkboard space. "In a classroom, I can write on six chalkboards, and the students can refer back to prior boards," he says. Ashoori found that by pairing his



computer and iPad with free OBS Studio software, he could display several screens to show himself talking, while displaying his work and previous pages of notes. Zoom-in functions could then emphasize as needed. “This is kind of like having multiple chalkboards, and that way you don’t end up having to scroll up and down all the time to show the students what you’re doing,” says Ashoori.

In another window he opens Notability, which combines handwriting, typing and photos. He syncs this via iCloud from his iPad so that he can project prior pages on the screen and uses the ChromaCam desktop webcam application so that his face and upper body float on the screen, and he can move his image around for emphasis. GitHub’s OBS Virtual Camera plugin lets him stream his OBS output to a virtual camera source to view on Zoom. “I actually often keep the image of myself mirrored so that I can then use my left hand to do cross products without getting confused myself.”

But Ashoori also likes Zoom for being able to talk and post problem sets at the same time, and seeing student names under their faces. “I like that I’m at my computer and can quickly pull things up in response to student questions,” he says. “I can do things, like cut and paste, that I can’t do on the blackboard.” But much of the interaction still feels the same as in real-time, he says. “I feel that I get just as many questions in the Zoom classroom as I did in person.”

Meanwhile, Iain Stewart was teaching 8.851 (Effective Field Theory) and its MOOC version on edX. “I was surprisingly well-prepared,” says Stewart about his remote-teaching shift.

FIGURE 6 (ABOVE):
Professor Ray Ashoori in action within his 8.022 virtual classroom, using OBS Studio software to create an enhanced blackboard-style lecture.

FIGURE 7 (RIGHT):
Professor Iain Stewart’s home office setup “after a flurry of March 2020 purchases,” he says. “I use the built-in laptop camera for teaching and the camera at the top for all my other non-teaching meetings. The image on the central tablet is some of my 8.851 lecture notes.”

During the early days of the lockdown he became the Department's remote-learning guru, including leading a Zoom-based faculty meeting to share tips on using Zoom, video editing, tablets, and MITx and edX. He later created a Piazza discussion forum, "8.Online-Edu," to share ideas.

> "We're not going back, we're going forward."
>
> IAIN STEWART

For 8.851's end-of-term video project, students presented during an all-day online session that accommodated different time zones. "We had students from the U.S., Iceland and Europe logging in over Zoom for eight hours, which was exhausting, but being able to do things like that opens up possibilities."

For Stewart's fall 2020 8.309 (Classical Mechanics III) course, he used Notability, moved his videos from a YouTube channel to the simpler Panopto, and dropped Stellar/Learning Modules in favor of Canvas for hosting the course and for exams. "Graders can mark up student solutions directly on a tablet and it's saved back in Canvas."

He has also been tinkering with Gather Town to encourage student interaction. "How do you simulate the experience of a student running into another student in the Physics common room, and then chatting about their homework?"

Stewart estimates that remote teaching takes 50 percent more of his time. "I can't just walk into a classroom with the knowledge in my head," he says. "Setting things up just takes longer."

For future classes, he'll keep Canvas, and he loves the option of teaching remotely if, say, he's at a conference. "We're not going back, we're going forward."

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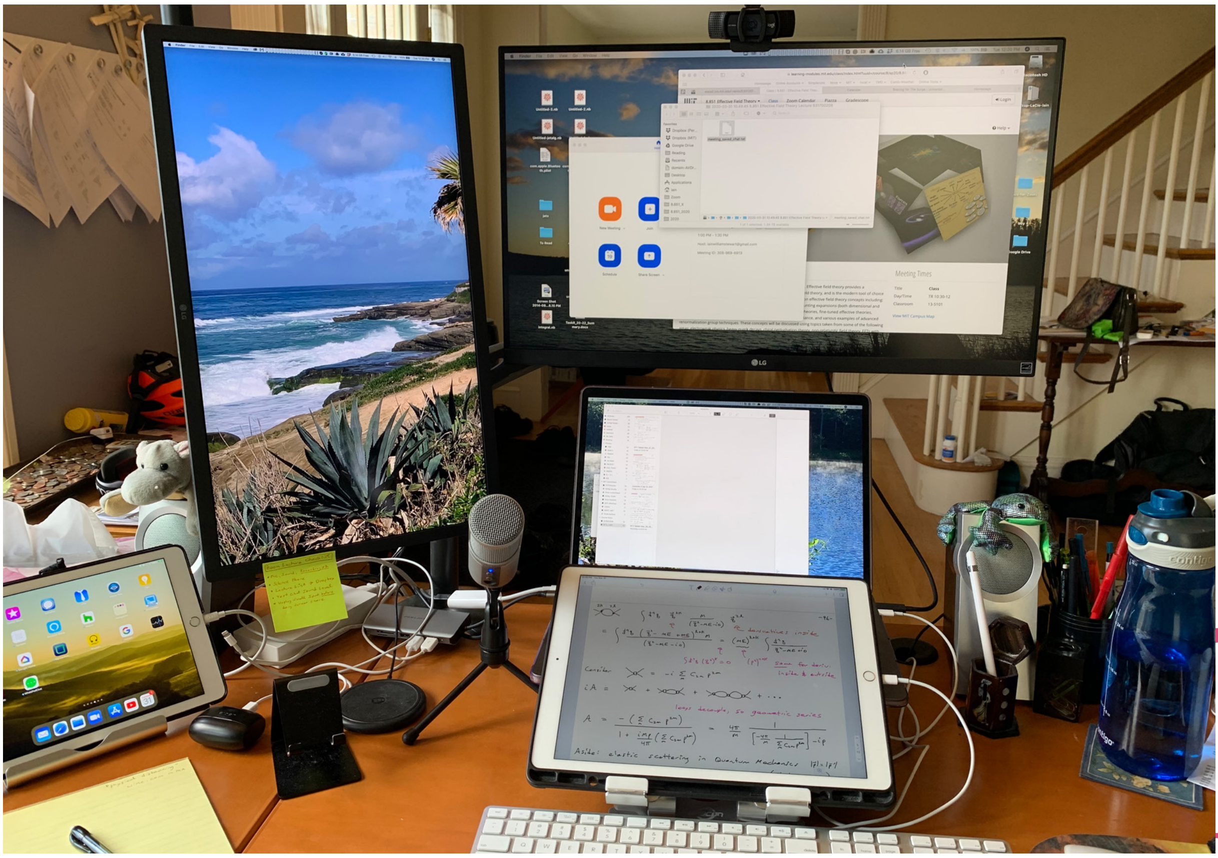

Alumni Notes

’61

Stephen Salomon (SB. Thesis advisor: Wayne Nottingham) is looking forward to his 60th Reunion via Zoom, and enjoys discussing preparations with fellow alumni, as well as topics such as climate change. During the lockdown, Steve sadly could not visit his daughter, a journalist based in Israel focused upon Middle Eastern peace issues. He misses his three grandchildren and tries to stay connected via WhatsApp. Steve is chair of the Landscape Committee of his condo and neighborhood association in Portland, Oregon. He thanks Heaven his wife is still active, and helps his son, a PhD candidate in urban studies, to integrate environment and neurodiversity.

Ronald Sundelin (SB; PhD *Physics*, Carnegie Institute of Technology. Thesis advisors: John King, Francis Low) has been working on improving airline safety by reducing angle-of-attack information unavailability caused by bird strikes (U.S. Patent); preventing boat lift collapse caused by accelerated galvanic corrosion (U.S. Patent); calculating Covid-19 travel distance as a function of droplet size and wind speed (unpublished); and calculating Covid-19 herd immunity thresholds as a function of virus reproduction rates (unpublished).

’64

Kenneth Brecher (SB; PhD ’69. Thesis advisor: Philip Morrison) is a professor of astronomy and physics emeritus at Boston University, where he has been on the faculty for 42 years. Recently, he has been designing “scientific wonders and curiosities”–physical objects that combine physics and mathematics (see *siriusenigmas.com*). In January 2021 he was awarded a U.S. Patent for the “DeltaCELT,” a chiral spinning object (a celt or rattleback), which is based on the fundamental dynamical constant delta ~ 4.6692.

Verne Jacobs (SB. Thesis advisor: John Slater) retired from the Naval Research Laboratory (NRL) in September 2017, where he was a research physicist in the Materials Science and Technology Division. Verne remains connected to the NRL through the voluntary emeritus program, continuing to work remotely after his recent move to Los Angeles. Further, he still collaborates with colleagues on papers in atomic physics and condensed matter physics, with an emphasis on non-liner optical and quantum optical phenomena. Verne notes he has carried out theoretical research based on a reduced density matrix approach. As well as attending a few scientific meetings, Verne maintains contact with a few of his former MIT classmates.

’67

Rick Dower (SB; PhD ’78. Thesis advisor: Hale Bradt) gave a webinar, “Neutrinos: Mystery and History,” on the history of neutrino ideas and experiments, to a national audience of high school teachers as part of a QuarkNet program. He also conducted a Zoom workshop for Boston-area physics teachers to accompany a QuarkNet short course on particle physics, sponsored by Fermilab.

’68

Owen Franken (SB) was the photo editor of *Technique*, and often worked for *Technology Review*. As a student, he took a leave of absence to travel as a photographer for the anti-Vietnam war campaign of Gene McCarthy. After graduation, Owen worked on visible light waves (textbook publishers, photojournalism worldwide, travel and culinary work), moving to Paris in 1988. For interviews, articles, “photos of the week,” and videos, visit *owenfranken.com*. [Editor’s note: Don’t miss it; truly outstanding work!]

’69

George D. J. Phillies (SB *Physics/Biology*; SM ’71, PhD ’73. Thesis advisor: Rainer Weiss) completed an affordable freshman physics book, *Physics One*. It’s a calculus-based, college-level text: students must solve problems by using symbolic reasoning, not by plugging numbers into calculators. The content includes mechanics and harmonic oscillators, and provides a unique set of “non-cookbook” lab exercises. Upcoming projects are two review volumes on polymer dynamics.

Benjamin Rouben (PhD. Thesis supervisor: Arthur Kerman) is still doing a fair bit of teaching, continuing as adjunct professor in nuclear science and engineering at both McMaster University and the University of Ontario Institute of Technology. His classes cover nuclear science, reactor physics, reactor kinetics, nuclear fuel management, and nuclear power plant operation. He is also Secretary/Treasurer of the University Network of Excellence in Nuclear Engineering (UNENE), and teaches graduate-level courses for UNENE. He finds the only real change is that all of the above, plus conferences/events, were hosted online.

’71

Timothy Maloney (SB. Thesis advisor: Daniel Kleppner) In preparation for 50th reunion events, Timothy wrote a piece for the 1971 reunion album on how MIT physics and other undergraduate events influenced his career long-term. The essay is listed as “Tim_Maloney-MIT_71” at *sites.google.com/site/tjmrand/documents*.

’72

Stephen Perrenod (SB. Thesis advisor: Philip Morrison) is an analyst and consultant at *OrionX.net*, assisting startup companies in the U.S., Europe and Asia in the fields of quantum computing, AI and cryptocurrency. He and his wife welcomed the arrival of their second son this past June.

’76

Eric Bogatin (SB. Thesis advisor: John King) is launching a fourth career track, as a professor in the EE department at the University of Colorado, Boulder. He transitioned from full-time at Teledyne LeCroy, where he remains a Fellow and signal integrity evangelist. Eric’s latest textbook on transmission lines was published by Artech and his newest science fiction novel is available on *amazon.com*. He graduated his first two PhD students last year, and claims to be looking forward to “warping many new young minds.”

’77

Sidney Redner (PhD. Thesis supervisor: Eugene Stanley) was awarded the 2021 Leo P. Kadanoff Prize of the American Physical Society for “leadership in transcending traditional disciplinary boundaries by applying and advancing deep concepts and methods of statistical physics to gain novel insights into diverse real-world phenomena.”

Dan Seligson (SB; PhD University of California, Berkeley. Thesis advisor: Michael Feld) co-authored a paper with historian Anne McCants (*Journal of Institutional Economics*, January 2021), the result of a four-year collaboration on dynamical systems theory of the coevolution of the economy and its institutions, providing insights to understanding the distribution of wealth among nations. A second paper has been accepted by *Social Science History*, spotlighting the role of family structure and marriage law on macro-scale social and economic development.

’81

Jim Pekar (SB. Thesis advisor: William Bertozzi) is manager of the F.M. Kirby Research Center for Functional Brain Imaging at Kennedy Krieger Institute, and professor, Russell H. Morgan Department of Radiology and Radiological Science, Johns Hopkins School of Medicine. Lately he has been studying brain/stomach synchronization, by mapping brain fluctuations with MRI, while using concurrent electrogastrography to monitor the gastric rhythm. This approach reveals multiple brain networks phase-locked with the intrinsic electrical rhythm of the stomach, implying communication between the enteric nervous system and several brain circuits not typically considered responsive to gastric state.

’84

Philip Kaaret (SB. Thesis advisor: Philip Morrison) was principal investigator on NASA’s HaloSat, the Astrophysics Division’s first CubeSat. HaloSat re-entered the atmosphere on January 5, 2021, after 2.5 years on orbit. The mission proved that “great things can come in small sizes,” as the tiny, cost-effective satellite helped understanding of how matter cycles in and out of galaxies. (Visit *go.nasa.gov/2Xclxsb* for more details.)

’85

Nuri Dagdeviren (PhD. Thesis supervisor: Arthur Kerman) continues at Microchip Technology in the San Francisco Bay Area. He is responsible for Microchip’s Secure Products business.

’87

Vanderlei S. Bagnato (PhD. Thesis supervisor: David Pritchard) and his group have developed new methods for the decontamination of organs for transplantation using photodynamic action, as well as investigations for the treatment of resistant pneumonia with photonic methods and using external body illumination. They have advanced the investigation of quantum turbulence in Bose-Condensate atoms, in single species and in double species.

Howard Branz (PhD. Thesis supervisors: David Adler, John Haggerty) is growing his early-stage renewable and sustainable energy technology assessment and R&D consulting business from his home in Colorado. Branz Technology Partners’ clients include startup ventures, investors, R&D labs and government agencies. Howard’s MIT research on thin-film semiconductors led to a wide-ranging R&D career at the National Renewable Energy Lab, including discoveries and inventions used in the expanding crystal-silicon PV industry. He broadened his perspective on the energy future while serving as a second-wave ARPA-E program director from 2012–2015. As ever, Howard looks forward to the start of backpacking and mushrooming season in the Rockies.

Gregory Francis (PhD. Thesis supervisor: Abraham Bers) was awarded the Robert A. Millikan Medal from the American Association of Physics Teachers. This award recognizes educators who have made notable and intellectually creative contributions to the teaching of physics.

’90

Jim Schwonek (SB. Thesis advisor: Daniel Kleppner) continues his work in FinTech at JP Morgan Chase & Co., involving infrastructure engineering and deployment with a future push to put infrastructure as a service (IaaS) into the private cloud. Jim and his wife have relocated to suburban Tampa, Florida. Sadly, they lost two 15-year-old cats (Abigail and Twinkii) to old age, but recently adopted two kittens, Aimy and Violet, to be with them for the next decade.

’96

Peter Unrau (PhD. Thesis supervisor: Xiangdong Ji) is a professor in the Department of Molecular Biology and Biochemistry at Simon Fraser University, Canada. His group has recently developed cutting-edge fluorogenic RNA aptamers that enable a broad range of single-molecule RNA imaging approaches. These RNA Mango tags have many applications for the study of RNA within living cells. The group has also evolved an RNA polymerase made entirely from RNA that has many of the features of extant bacterial RNA polymerase enzymes.

’00

Jesse Wodin (SB. Thesis advisor: Peter Fisher) After some years working in neutrino physics in the San Francisco Bay Area, Jesse is now running the applied sciences group at SRI in Boulder, CO, a non-profit R&D institute. They conduct applied R&D in space-based optical communications, RF photonics, radar, navigation, precision timing systems and quantum sensing. SRI is always on the lookout for MIT grads, and Jesse affirms that Colorado is great for the outdoor lifestyle.

’02

Teresa A. Fazio (SB. Thesis advisor: Ulrich Becker) published her first book, *Fidelis*, a memoir of her service in Iraq and its aftermath. She recently moved back to the Boston area and now works as a ventures officer at MIT Lincoln Laboratory, where she focuses on finding civil and commercial applications for technologies originally designed for national security.

’03

Joshua Jackson (SB, *Physics and Mathematics*. Thesis advisor: David Pritchard) had a crazy year, starting two companies in February right before the lockdown, but now both are flourishing. His teams are developing a new accelerated testing system for rapidly evaluating hydrogen embrittlement and other cracking mechanisms at U.S. Corrosion Services, and developing a new coating for corrosion prevention at Metallum Tech. This coming year they will be working on getting both accepted in various regulatory bodies as certified options for testing and coating, as well as publishing papers on these new methods.

Alex Wissner-Gross (SB *Physics/Electrical Science and Engineering/Mathematics*. Thesis advisor: Bolek Wyslouch) most recently has published papers on new methods for computationally reconstructing electrocardiogram lead placement; tamper-proofing imagery from distributed sensors using blockchains; and self-supervised learning of sparse graph representations. Visit *alexwg.org* to learn more.

’10

Amanda (**Levy**) **Ryzowy** (SB) lives in Williamsburg, Brooklyn, NY, with her husband Joel and two children, Rafa (2) and Camille (3 months). She works in real estate private equity, investing and helping create workforce and affordable housing throughout the country.

’12

Teppo Jouttenus (PhD. Thesis supervisor: Iain Stewart) continues to work at Kepler in Rwanda, where he took on a new role as the Chief Innovation Officer. This past year, his efforts focused on building an eight-week Graduate Employment Program in Ethiopia that teaches vocational school graduates professional skills needed in the workplace. He has also been building the data team and analysis frameworks to improve Kepler’s academic and employment outcomes in Rwanda and Ethiopia.

’15

Kelly Kochanski (SB *Physics/Earth, Atmospheric and Planetary Sciences*) recently finished her PhD in geological sciences at the University of Colorado, Boulder, where she spent winters watching blizzards and summers modeling the impact of wind-blown snow on polar climate change. She is now working on climate analytics at McKinsey & Company in Denver, and glad to be staying in climate science and in Colorado!

Prajwal T. Mohan Murthy (SM. Thesis supervisors: Joseph Formaggio, Richard Milner) notes that after five years of collecting data, the neutron electric dipole moment search experiment at ETH Zurich’s Paul Scherrer Institute reports the world’s best measured value (*Phys.Rev.Lett*. 124, February 2020). The experiment also sets the world’s best constraints on axions, neutron oscillation and Lorentz violation, besides constraining neutron charge and lifetime using novel techniques.

’17

Alexander Ji (PhD. Thesis supervisor: Anna Frebel) joined the Astronomy and Astrophysics Department at the University of Chicago in Summer 2021 as an assistant professor, where he will pursue a research program in near field cosmology.

’20

Alfred Zong (PhD. Thesis supervisor: Nuh Gedik) received a Springer Theses Award for outstanding PhD research. An experimental condensed matter physicist, he is now a postdoctoral fellow at the University of California, Berkeley.


Massachusetts Institute of Technology
Thomas
Frank
'77 (VIII), PhD '85 (VIII)
MIT Massachusetts Institute of Technology
Peter
Fisher
Department Head of Physics

Peter Fisher appointed the inaugural Thomas A. Frank (1977) Professor of Physics

by Elizabeth Chadis

Yes, it was a tough year, but it wasn’t all bad. In early 2021 Peter Fisher, Head of the Department of Physics, was named the Thomas A. Frank (1977) Professor of Physics, a newly-endowed Chair made possible by the generosity of Tom Frank. When asked how it felt to be a Chair holder, Peter replied, “I like it. I like that I actually know Tom and I do feel honored to be the Thomas A. Frank (1977) Professor of Physics.”

ABOUT THE SAME AGE, Tom and Peter grew up on different U. S. coasts, Peter in Marin County, California, and Tom in Staten Island, New York. Both men share a love of programming, computers and ultimately, physics.

As youngsters, both Peter and Tom played with early hobbyist computers. Peter had an HP-65 programmable handheld calculator and thrilled to the magnetic cards that allowed him to program. Tom had a Rube Goldberg machine, a DigiComp I (*Fig. 2*) that fired his imagination, and still has his battered and worn PDP-11 handbook. (Tom and Peter agree that DEC’s PDP-11 was the best 32-bit computer ever made.)

FIGURE 1:
From left: Tom Frank (1977) and Physics Department Head Peter Fisher. Credit: MIT Physics Department

Tom decided in the sixth grade he would attend MIT when he grew up, and did so. He completed an SB, then a PhD under the supervision of Professor Dick Yamamoto. Peter applied to MIT after reading a *Technology Review* article on MIT's hunt for the Loch Ness Monster,[1] but he did not get in, so instead attended the University of California, Berkeley, and studied engineering physics, although he was really more interested in computing. This love of computers led him to high energy physics. Why? "Because they had the best computers."

At MIT, Tom checked out the Center for Theoretical Physics and although he developed a relationship with Francis Low, he ultimately chose experimental particle physics, spending lots of time at Fermilab where he found that "They still believed it was 1945—that physicists could do everything." At other labs like CERN, there were slews of engineers that built things for you but at Fermilab, notes Tom, "You had to do it all yourself. Anything I wanted to learn about, I could."

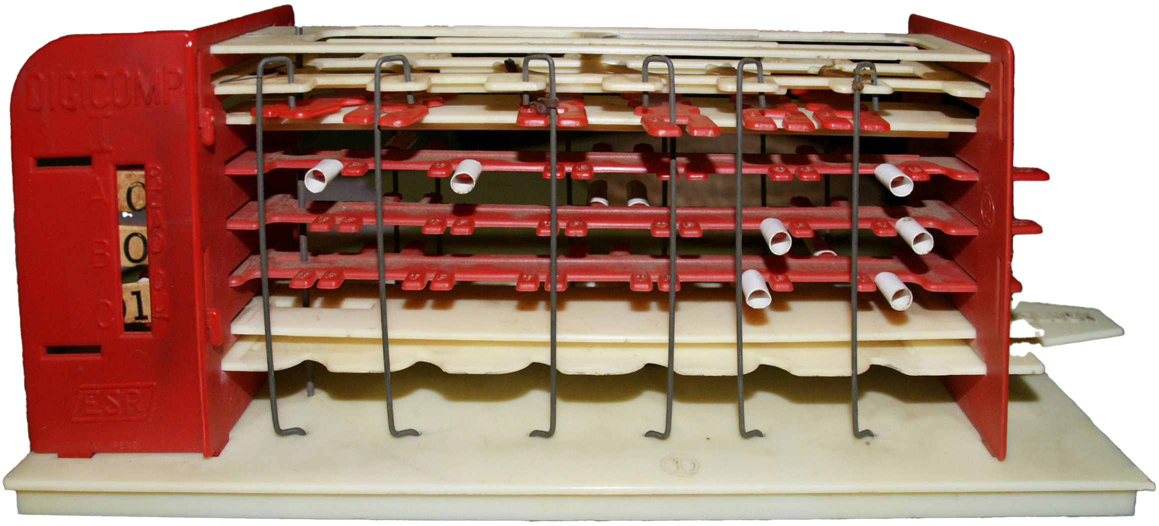

FIGURE 2:
The original Digicomp I.
Credit: Pterre, CC B-SA 3.0 <*creativecommons.org/licenses/by-sa/3.0*>, via Wikimedia Commons

Peter was recruited to MIT by Nobel Laureate (1976) Samuel Ting in 1994, and has been on a relentless search to detect dark matter for the past 25 years. Meanwhile, Tom realized halfway through his graduate program that an academic career was not for him. In his last year, he interviewed with a few banks, then was introduced by a friend to Tom Peterffy, a digital trading pioneer who wanted to put Wall Street on a chip. On the way to the interview, Tom read a book about options—but it didn't really matter. "We talked for hours about everything but options and then he offered me a job on the spot." Tom has been with Interactive Brokers ever since.

Nergis Mavalvala, Dean of the School of Science, thinks Peter Fisher is one of MIT's unsung heroes. "When the pandemic forced us to send people home, it was Peter who offered a lifeline to the community through his daily email letters of encouragement, compassion and true leadership." Everyone agrees that appointing Peter as the inaugural Thomas A. Frank (1977) Professor of Physics is a great match. In addition to the professorship, Tom has been supporting physics graduate students with fellowships for almost two decades. For Tom, "It is a privilege to be able to contribute to the great things happening in the Physics Department at MIT."

[1] *https://fisherp.mit.edu/wp-content/uploads/2014/12/MIT-Technology-Review-1976-03.pdf*

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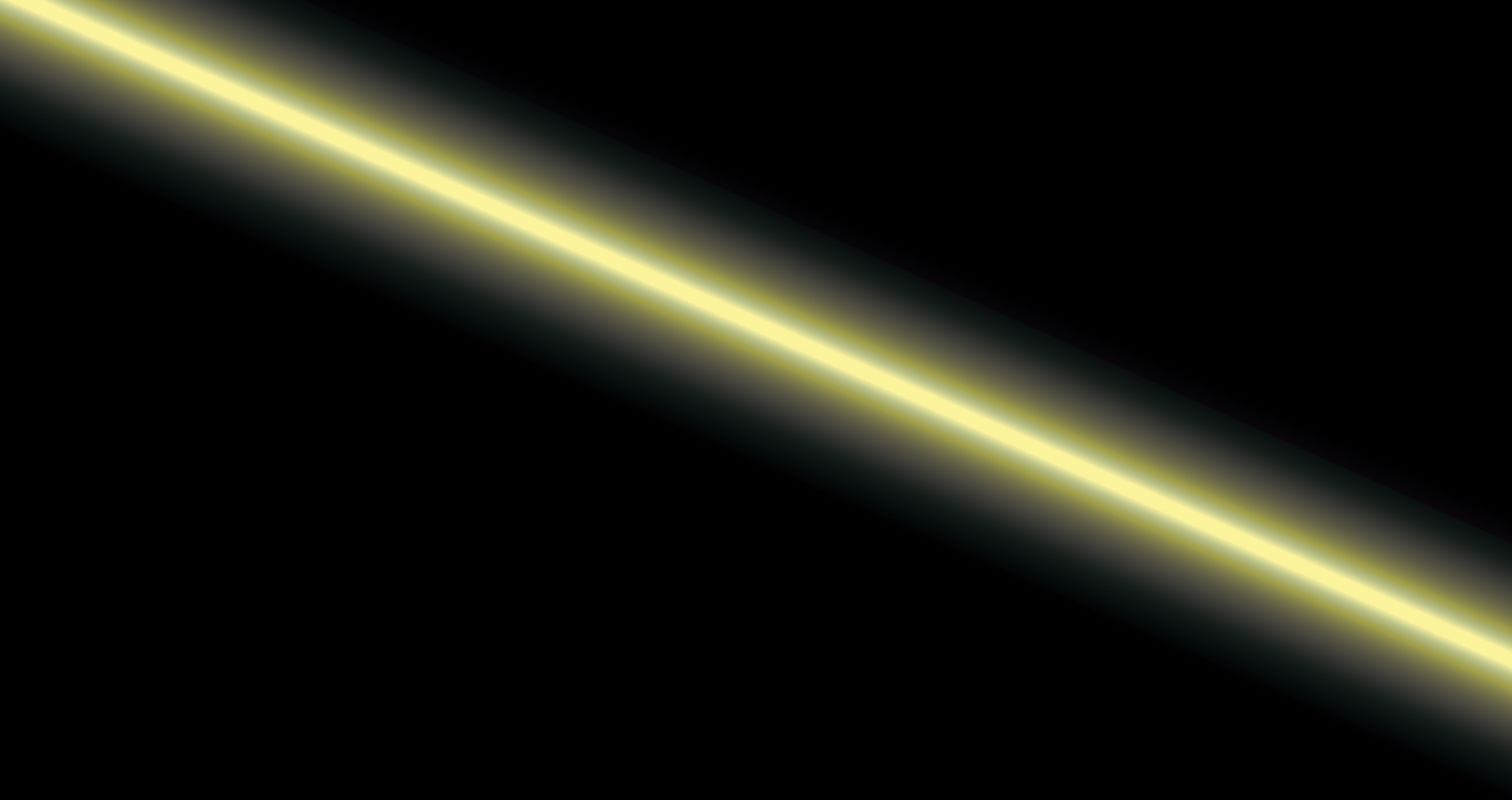

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