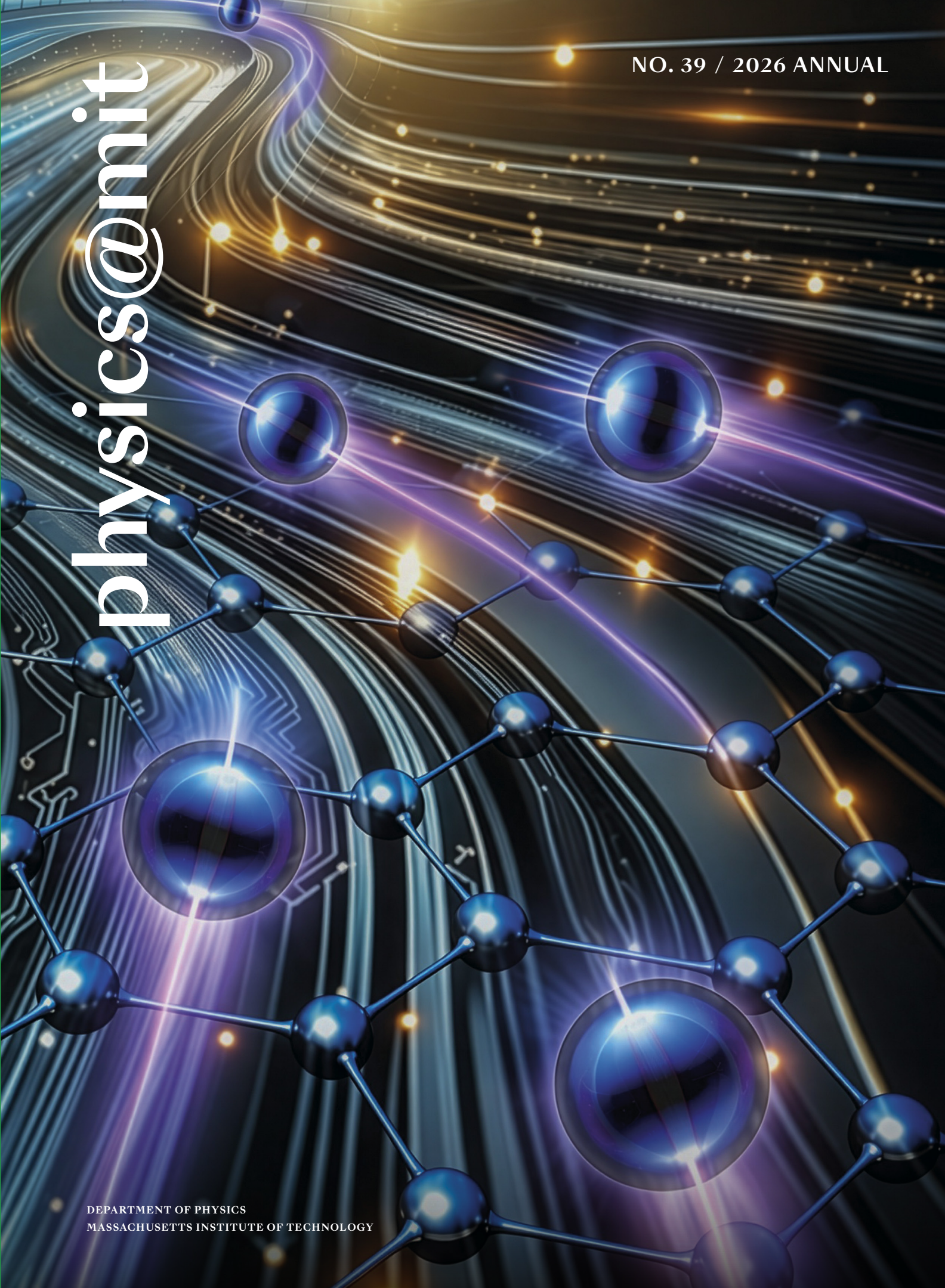
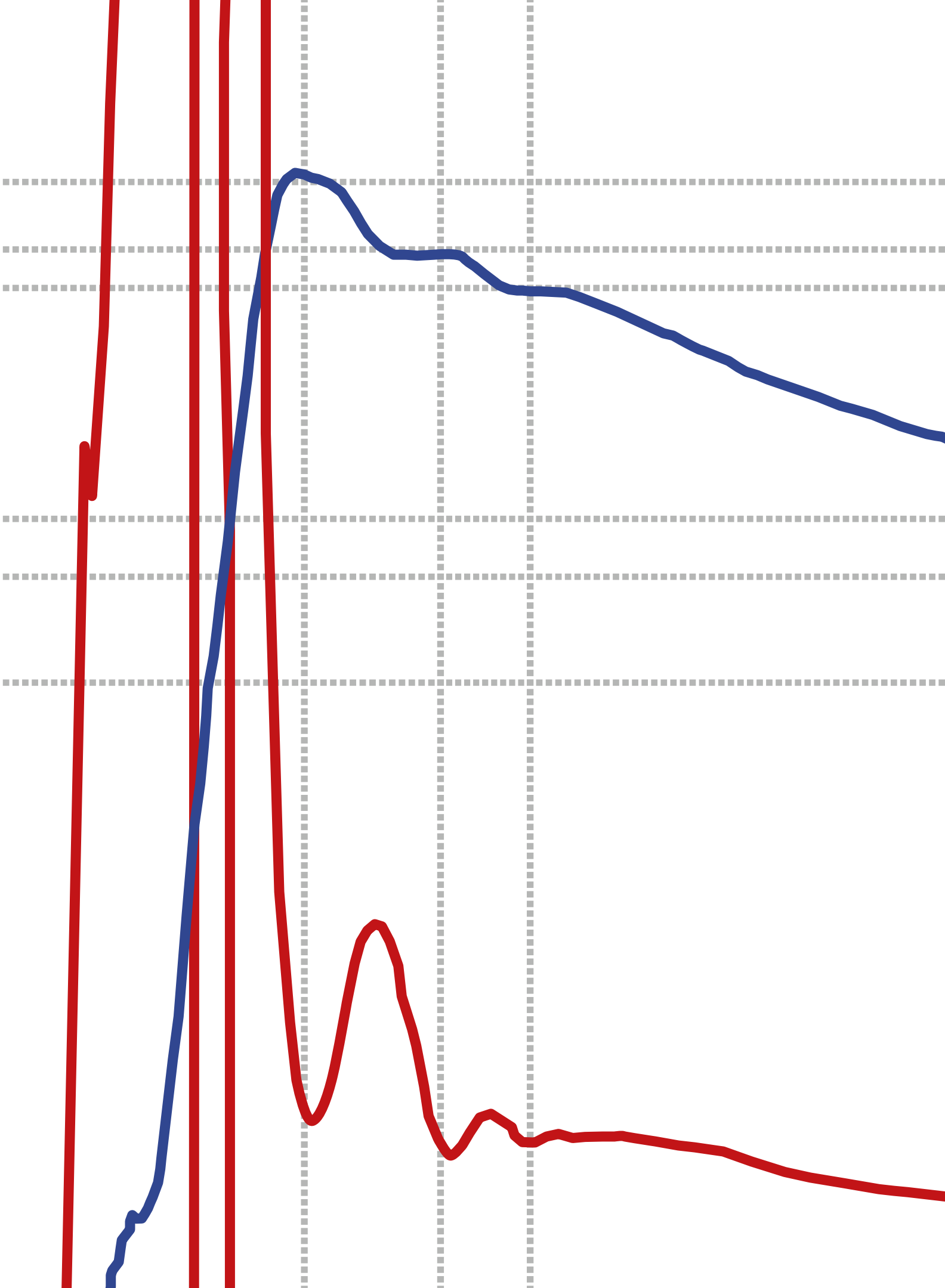
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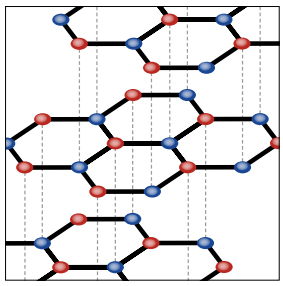
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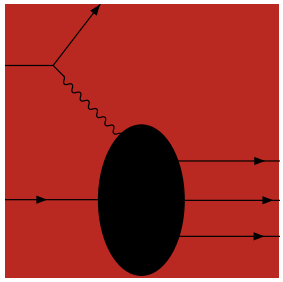
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Exterior and interior cover designs adapted from figures in Prof. Long Ju's feature article.

Message from the Department Head

DEAR MIT PHYSICS COMMUNITY MEMBERS,

This issue of *physics@mit* includes three major feature articles. **Professor Long Ju** discusses the power of rhombohedral graphene (a single layer of carbon atoms in a hexagonal lattice) for studying the exotic properties of quantum materials, particularly the *quantum anomalous Hall effect*. The other two articles look back five decades to help us remember and celebrate epochal events in the history of physics. **Professor Frank Wilczek** (2004 Nobel laureate) recalls the 1973 discovery of *asymptotic freedom* in particle physics and the emergence of quantum chromodynamics (QCD). **Professors Peter Fisher** and **David Kaiser** discuss MIT's important role in the so-called *November revolution* of 1974 (including the discovery of the J/ψ particle for which **Prof. Samuel Ting** shared the 1976 Nobel Prize in Physics) that established the Standard Model of particle physics.

It has been an impactful year. Thanks to a transformational gift from **Philip** (**Terry**) and **Susan Ragon**, MIT joined the Giant Magellan Telescope consortium as a Founder institution, ensuring that MIT and the Department will stay at the frontier of observational astrophysics for decades to come. A very generous gift from the Leinweber Foundation has endowed the MIT Center for Theoretical Physics—A Leinweber Institute, further empowering our theoretical physics program and connecting us to a network of Leinweber Institutes across the nation. We have also seen the launch of the MIT Quantum Initiative (QMIT), an Institute-wide effort (with a robust Physics component) to accelerate progress in quantum science and engineering.

We welcomed two new faculty members to the Department: **Profs. Ore Gottlieb** (theoretical astrophysics) and **Zhurun** (**Judy**) **Ji** (condensed matter experiment). Nine of our current faculty received promotions this year, including awards of tenure to **Profs. Long Ju** (condensed matter experiment) and **Kiyoshi Masui** (astrophysics). On a sad note, we mourned the passing of **Profs. John Joannopoulos** (condensed matter theory) and **Rainer Weiss** (experimental astrophysics, 2017 Nobel laureate). We were then shocked and heartbroken by the murder of **Prof. Nuno Loureiro** (plasma physics).

The Department also mourned the loss of our long-time friend and benefactor **A. Neil Pappalardo EE '64**. Neil was a leading supporter of the Department for decades, securing MIT's membership in the original Magellan Telescope consortium, supporting major renovation of space that became the Green Center for Physics in Buildings 6, 6C, and 4, endowing an annual lecture in physics, and enabling substantial startup resources for numerous junior faculty members. We recently celebrated the 25th anniversary of the Pappalardo Fellowships in Physics, created and endowed by Neil and his wife **Jane**. This postdoctoral program has been transformative for us. Neil left an indelible mark on the Department, and we are much, much stronger because of his help.

This has been a challenging and uncertain year for federal funding of science, with debates in Washington about the value of basic research. The Department will adapt to whatever funding equilibrium eventually emerges. However, we continue to worry about the short-term risk to current students, postdocs, and junior faculty working on projects whose federal support might be abruptly canceled in mid-stream. We will do our best to offer transitional support in such cases.


Credit: Steph Stevens

In recent years, we have been very lucky to be able to recruit–and retain–some of the best physicists in the world to be our students, postdocs, and faculty. It is a testament to the Department's positive, stimulating, and collaborative environment and to the support that the Department is able to offer. The tools that help enable this support–graduate fellowships, postdoctoral fellowships, junior faculty startups, senior faculty retentions–are largely funded through gifts from our alumni, parents, and friends. This generous support is critical to our recruitment success and our strength as a department. Gifts in any amount to our Physics Unrestricted Fund (#2657500) or our Alumni Fellowship Fund (#2738023) are greatly appreciated. Please consider supporting the Physics Department! For more information, please contact our Senior Director of Development, **Erin McGrath Tribble**, at 617-452-2807 or emcgrath@mit.edu.

With best regards,



DEEPTO CHAKRABARTY '88
William A. M. Burden Professor of Astrophysics
Head, Department of Physics

New Faculty

January 2026

Ore Gottlieb

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

Research Interests

Ore Gottlieb is a theoretical and computational astrophysicist who studies some of the most extreme events in the universe. His research focuses on black holes, neutron stars, the collapse of massive stars, and cosmic explosions such as supernovae, compact-object mergers, and gamma-ray bursts. These cataclysmic events not only shape the evolution of the universe but also create many of the heavy elements and the most powerful astrophysical events we observe today.

To study them, Gottlieb combines large-scale 3D general-relativistic magnetohydrodynamic simulations with analytic calculations. This approach makes it possible to model the complex physics of these extreme environments and connect the theory directly to observations. His work explores how these systems generate multi-messenger signals: electromagnetic and gravitational waves, neutrinos, and cosmic rays, which allow us to probe the hidden physics behind cosmic explosions and compact objects. Through this combination of tools, his research reveals new insights into how nature's most cataclysmic events unfold.



Ore Gottlieb
Credit: MIT Physics

Biographical Sketch

Ore Gottlieb grew up in Israel and first completed a BSc in Computer Science at the Technion in 2011. During this time, he discovered his passion for physics and decided to change course, pursuing a BSc in Physics (2014), and MSc in Physics *cum laude* under the supervision of Amiel Sternberg (2016), and a PhD in Physics and Astronomy under the supervision of Ehud Nakar (2021), all at Tel Aviv University.

He has been recognized with several prestigious fellowships, including the Rothschild Postdoctoral Fellowship (2021) and the CIERA Postdoctoral Fellowship (2021) at Northwestern University, as well as the Flatiron Research Fellowship (2023) and the Columbia THEA Postdoctoral Fellowship (2023), held jointly at the Center for Computational Astrophysics at the Flatiron Institute. His scientific achievements have also been honored by the Israel Physical Society with the Yoel Rakah Prize for Outstanding Theoretical Physics Student (2021) and by Tel Aviv University with the Yuval Ne'eman Award for Outstanding Academic Achievement (2019). In January 2026, he joined the MIT Department of Physics as an Assistant Professor.

Inspired by the excitement he felt upon discovering physics while studying computer science, Gottlieb has been deeply committed to outreach and education. He developed educational programs for schools in Israel and has taught and mentored students of all levels, from elementary and high school through graduate research.

For a list of Prof. Gottlieb's selected publications, as well as recent awards and honors, visit his faculty web page at *physics.mit.edu/faculty/ore-gottlieb/*.

Zhurun (Judy) Ji

Assistant Professor of Physics, Experimental Condensed Matter Physics

Research Interests

Zhurun (Judy) Ji's group explores the intersection of quantum sensing, quantum materials, and quantum devices, to drive breakthroughs in both fundamental science and next-generation technologies. The Ji group's work is centered around two major directions:

1 Developing new scanning probe techniques (RFlexiscope), using microwave techniques to study the local electrical properties and noise phenomena of quantum materials, especially two-dimensional materials. With these methods, they study quantum phenomena such as electron topology and correlation, with the aim to discover and understand macroscopic quantum phenomena.

2 Using non-local spectroscopic techniques, the Ji group studies coherence properties in emerging materials. Their goal is to gain insight into quantum phase transitions, collective excitations, and apply these insights in designing next-generation solid-state quantum circuits.

Integrating these pursuits, the Ji group aims to drive the quantum understanding of quantum phenomena and accelerate the realization of practical quantum devices.

Biographical Sketch

Zhurun (Judy) Ji received her bachelor's degree from the University of Science and Technology of China, class for gifted youth, in 2015. She earned her PhD in physics from the University of Pennsylvania in 2021. From 2021 to 2024, she was a Stanford Science Fellow and Urbanek-Chodorow Postdoctoral Fellow at Stanford University.

Ji was named a Panofsky Fellow at SLAC National Laboratory, prior to joining the MIT Physics Department as an Assistant Professor of Physics in January 2026.



Zhurun (Judy) Ji
Credit: MIT Physics

For a list of Prof. Ji's selected publications, please visit her faculty web page at *physics.mit.edu/faculty/zhurun-judy-ji/*.

In Remembrance

Professor John Joannopoulos, photonics pioneer and Institute for Soldier Nanotechnologies director, dies at 78

Over 50 years at MIT, the condensed-matter physicist led the development of photonic crystals, translating discoveries into wide-ranging applications in energy, medicine, and defense.

by Jennifer Chu | MIT News



John "J.J." Joannopoulos, the Francis Wright Davis Professor of Physics at MIT; Director of the MIT Institute for Soldier Nanotechnologies. Credit: MIT Physics.

John "J.J." Joannopoulos, the Francis Wright Davis Professor of Physics at MIT and director of the MIT Institute for Soldier Nanotechnologies (ISN), passed away on August 17, 2025. He was 78.

Joannopoulos was a prolific researcher in the field of theoretical condensed-matter physics, and an early pioneer in the study and application of photonic crystals. Many of his discoveries, in the ways materials can be made to manipulate light, have led to transformative and life-saving technologies, from chip-based optical wave guides, to wireless energy transfer to health-monitoring textiles, to precision light-based surgical tools.

His remarkable career of over 50 years was spent entirely at MIT, where he was known as much

for his generous and unwavering mentorship as for his contributions to science. He made a special point to keep up rich and meaningful collaborations with many of his former students and postdocs, dozens of whom have gone on to faculty positions at major universities, and to leadership roles in the public and private sectors. In his five decades at MIT, he made lasting connections across campus, both in service of science, and friendship.

> "J.J. was a very special colleague: a brilliant theorist who was also adept at identifying practical applications; a caring and inspiring mentor of younger scientists; a gifted teacher who knew every student in his class by name."
>
> DEEPTO CHAKRABARTY '88

"A scientific giant, inspiring leader, and a masterful communicator, John carried a generous and loving heart," says Yoel Fink PhD '00, an MIT professor of materials science and engineering who was Joannopoulos' former student and a longtime collaborator. "He chose to see the good in people, keeping his mind and heart always open. Asking little for himself, he gave everything in care of others. John lived a life of deep impact and meaning–savoring the details of truth-seeking, achieving rare discoveries and mentoring generations of students to achieve excellence. With warmth, humor, and a never-ending optimism, J.J. left an indelible impact on science and on all who had the privilege to know him. Above all, he was a loving husband, father, grandfather, friend, and mentor."

"In the end, the most remarkable thing about him was his unmatched humanity, his ability to make you feel that you were the most important thing in the world that deserved his attention, no matter who you were," says Raul Radovitzky, ISN associate director and the Jerome C. Hunsaker Professor in MIT's Department of Aeronautics and Astronautics. "The legacy he leaves is not only in equations and innovations, but in the lives he touched, the minds he inspired, and the warmth he spread in every room he entered."

"J.J. was a very special colleague: a brilliant theorist who was also adept at identifying practical applications; a caring and inspiring mentor of younger scientists; a gifted teacher who knew every student in his class by name," says Deepto Chakrabarty '88, the William A. M. Burden Professor in Astrophysics and head of MIT's Department of Physics. "He will be deeply missed."

Layers of light

John Joannopoulos was born in 1947 in New York City, where his parents both emigrated from Greece. His father was a playwright, and his mother worked as a psychologist. From an early age, Joannopoulos knew he wanted to be a physicist, mainly because the subject was his most challenging in school. In a recent interview with *MIT News*, he enthusiastically shared: "You probably wouldn't believe this, but it's true: I wanted to be a physics professor since I was in high school! I loved the idea of being able to work with students, and being able to have ideas."

He attended the University of California at Berkeley, where he received a bachelor's degree in 1968, and a PhD in 1974, both in physics. That same year, he joined the faculty at MIT, where he would spend his 50-plus-year career–though at the time, the chances of gaining a long-term foothold at the Institute seemed slim, as Joannopoulos told *MIT News*.

"The chair of the physics department was the famous nuclear physicist, Herman Feshbach, who told me the probability that I would get tenure was something like 30 percent," Joannopoulos recalled. "But when you're young and just starting out, it was certainly better than zero, and I thought, that was fine–there was hope down the line."

Starting out at MIT, Joannopoulos knew exactly what he wanted to do. He quickly set up a group to study theoretical condensed-matter physics, and specifically, *ab initio* physics, meaning physics "from first principles." In this initial work, he sought to build theoretical models to predict the electronic behavior and structure of materials, based solely on the atomic numbers of the atoms in a material. Such foundational models could be applied to understand and design a huge range of materials and structures.

Then, in the early 1990s, Joannopoulos took a research turn, spurred by a paper by physicist Eli Yablonovitch at the University of California at Los Angeles, who did some preliminary work on materials that can affect the behavior of photons, or particles of light. Joannopoulos recognized a connection with his first-principles work with electrons. Along with his students, he applied that approach to predict the fundamental behavior of photons in different classes of materials. His group was one of the first to pioneer the field of photonic crystals, and the study of how materials can be manipulated at the nanoscale to control the behavior of light traveling through. In 1995, Joannopoulos co-authored the first textbook on the subject.

And in 1998, he took on a more-than-century-old assumption about how light should reflect, and turned it on its head. That assumption predicted that light, shining onto a structure made of multiple refractive layers, could reflect back, but only for a limited range of angles. But in fact, Joannopoulos and his group showed that the opposite is true: If the structure's layers followed a particular design criteria, the structure as a whole could reflect light coming from any and all angles. This structure, was called the "perfect mirror."

That insight led to another: If the structure were rolled into a tube, the resulting hollow fiber could act as a perfect optical conduit. Any light traveling through the fiber would reflect and bounce around within the fiber, with none scattering away. Joannopoulos and his group applied this insight to develop the first precision "optical scalpel"—a fiber that can be safely handled, while delivering a highly focused laser, precise and powerful enough to perform delicate surgical procedures. Joannopoulos helped to commercialize the new tool with a startup, Omniguide, that has since provided the optical scalpel to assist in hundreds of thousands of medical procedures around the world.

Legendary mentor

In 2006, Joannopoulos took the helm as director of MIT's Institute for Soldier Nanotechnologies—a post he steadfastly held for almost 20 years. During his dedicated tenure, he worked with ISN members across campus and in departments outside his own, getting to know and champion their work. He has facilitated countless collaborations between MIT faculty, industry partners, and the U.S. Department of Defense. Among the many projects he raised support for were innovations in lightweight armor, hyperspectral imaging, energy-efficient batteries, and smart and responsive fabrics.

Joannopoulos helped to translate many basic science insights into practical applications. He was a cofounder of six spinoff companies based on his fundamental research, and helped to create dozens more companies, which have advanced technologies as wide-ranging as laser surgery tools, to wireless electric power transmission, transparent display technologies, and optical computing. He was awarded 126 patents for his many discoveries, and has authored over 750 peer-reviewed papers.

In recognition of his wide impact and contributions, Joannopoulos was elected to the National Academy of Sciences and the American Academy of Arts and Sciences. He was also a fellow of both the American Physical Society and the American Association for the Advancement of Science. Over his 50-plus-year career, he was the recipient of many scientific awards and honors including the Max Born Award, and the Aneesur Rahman Prize in Computational Physics. Joannopoulos was also a gifted classroom teacher, and was recognized at MIT with the Buechner Teaching Prize in Physics and the Graduate Teaching Award in Science.

In 2025, Joannopoulos was the recipient of MIT's Killian Achievement Award, which recognizes the extraordinary lifetime contributions of a member of the MIT faculty. In addition to the many accomplishments Joannopoulos has made in science, the award citation emphasized his lasting impact on the generations of students he has mentored:

"Professor Joannopoulos has served as a legendary mentor to generations of students, inspiring them to achieve excellence in science while at the same time facilitating the practical benefit to society through entrepreneurship," the citation reads. "Through all of these individuals he has impacted—not to mention their academic descendants—Professor Joannopoulos has had a vast influence on the development of science in recent decades."

"J.J. was an amazing scientist: He published hundreds of papers that have been cited close to 200,000 times. He was also a serial entrepreneur: Companies he cofounded raised hundreds of millions of dollars

and employed hundreds of people," says MIT Professor Marin Soljačić '96, a former postdoc under Joannopoulos who with him cofounded a startup, Witricity. "He was an amazing mentor, a close friend, and like a scientific father to me. He always had time for me, any time of the day, and as much as I needed."

Indeed, Joannopoulos strived to meaningfully support his many students. In the classroom, he "was legendary," says friend and colleague Patrick Lee '66, PhD '70, who recalls that Joannopoulos would make a point of memorizing the names and faces of more than 100 students on the first day of class, and calling them each by their first name, starting on the second day, and for the rest of the term.

What's more, Joannopoulos encouraged graduate students and postdocs to follow their ideas, even when they ran counter to his own.

> "John did not produce clones. He showed them the way to do science by example, by caring and by sharing his optimism. I have never seen someone so deeply loved by his students."
>
> PATRICK LEE '66, PhD '70

"John did not produce clones," says Lee, who is an MIT professor emeritus of physics. "He showed them the way to do science by example, by caring and by sharing his optimism. I have never seen someone so deeply loved by his students."

Even students who stepped off the photonics path have kept in close contact with their mentor, as former student and former MIT professor Josh Winn '94, SM '94, PhD '01 has done.

"Even though our work together ended more than 25 years ago, and I now work in a different field, I still feel like part of the Joannopoulos academic family," says Winn, who is now a professor of astrophysics at Princeton University. "It's a loyal group with branches all over the world. We even had our own series of conferences, organized by former students to celebrate John's 50th, 60th, and 70th birthdays. Most professors would consider themselves fortunate to have even one such 'festschrift' honoring their legacy."

MIT professor of mathematics Steven Johnson '95, PhD '01, a former student and frequent collaborator, has experienced personally, and seen many times over, Joannopoulos' generous and open-door mentorship.

"In every collaboration, I've unfailingly observed him ensure that everyone feels included and valued, and to encourage collaborations across groups and fields and institutions," Johnson says. "Kind, generous, and brimming with infectious enthusiasm and positivity, he set an example so many of his lucky students have striven to follow."

Joannopoulos started at MIT around the same time as Marc Kastner, who had a nearby office on the second floor of Building 13.

"I would often hear loud arguments punctuated by boisterous laughter, coming from John's office, where he and his students were debating physics," recalls Kastner, who is the Donner Professor of Science Emeritus at MIT. "I am sure this style of interaction is what made him such a great mentor."

"He exuded such enthusiasm for science and good will to others that he was just good fun to be around," adds friend and colleague Erich Ippen, MIT professor emeritus of physics.

"John was indeed a great man—a very special one. Everyone who ever worked with him understands this," says Stanford University physics professor Robert Laughlin PhD '79, one of Joannopoulos' first graduate students, who went on to win the 1998 Nobel Prize in Physics. "He sprinkled a kind of transformative magic dust on people that induced them to dedicate every waking moment to the task of making new and wonderful things. You can find traces of it in lots of places around the world that matter, all of them the better for it. There's quite a pile of it in my office."

Joannopoulos is survived by his wife, Kyri Dunussi-Joannopoulos; their three daughters, Maria, Lena, and Alkisti; and their families.

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Professor Emeritus Rainer Weiss, influential physicist who forged new paths to understanding the universe, dies at 92

The longtime MIT professor shared a Nobel Prize for his role in developing the LIGO observatory and detecting gravitational waves.

by Kathy Wren | MIT News

MIT Professor Emeritus Rainer Weiss ’55, PhD ’62, a renowned experimental physicist and Nobel laureate whose groundbreaking work confirmed a longstanding prediction about the nature of the universe, passed away on August 25, 2025. He was 92.

Weiss conceived of the Laser Interferometer Gravitational-Wave Observatory (LIGO) for detecting ripples in space-time known as gravitational waves, and was later a leader of the team that built LIGO and achieved the first-ever detection of gravitational waves. He shared the Nobel Prize in Physics for this work in 2017. Together with international collaborators, he and his colleagues at LIGO would go on to detect many more of these cosmic reverberations, opening up a new way for scientists to view the universe.

During his remarkable career, Weiss also developed a more precise atomic clock and figured out how to measure the spectrum of the cosmic microwave background via a weather balloon. He later cofounded and advanced the NASA Cosmic Background Explorer project, whose measurements



MIT Professor Emeritus Rainer Weiss ’55, PhD ’62. Credit: Bryce Vickmark.

helped support the Big Bang theory describing the expansion of the universe.

"Rai leaves an indelible mark on science and a gaping hole in our lives," says Nergis Mavalvala PhD '97, dean of the MIT School of Science and the Curtis and Kathleen Marble Professor of Astrophysics. As a doctoral student with Weiss in the 1990s, Mavalvala worked with him to build an early prototype of a gravitational-wave detector as part of her PhD thesis. "He will be so missed but has also gifted us a singular legacy. Every gravitational wave event we observe will remind us of him, and we will smile. I am indeed heartbroken, but also so grateful for having him in my life, and for the incredible gifts he has given us—of passion for science and discovery, but most of all to always put people first," she says.

A member of the MIT physics faculty since 1964, Weiss was known as a committed mentor and teacher, as well as a dedicated researcher.

"Rai's ingenuity and insight as an experimentalist and a physicist were legendary," says Deepto Chakrabarty '88, the William A. M. Burden Professor in Astrophysics and head of the Department of Physics. "His no-nonsense style and gruff manner belied a very close, supportive and collaborative relationship with his students, postdocs, and other mentees. Rai was a thoroughly MIT product."

"Rai held a singular position in science: He was the creator of two fields—measurements of the cosmic microwave background and of gravitational waves. His students have gone on to lead both fields and carried Rai's rigor and decency to both. He not only created a huge part of important science, he also populated them with people of the highest caliber and integrity," says Peter Fisher, the Thomas A. Frank (1977) Professor of Physics and former head of the physics department.

Enabling a new era in astrophysics

LIGO is a system of two identical detectors located 1,865 miles apart. By sending finely tuned lasers back and forth through the detectors, scientists can detect perturbations caused by gravitational waves, whose existence was proposed by Albert Einstein. These discoveries illuminate ancient collisions and other events in the early universe, and have confirmed Einstein's theory of general relativity. Today, the LIGO Scientific Collaboration involves hundreds of scientists at MIT, Caltech, and other universities, and with the Virgo and KAGRA observatories in Italy and Japan makes up the global LVK Collaboration—but five decades ago, the instrument concept was an MIT class exercise conceived by Weiss.

As he told *MIT News* in 2017, in generating the initial idea, Weiss wondered: "What's the simplest thing I can think of to show these students that you could detect the influence of a gravitational wave?"

To realize the audacious design, Weiss teamed up in 1976 with physicist Kip Thorne, who, based in part on conversations with Weiss, soon seeded the creation of a gravitational wave experiment group at Caltech. The two formed a collaboration between MIT and Caltech, and in 1979, the late Scottish physicist Ronald Drever, then of the University of Glasgow, joined the effort at Caltech. The three scientists—who became the co-founders of LIGO—worked to refine the dimensions and scientific requirements for an instrument sensitive enough to detect a gravitational wave. Barry Barish later joined

"Rai held a singular position in science: He was the creator of two fields—measurements of the cosmic microwave background and of gravitational waves. His students have gone on to lead both fields and carried Rai's rigor and decency to both. He not only created a huge part of important science, he also populated them with people of the highest caliber and integrity." PETER FISHER

the team at Caltech, helping to secure funding and bring the detectors to completion.

After receiving support from the National Science Foundation, LIGO broke ground in the mid-1990s, constructing interferometric detectors in Hanford, Washington, and in Livingston, Louisiana.

Years later, when he shared the Nobel Prize with Thorne and Barish for his work on LIGO, Weiss noted that hundreds of colleagues had helped to push forward the search for gravitational waves.

"The discovery has been the work of a large number of people, many of whom played crucial roles," Weiss said at an MIT press conference. "I view receiving this [award] as sort of a symbol of the various other people who have worked on this."

> "While I have always been amazed and guided by Rai's ingenuity, integrity, and humility, I was most impressed by his breadth of vision and ability to move between worlds."
>
> MATTHEW EVANS

He continued: "This prize and others that are given to scientists is an affirmation by our society of [the importance of] gaining information about the world around us from reasoned understanding of evidence."

"While I have always been amazed and guided by Rai's ingenuity, integrity, and humility, I was most impressed by his breadth of vision and ability to move between worlds," says Matthew Evans, the MathWorks Professor of Physics. "He could seamlessly shift from the smallest technical detail of an instrument to the global vision for a future observatory. In the last few years, as the idea for a next-generation gravitational-wave observatory grew, Rai would often be at my door, sharing ideas for how to move the project forward on all levels. These discussions ranged from quantum mechanics to global politics, and Rai's insights and efforts have set the stage for the future."

A lifelong fascination with hard problems

Weiss was born in 1932 in Berlin. The young family fled Nazi Germany to Prague and then emigrated to New York City, where Weiss grew up with a love for classical music and electronics, earning money by fixing radios.

He enrolled at MIT, then dropped out of school in his junior year, only to return shortly after, taking a job as a technician in the former Building 20. There, Weiss met physicist Jerrold Zacharias, who encouraged him in finishing his undergraduate degree in 1955 and his PhD in 1962.

Weiss spent some time at Princeton University as a postdoc in the legendary group led by Robert Dicke, where he developed experiments to test gravity. He returned to MIT as an assistant professor in 1964, starting a new research group in the Research Laboratory of Electronics dedicated to research in cosmology and gravitation.

With the money he received from the Nobel Prize, Weiss established the Barish-Weiss Fellowship to support student research in the MIT Department of Physics.

Weiss received numerous awards and honors in addition to the Nobel Prize, including the Medaille de l'ADION, the 2006 Gruber Prize in Cosmology, and the 2007 Einstein Prize of the American Physical Society. He was a fellow of the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and the American Physical Society, as well as a member of the National Academy of Sciences. In 2016, Weiss received a Special Breakthrough Prize in Fundamental Physics, the Gruber Prize in Cosmology, the Shaw Prize in Astronomy, and the Kavli Prize in Astrophysics, all shared with Drever and Thorne. He also shared the Princess of Asturias Award for Technical and Scientific Research with Thorne, Barry Barish of Caltech, and the LIGO Scientific Collaboration.

Weiss is survived by his wife, Rebecca; his daughter, Sarah, and her husband, Tony; his son, Benjamin, and his wife, Carla; and a grandson, Sam, and his wife, Constance.

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Nuno Loureiro, professor and director of MIT's Plasma Science and Fusion Center, dies at 47

In his 10 years at MIT, Loureiro helped illuminate the physics occurring at the center of fusion vacuum chambers and at the edges of the universe.

by MIT News

Nuno Loureiro, a professor of nuclear science and engineering and of physics at MIT, tragically died early in the morning of December 16, 2025, from gunshot wounds he sustained a few hours before. He was 47.

A lauded theoretical physicist and fusion scientist, Loureiro joined MIT's faculty in 2016. His research addressed complex problems lurking at the center of fusion vacuum chambers and at the edges of the universe.

Loureiro's research at MIT advanced scientists' understanding of plasma behavior, including turbulence, and uncovered the physics behind astronomical phenomena like solar flares. He was the Herman Feshbach (1942) Professor of Physics at MIT and was named director of the Plasma Science and Fusion Center in 2024, though his contributions to fusion science and engineering began far before that.

His research on magnetized plasma dynamics, magnetic field amplification, and confinement and transport in fusion plasmas helped inform the design of fusion devices that could harness the energy of fusing plasmas, bringing the dream of clean, near-limitless fusion power closer to reality.



Nuno Loureiro, Herman Feshbach (1942) Professor of Physics; Professor of Nuclear Science and Engineering; Director, Plasma Science and Fusion Center. Credit: MITEI.

"Nuno was not only a brilliant scientist, he was a brilliant person," says Dennis Whyte, the Hitachi America Professor of Engineering, who previously served as the head of the Department of Nuclear Science and Engineering and director of the Plasma Science and Fusion Center. "He shone a bright light as a mentor, friend, teacher, colleague and leader,

and was universally admired for his articulate, compassionate manner. His loss is immeasurable to our community at the PSFC, NSE and MIT, and around the entire fusion and plasma research world."

"Nuno was a champion for plasma physics within the Physics Department, a wonderful and engaging colleague, and an inspiring and caring mentor for graduate students working in plasma science. His recent work on quantum computing algorithms for plasma physics simulations was a particularly exciting new scientific direction," says Deepto Chakrabarty '88, the William A. M. Burden Professor in Astrophysics and head of the Department of Physics.

Whether working on fusion or astrophysics research, Loureiro merged fundamental physics with technology and engineering, to maximize impact.

"There are people who are driven by technology and engineering, and others who are driven by fundamental mathematics and physics. We need both," Loureiro said in 2019. "When we stimulate theoretically inclined minds by framing plasma physics and fusion challenges as beautiful theoretical physics problems, we bring into the game incredibly brilliant students—people who we want to attract to fusion development."

> "Nuno was a champion for plasma physics within the Physics Department, a wonderful and engaging colleague, and an inspiring and caring mentor for graduate students working in plasma science."
>
> DEEPTO CHAKRABARTY '88

Loureiro majored in physics at Instituto Superior Tecnico (IST) in Portugal and obtained a PhD in physics at Imperial College London in 2005. He conducted postdoctoral work at the Princeton Plasma Physics Laboratory for the next two years before moving to the UKAEA Culham Center for Fusion Energy in 2007. Loureiro returned to IST in 2009, where he was a researcher at the Institute for Plasmas and Nuclear Fusion until coming to MIT in 2016.

He wasted no time contributing to the intellectual environment at MIT, spending part of his first two years at the Institute working on the vexing problem of plasma turbulence. Plasma is the superhot state of matter that serves as the fuel for fusion reactors. Loureiro's lab at PSFC illuminated how plasma behaves inside fusion reactors, which could help prevent material failures and better contain the plasma to harvest electricity.

"Nuno was not only an extraordinary scientist and educator, but also a tremendous colleague, mentor, and friend who cared deeply about his students and his community. His absence will be felt profoundly across NSE and far beyond," Benoit Forget, the KEPCO Professor and head of the Department of Nuclear Science and Engineering, wrote in an email to the department.

On other fronts, Loureiro's work in astrophysics helped reveal fundamental mechanisms of the universe. He put forward the first theory of turbulence in pair plasmas, which differ from regular plasmas and may be abundant in space. The work was driven, in part, by unprecedented observations of a binary neutron star merger in 2018.

As an assistant professor and then a full professor at MIT, Loureiro taught course 22.612 (Intro to Plasma Physics) and course 22.615 (MHD Theory of Fusion Systems), for which he was twice recognized with the Department of Nuclear Science and Engineering's PAI Outstanding Professor Award.

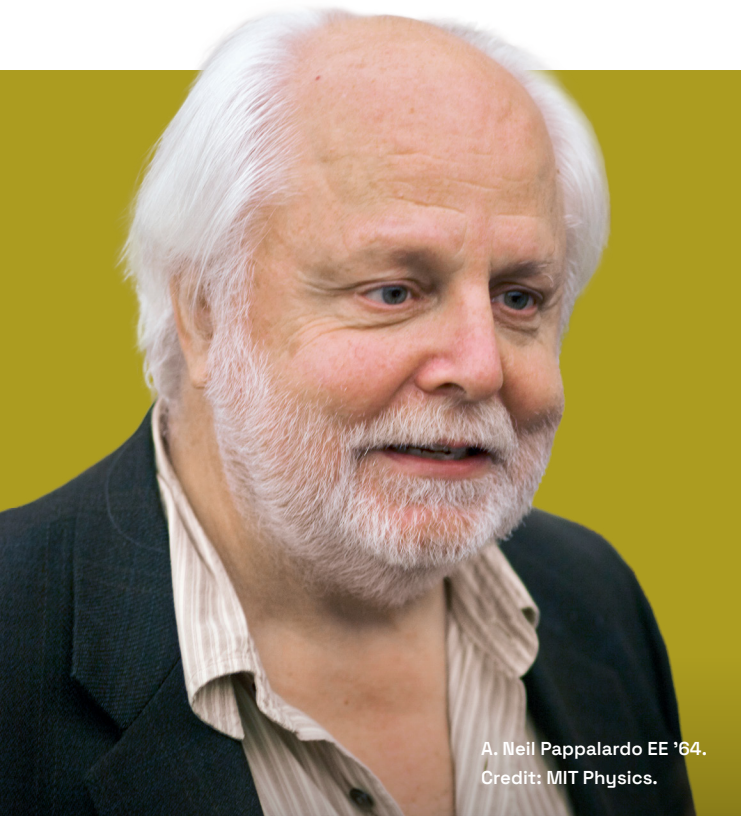
Loureiro's research earned him many prominent awards throughout his prolific career, including the National Science Foundation Career Award and the American Physical Society Thomas H. Stix Award for Outstanding Early Career Contributions to Plasma Physics Research. He was also an American Physical Society Fellow. Earlier this year, he earned the Presidential Early Career Award for Scientists and Engineers.

The Nuno Loureiro Memorial Fund (*https://www.psfc.mit.edu/support/*) has been established to support MIT graduate students at NSE and PSFC. Reprinted by kind permission, *MIT News Online*.

A. Neil Pappalardo EE ’64

Longstanding benefactor remembered for his lasting impact on the Department of Physics.

by Stephanie Koperniak | MIT Physics



A. Neil Pappalardo EE ’64. Credit: MIT Physics.

A. Neil Pappalardo ’64, co-founder of MEDITECH (Medical Information Technology, Inc.) and a leading supporter of the MIT Department of Physics for decades, died on January 27, 2026, at age 83. He leaves behind his wife of 61 years, Jane; their four children; and 13 grandchildren.

Pappalardo’s generosity is visible throughout the community, research, and buildings of MIT Physics. For 25 years, the prestigious and innovative MIT Pappalardo Fellowships in Physics program has supported selected postdoctoral physics researchers early in their careers. His generous support enabled MIT’s membership in the Magellan Telescopes consortium; supported major renovation of Physics space that became the Green Center for Physics in Buildings 6, 6C, and 4; provided substantial resources to many junior faculty; and endowed an annual distinguished lecture series in physics. One can quickly see why 2004 Nobel Laureate Frank Wilczek called him “the soul of the Physics Department.”

“Neil’s love of physics, our work, and our researchers was broad and inclusive,” says Deepto Chakrabarty ’88, MIT Physics Department Head and William A. M. Burden Professor in Astrophysics. “His decades of generosity and attendance at Physics Department events was borne of his passion and commitment. Neil has left an indelible mark on the Department, and we are much, much stronger because of his help.”

Pappalardo’s service extended throughout the Institute. He was a life member emeritus of the MIT Corporation; a long-term member of MIT Executive, Audit and Salary Committees; a member of the School of Engineering and School of Science Dean’s Advisory Councils. He served on Visiting Committees for Physics, Mechanical Engineering (chairing from 1997–2010), the Libraries, and Earth, Atmospheric and Planetary Sciences (EAPS).

In a 2016 Infinite History Project interview, Pappalardo shared anecdotes from his youth, growing up in a small town outside of Rochester, NY. He was always interested in science, and when he got to MIT, he was very excited to run into cosmic ray expert Bruno Rossi, whom he had previously seen on a television program. Pappalardo majored in physics for the first three and a half years of his time at MIT,

but he ultimately graduated with a degree in electrical engineering. He said that while he was drawn to study physics, he quickly learned that "if you're going to be an experimentalist, as opposed to a theorist, you have to learn how to build things." He said he and many physics majors at the time also took subjects in electrical engineering, although there wasn't a formal option for a double major at the time. His thesis project helped physicians develop a medical device that would electronically examine the electrical signal from a patient's heart for arrhythmia.

After graduating, he continued to be interested in working in a medical setting. He began his career at Massachusetts General Hospital, where he experienced first-hand the complexity of a hospital environment and observed how error-prone the various clinical processes could be. ("Reflections on an MIT Education," 2008: *youtube.com/watch?v=5R64HGsk0qg*.) In order to better manage this complexity, he co-created MGH Utility Multi-Programming System (MUMPS), a healthcare-specific programming language. Building on this work, he became the chairman and co-founder of MEDITECH in 1969, which pioneered health care information systems for hospitals and medical facilities and is widely recognized as the first Electronic Health Record (EHR) company.

Growing MIT's astrophysics capabilities

In the late 1990s, there was concern among physics faculty that MIT might not be able to attract the next generation of astrophysicists without access to the state-of-the-art, optical telescopes that were being built at the time. Professors Claude Canizares and Paul Schechter expressed these concerns, and the Pappalardos decided to help fund the construction of twin optical telescopes for the Magellan Consortium—comprising five institutions, including MIT—at the Las Campanas Observatory in Chile.

"This contribution toward the Magellan Consortium telescopes marked a turning point for MIT astrophysics," says Francis L. Friedman Professor of Physics Robert Simcoe, director of the MIT Kavli Institute for Astrophysics and Space Research, and a former Pappalardo Fellow (2003–2006). "MIT was a primary partner in the building of these telescopes, which are among the best in the world, and having access to these instruments dramatically expanded our capabilities."

Pappalardo's contributions to astrophysics also extended to the Kavli Institute, often supporting important research when regular funding avenues couldn't do so within the preferred timing. His critical support helped to recruit and retain junior faculty, and he became focused on the researchers and their work.

"Neil and Jane really invested in people and not just projects," says Simcoe. "They genuinely wanted to know *why* we were interested in what we were interested in."

Nurturing physics postdocs

Shortly after Marc Kastner, Donner Professor of Science Emeritus and Dean Emeritus, MIT School of Science, began as Physics department head in 1998, he met with Pappalardo, who wanted to help the department in some substantial way. At that time, he had already contributed toward the Magellan Consortium telescopes, and because of that gift, the Pappalardo Distinguished Lecture Series (focusing on astrophysics) had been established in his honor.

Kastner and Robert Birgeneau, Professor of Physics Emeritus and Chancellor Emeritus, UC-Berkeley, who was the MIT Dean of Science then, had admired Harvard's Junior Fellowship program, which attracted top young scientists from around the world. They wanted a similar program at MIT Physics, particularly for physics postdocs. Members of the Physics Council agreed that this would be very beneficial. Kastner says that Pappalardo was a little hesitant at first, as he wasn't familiar with the idea of postdocs, but he agreed to fund the program and it launched in 2000. After the first five years, Pappalardo asked for a meeting of the committee that was choosing the fellows, to make sure the program should continue. All agreed that the program had been a success, and Pappalardo ultimately decided to endow the program.

"Having the Pappalardo Fellowships Program incorporated into the Physics Department has been really wonderful," says Kastner. "One thing which I never could have anticipated is that he and Jane really adopted the fellows. They invited them to their Boston home for the holidays in the winter, and to their home on Buzzards Bay in the summer. As we started to hire some of them as faculty members, he kept those relationships for many years."

Having recently celebrated its 25th anniversary, the Pappalardo Fellowships in Physics continues to sustain a distinguished postdoctoral fellowship program that recruits and supports promising young physicists at the start of their careers. The Fellows are brought together with faculty for weekly luncheons, showcase their work at the annual Pappalardo Fellowships symposium, and enjoy complete freedom in research direction throughout the fellowship. Of the 78 former Fellows, 57 hold faculty positions in six different countries, including eight currently with MIT Physics.

> "Neil had a very enthusiastic sense of possibility and embraced the thought of doing something that was new. At the time, I didn't realize how unusual that was, but it was so impactful in what I went on to do."
>
> JOCELYN MONROE

"One thing I especially loved about talking with Neil early on in my career is that he was always up for a disruptive idea," says Jocelyn Monroe (2006–2009 Pappalardo Fellow), Professor of Physics at the University of Oxford. She says that the Fellowship gave her the freedom to shift her research focus from neutrino oscillation physics, which she had studied in her doctoral research, to focus on dark matter.

"Neil had a very enthusiastic sense of possibility and embraced the thought of doing something that was new," says Monroe. "At the time, I didn't realize how unusual that was, but it was so impactful in what I went on to do."

Securing much-needed space for Physics

At the beginning of Kastner's time as department head, he learned that Cecil Green had given a gift to the department to renovate space, but the department couldn't agree on a plan. Around seven years later, there was a plan, but due to so much spending on MIT buildings at the time, the executive committee of the MIT Corporation, of which Pappalardo was a member, said the plan couldn't move forward. Kastner spoke about this problem to the Physics Visiting Committee, of which Pappalardo was also a member. Pappalardo ultimately said he would give a $5 million gift, if matched, and together with the gift from Cecil Green, this was enough to proceed with the plans. The space was completed in 2008.

"We asked Neil if he wanted us to name something in the center for him, and he said 'no,' but we decided that the room that the department uses most would be called the Pappalardo Room," says Kastner. "The department headquarters and the education headquarters, which used to be on different floors, were brought together. The whole department functions much better."

Bringing people together for collaboration and support is a theme that echoes throughout Pappalardo's many contributions to the Physics Department, as well as his genuine interest in and excitement for the early-career researchers the Pappalardo Fellowships supported.

"It became a tradition that Neil was the first to ask a question when a Fellow presented their research at the Pappalardo Fellowships Symposium, and he would follow up on that question the next time you saw him," says Juliana García-Mejía, a current Pappalardo Fellow (2026–2028). "Neil was an incredibly caring, curious overseer. There's something so deeply motivating about having somebody support your research, not solely through finances—although that is certainly important—but also through their care and attention. It's a very unique experience that I think is quite rare in the sciences."

Pappalardo received honorary degrees from Suffolk University and the Korean Advanced Institute of Science and Technology [KAIST]. The International Astronomical Union named an asteroid in his honor and in 2008 he received the Order of Science and Technology Medal from the Prime Minister of the Republic of Korea. In 2010, the Pappalardo Medical Center was dedicated in his honor at KAIST.

To view the Physics Department's Remembrance of A. Neil Pappalardo '64 at the May 14, 2026, Spring 2026 Pappalardo Fellowships Symposium, please visit *https://www.youtube.com/watch?v=_c9d7Jqmq1c*.

Faculty & Staff Notes

Honors + Awards


Anna-Christina Eilers

Anna-Christina Eilers, Assistant Professor of Physics and Victor F. Weisskopf Career Development Professor, was awarded a 2026 Sloan Research Fellowship; received the Ludwig Biermann Prize from the German Astronomical Society in 2025; was named a Committed to Caring honoree by the MIT Office of Graduate Education.

Gian Michele Innocenti, Assistant Professor of Physics, won the Department of Energy Early Career Award in 2025.

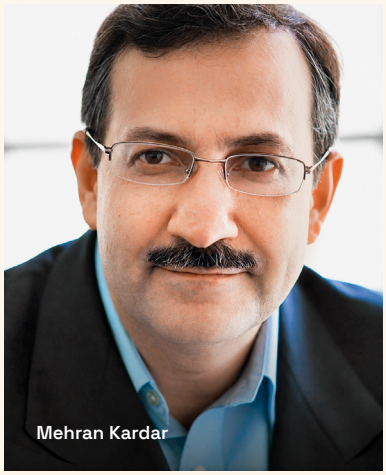
Pablo Jarillo-Herrero, Cecil and Ida Green Professor of Physics, received the 2026 Kavli Prize in Nanoscience alongside his co-recipients "for foundational work that established the field of twistronics." He was named an American Academy of Arts and Sciences Member (2026); received a 2025 BBVA Foundation Frontiers of Knowledge Award; delivered the 2025 H. L. Welsh Lecture at the University of Toronto.

Long Ju, Associate Professor of Physics, was named the Lawrence and Sarah W. Biedenharn Career Development Professor in 2024 by the MIT School of Science.


Long Ju

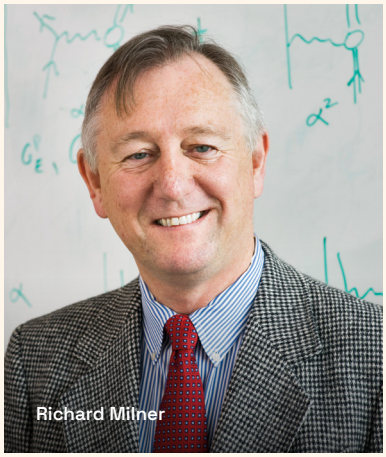
Erin Kara, Associate Professor of Physics, received a 2025 MIT Postdoctoral Association Excellence in Postdoctoral Mentoring Award; received a 2025–2027 MIT Committed to Caring Award, MIT Office of Graduate Education.

Mehran Kardar PhD '83, the Francis Friedman Professor of Physics, was awarded the Lars Onsager Prize of the American Physical Society, for his "ground-breaking contributions to statistical physics, including the Kardar-Parisi-Zhang equation, Casimir forces, active matter, and aspects of biological physics."

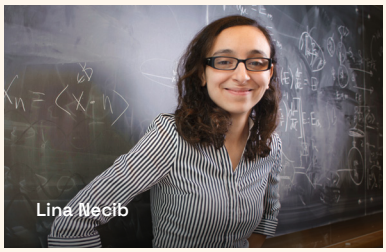

Mehran Kardar

Yen-Jie Lee PhD '11, Professor of Physics, received a 2025 American Physical Society Division of Nuclear Physics Fellowship "for pioneering measurements of jet quenching, medium response and heavy-quark diffusion in the quark-gluon plasma, and for using electron-positron collisions as an innovative control to understand collectivity in small collision systems"; and was awarded a 2025 Breakthrough Prize in Fundamental Physics with co-recipients.


Yen-Jie Lee
Credit: Justin Knight Photography


Richard Milner

Richard Milner was named the Cecil and Ida Green Professor of Physics.


Lina Necib

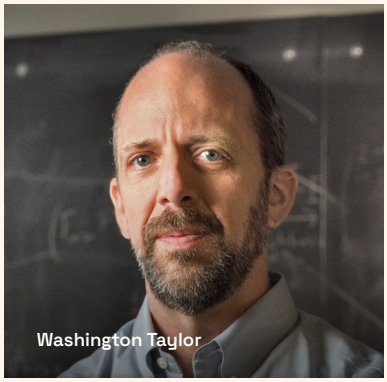
Lina Necib, Associate Professor of Physics, was named a 2025–2027 Committed to Caring honoree by the MIT Office of Graduate Education.

Christoph M.E. Paus, Professor of Physics, was named the Large Hadron Collider Physics Center Senior Distinguished Researcher for 2026 at Fermilab.

Iain Stewart, Otto (1939) and Jane Morningstar Professor of Science, was named a 2025 Committed to Caring honoree by the MIT Office of Graduate Education.

Julien Tailleur, Professor of Physics, received an MIT School of Science Award for Excellence in Mentoring and Advising in 2026; received an American Physical Society, Division of Soft Matter Fellowship in 2025 "for foundational theoretical work on motility-induced phase separation and emergent collective behavior in scalar active matter."


Julien Tailleur


Washington Taylor

Washington Taylor was named the Herman Feshbach (1942) Professor of Physics.


Jesse Thaler

Jesse Thaler was named the William and Emma Rogers Professor of Physics; appointed the Director of the MIT Laboratory for Nuclear Science in 2026; received the 2026 Humboldt Research Award (Alexander von Humboldt Foundation in Germany); was named 2025–26 Schlumberger Chair for Mathematical Sciences, Institut des Hautes Études Scientifiques (IHES).

Boleslaw Wyslouch was named the Jerrold R. Zacharias Professor of Physics.


Boleslaw Wyslouch

Promotions



Long Ju



Kiyoshi Masui

Soonwon Choi
to Associate Professor of Physics without tenure.

Nikta Fakhri
to Full Professor of Physics.

Richard Fletcher
to Associate Professor of Physics without tenure.

Long Ju
to Associate Professor of Physics with tenure.

Kiyoshi Masui
to Associate Professor of Physics with tenure.

Michael McDonald
to Full Professor of Physics.

Lina Necib
to Associate Professor of Physics without tenure.

Phiala Shanahan
to Full Professor of Physics.

Julien Tailleur
to Full Professor of Physics.

Retirements

Edmund Bertschinger

Professor of Physics

Ed Bertschinger joined the MIT faculty in 1986 as assistant professor. A theoretical astrophysicist, he has made important contributions to our understanding of the cosmic microwave background radiation and the formation of galaxies and larger structures in the universe. Bertschinger is best known for his mentorship and training of students and for his support and advocacy of people underrepresented in STEM. He served as Physics Department Head and as the Institute Community and Equity Officer. Bertschinger is a faculty affiliate of the Program in Women's and Gender Studies. He is an honorary member of the MIT Alumni Association and has won the Everett Moore Baker Award for Excellence in Undergraduate Teaching and the Dr. Martin Luther King, Jr. Leadership Award.





Edmund Bertschinger



Alan Guth '69, PhD '72
Credit: Jae Guth

Alan Guth '69, PhD '72

Victor F. Weisskopf Professor of Physics, Post-tenure; MacVicar Fellow

While a postdoc at Cornell, Guth began studying the production of magnetic monopoles in the early universe at the urging of fellow postdoc Henry Tye, also a recent MIT PhD. It turned out that standard theories implied a huge overproduction of magnetic monopoles, so Guth and Tye began a search for possible alternatives. The work led Guth to develop what is now the leading theory of the early universe, cosmic inflation. For this and continued work in cosmology, Guth has been elected to the National Academy of Sciences and the American Academy of Arts and Sciences, and has been awarded the Kavli Prize in Astrophysics and the Breakthrough Prize in Fundamental Physics.

Sara Seager

Class of 1941 Professor of Planetary Science; Professor of Physics; Professor of Aerospace Engineering

Sara Seager joined the MIT faculty in 2007. She made foundational contributions to exoplanet science, including pioneering exoplanet atmospheric retrieval, defining the class of sub-Neptune planets, advancing the search for biosignature gases on exoplanets, and serving as overall lead on major concept studies in space-based direct imaging, including Starshade. She PI'd the ASTERIA CubeSat, initially with Draper Laboratory and later led by JPL; on orbit from 2017 to 2019, ASTERIA demonstrated precision pointing 100 times better than other spacecraft in its mass category, serving as a prototype for a constellation mission. As Deputy Science Director of the MIT-led NASA Explorer-class TESS mission, Seager helped establish planet finding as a major pillar of MIT space research. She is a member of the National Academy of Sciences and the American Philosophical Society, a MacArthur Fellow, a recipient of the Kavli Prize in Astrophysics, and author of the memoir *The Smallest Lights in the Universe*.



Sara Seager

News & Events in Physics

Pappalardo Distinguished Lecture

On October 9, 2025, the Department held the annual Pappalardo Distinguished Lecture in Physics. This year's speaker was MIT Professor **Matthew Evans**, MathWorks Professor of Physics. Professor Evans gave a talk titled "Gravitation Waves: Past, Present, and Future." Physics Department Head and William A. M. Burden Professor in Astrophysics **Deepto Chakrabarty '88** thanked Neil and Jane Pappalardo for their continued support of the Pappalardo Fellowships and this annual distinguished lecture. *(D. Forde)*

2026–2029 Pappalardo Fellowships in Physics Competition

The Department's flagship postdoctoral fellowship program, the Pappalardo Fellowships in Physics, completed its annual competition in January 2026 with the appointment of three Fellows.

Kehang Bai PhD '26 (**University of Oregon**) is an experimental particle physicist who seeks to discover new fundamental particles and forces at the Large Hadron Collider (LHC). With the ATLAS experiment, Kehang specialized in searching for unconventional signatures from hidden-sector physics using novel analysis techniques. Moving forward, she aims to study the Higgs boson as a portal to new physics by measuring its fundamental properties at the CMS experiment.

Jonah Herzog-Arbeitman (**Princeton University**) is a condensed matter theorist whose research has centered around flat bands: their classification by space group symmetry, their favored symmetry breaking orders and characteristic collective modes, and the strongly correlated phases they may host in real materials.

Qian-Ze "Rosella" Zhu (**Harvard University**) is a biophysicist whose research uses statistical physics, differentiable simulation, and machine learning to connect structure, dynamics, and computation across scales, and to derive limits and design principles testable in experiments.

For detailed biographies, including research descriptions and selected publications for all Pappalardo Fellows, please visit *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. Breen)*

Memorial Symposia: Weiss, Kleppner, and Loureiro

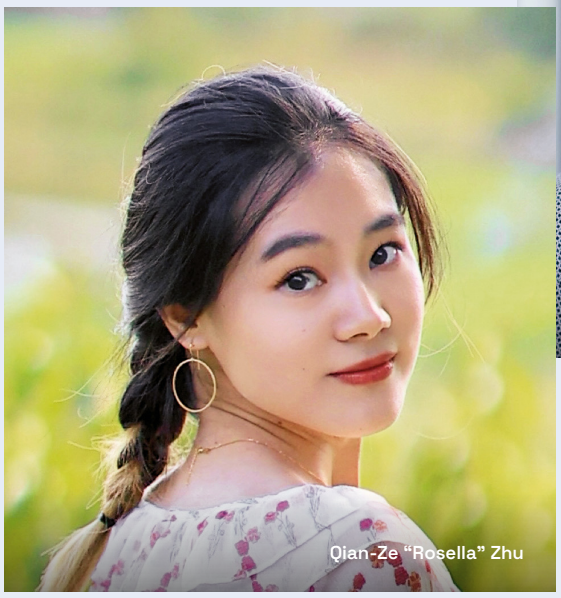
This spring, the memories of three Department faculty members were honored with symposia: Professors **Rainer** (**Rai**) **Weiss**, **Daniel Kleppner**, and **Nuno Loureiro**.

On February 27, 2026, MIT's LIGO group hosted a full day of talks and panel discussions honoring the legacy of **Rainer Weiss** '55, '62 PhD, Professor of Physics and 2017 Nobel Laureate. Featured speakers included Peter Fritschel, Director of the MIT LIGO Laboratory, on Weiss' scientific legacy, followed by multiple panel discussions reflecting the broad and deep scientific–and personal–impact of Weiss' long career. Topics ranged from "Big Questions in Astrophysics" to the "Cosmic Microwave Background," "Primordial Black Holes," "Cosmic Coda," "LIGO Instrumentation," concluding with "Rai's Stories" and "Bringing Rai's Legacy into the Future."

On March 14, 2026, the MIT-Harvard Center for Ultracold Atoms hosted a day of talks and personal


Kehang Bai


Jonah Herzog-Arbeitman


Qian-Ze "Rosella" Zhu

remembrances of renowned atomic physics pioneer **Daniel Kleppner**, the Lester Wolfe Professor of Physics Emeritus. Joining family members at the event were three Nobel laureates and multiple atomic physicists from across the globe. Talks showcasing Kleppner's legacy included: "Dan's Love Affair with Hydrogen: From Masers to Bose-Einstein Condensation" (Nobel laureate William Phillips), "Remembering Dan as a Scientist and as a Friend" (Nobel laureate Serge Haroche), "Dan, the Godfather of BEC" (Nobel laureate Wolfgang Ketterle), and former Kleppner student (at Harvard) and postdoc (at MIT) Cecil and Ida Green Professor of Physics, Post-tenure David Pritchard on "Dan: From Advisor to Colleague, 60 Years of Words."

On June 20, 2026, the Institute hosted a memorial service and academic symposium in honor of theoretical physicist and fusion scientist **Nuno F. G. Loureiro**, the Herman Feshbach (1942) Professor of Physics, Professor of Nuclear Science and Engineering, and Director of MIT's Plasma Science and Fusion Center, whose life was tragically cut short at age 47 last December. MIT Provost Anantha Chandrakasan and Institute Chaplain Thea Keith-Lucas led a service for family, colleagues, and students to share personal and professional reflections on Loureiro's impact. MIT Vice President for Research Ian Waitz then opened the academic symposium on Loureiro's research, which featured a scientific panel of speakers from Oxford and Lisbon Universities, Lawrence Livermore National Lab, MIT's Nuclear Science and Engineering Department, and concluded with an audience question and answer period. *(C. Breen)*

California Trip

Physics Department Head **Deepto Chakrabarty** traveled to Palo Alto, CA, on March 4, 2026. At a breakfast reception at the Crown Plaza, he introduced **Professor Scott Hughes**, Margaret MacVicar Faculty Fellow and Interim Associate Department Head. Professor Hughes gave a talk titled "Einstein's Ears: The Astronomy of Gravitational Waves." Eighty-six alumni and friends gathered that morning to welcome the Physics Department. *(D. Forde)*

Patrons of Physics Fellows

This year the Department held its annual Celebration of the Patrons of Physics Fellows Society on Friday, April 10, 2026. Physics Department Head **Deepto Chakrabarty** introduced the following students supported by Department fellowships as speakers for the evening: **Eleanor Richard**, **Frank Fellow**; **Sergio Eraso**, **Thomas Fellow**; and **Thomas Barbera, Whiteman Fellow**. Professor Chakrabarty concluded the evening thanking all Patrons for their continued support of the Department through these instrumental fellowships. Patrons in attendance were **Dr. Neil Constable**, **Dr. Marc Gorenstein '72** (**VIII**), **Curtis Marble '63** (**VI**), **Marina Sakharov-Liberman**, **Douglas Smith SM '96**, and **Dr. Paul A. Swartz '73** (**VIII**), **PhD '79** (**VIII**). *(D. Forde)*

London Trip

On Thursday, April 30, 2026, Department Head **Deepto Chakrabarty** hosted an evening talk at the IET London Savoy, featuring **Professor Scott Hughes**. Professor Hughes gave a talk titled "The End of the Beginning: Gravitational-wave Astronomy So Far, and the Road Ahead," to sixty-five alumni and friends of the Department. *(D. Forde)*



Marina Sakharov-Liberman and Douglas Smith SM '96 with Department Head Deepto Chakrabarty and graduate student Tony Teng. Credit: Justin Knight Photography.



Professor of Physics Tracy Slatyer, Director, MIT Center for Theoretical Physics—A Leinweber Institute, with Dr. Neil Constable and graduate student fellows. Credit: Justin Knight Photography.

Spring 2026 Pappalardo Fellowships in Physics Annual Symposium with Remembrance of A. Neil Pappalardo EE '64

The Pappalardo Fellowships in Physics program held its annual spring symposium on May 14, 2026, featuring five research talks from current fellows, followed by the Department's community remembrance of longstanding benefactor and Pappalardo Fellowships Program founder **A. Neil Pappalardo EE '64**.

This year's five speakers for the symposium included Pappalardo Fellows Drs. **Gillian Kopp** ("Low-Level Detector Information as a Window into New Physics"), **Leyna Shackleton** ("Mapping the Quantum Limits of Classical Simulatability"), **Jens Hertkorn** ("Quantum Gases Under the Microscope: New Windows into Strongly Correlated Matter"), **Ross Dempsey** ("Colliders from First Principles"), and **Kevin Nuckolls** ("Moiré Crystals").

Physics Department Head **Deepto Chakrabarty '88**, William A. M. Burden Professor in Astrophysics, then led the community Remembrance of **A. Neil Pappalardo EE '64**, featuring remarks from himself (overview of Neil's deep impact on myriad areas of MIT Physics, as well as his personal perspective on Neil's support of Physics department heads); **Marc Kastner**, Donner Professor of Science Emeritus and Dean Emeritus, School of Science (founding of the Pappalardo Fellowships program, Neil's critical support of the Green Center for Physics, and the Department's Pappalardo Distinguished Lecture series); **Robert Simcoe** (2003–2006 Pappalardo Fellow), Francis L. Friedman Professor of Physics and Director, MIT Kavli Institute for Astrophysics and Space Research (Neil's critical role for the Magellan Telescope project, his support of astrophysics junior faculty, and impact of astrophysics Pappalardo fellows); and **Peter Fisher**, Thomas A. Frank (1977) Professor of Physics and Head, Office of Computing and Data, Associate Vice President of Research (his experience serving upon inaugural Pappalardo Fellowships Committee, nurturing the program's development, and seeing the widespread, positive impact upon faculty involved with the program over the years).

Videos of all talks, including the remembrance of A. Neil Pappalardo, are available on the Department's YouTube page at *www.youtube.com/@MITDepartmentofPhysics/videos*. *(C. Breen)*

A. Neil Pappalardo EE '64 (1942–2026) Remembered by MIT Physics



From left: Former Department Head Ed Bertschinger, Cecil & Ida Green Professor of Physics and 2000–2003 Pappalardo Fellow Marin Soljačić '96, Neil Pappalardo.

"We have a large department, and it is only through the Pappalardo Fellowships that faculty from across the department come together for a shared purpose....this shared work and resulting relationships have contributed greatly to make our department one of the most supportive environments to be found anywhere."

Jeff Gore '99
Professor of Physics;
2007–2010 Pappalardo Fellow

"The Pappalardo Fellowship has been totally transformative, not just for me but for everyone fortunate enough to receive one. I will always remember Neil's enthusiasm, interest, and above all his support."

Richard Nally
2024–2027 Pappalardo Fellow

"When I first heard about the Pappalardo Fellowship, I knew it was one of the premier postdoctoral positions in physics. When I joined the MIT faculty in 2010, I learned that Neil Pappalardo was a real person, very much alive and highly engaged with the MIT Physics community. Neil was deeply curious about physics. He encouraged all of us at MIT to reach for the stars, both figuratively and in some cases literally. Neil reveled in our successes, however we defined them, and was passionate about cultivating connections. Neil's commitment to supporting the next generation of physics talent lives on in the Pappalardo Fellows (past, present, and future), and in the many faculty like myself who benefited from his engagement and advocacy."

Jesse Thaler
William and Emma Rogers Professor of Physics and Director, Laboratory for Nuclear Science

"We owe anything we have in our careers to [Neil's] generosity, support, and encouragement."

Lu Li
Professor of Physics, University of Michigan, Ann Arbor; 2008–2011 Pappalardo Fellow

"Neil's larger-than-life presence, his wisdom and intellect, his deep interest in science and people, his humor and wit, his self-effacing self-assurance, his love of us all, are forever the gifts he has given me..."

Nergis Mavalvala
Curtis (1963) and Kathleen Marble Professor of Astrophysics and Dean, School of Science

"I admire Neil for what he has done for MIT and the whole world."

Wolfgang Ketterle
John D. MacArthur Professor of Physics; 2001 Nobel Laureate

"*The Pappalardo Fellows program at MIT is arguably the most successful postdoctoral program in physics in the world; it has produced many outstanding physicists who are pushing back the frontiers of science around the world. We all owe Neil and Jane a huge debt of gratitude for this.*"

Robert J. Birgeneau
Professor of Physics Emeritus and Chancellor Emeritus, University of California, Berkeley

"I am so lucky to have met Neil during my first year as a Pappalardo Fellow. His sharp and insightful questions are legendary in the Department. I know I will strive to emulate that energetic curiosity of his..."

Ross Dempsey
2025–2028 Pappalardo Fellow

"...one of my most cherished memories is sharing the holiday brunch this past December—a day filled with warmth, laughter, and Neil's wonderful curiosity."

Xiaoyuan Zhang
2025–2028 Pappalardo Fellow

"*He touched so many lives with his charitable work, his genuine enthusiasm for science, and his love of MIT. He also changed my life by empowering me to pursue my dreams.*"

Sepehr Ebadi
2024–2025 Pappalardo Fellow

"[Neil] touched our lives and the lives of everyone who knew him with warmth and kindness. He inspired so many young physicists and created a community of Pappalardo Fellows. His was a life filled with meaning."

Alan (and Susan) Guth
Victor F. Weisskopf Professor of Physics, Post-tenure

"The Pappalardo Fellowships are one of the truly great things about the MIT Physics Department. I have enjoyed tremendously interacting with the amazing Pappalardo Fellows over the years, and serving on the Pappalardo Fellowships Committee."

Mike Williams
Professor of Physics and IAIFI Interim Director

"It is hard to overstate the impact and influence that the Pappalardo family has had in my life."

Pablo Jarillo-Herrero
Cecil and Ida Green Professor of Physics

"Neil made the Physics Department better in so many ways. He helped us join the Magellan Telescope consortium; he made it possible for us to renovate space for the Department in buildings 4 and 6 with the spectacular Sol LeWitt floor; he gave us funds we needed to renovate space to recruit two of our top researchers in condensed-matter physics. But the Pappalardo Fellowship program will be his most important legacy, because of the support it has provided for so many of the world's best physicists. His connection with these young people is something they will cherish throughout their careers. I will be forever grateful to Jane and Neil for their generosity and, especially, for welcoming the fellows into what has become an extended Pappalardo family."

Marc Kastner
Donner Professor of Science Emeritus and Dean Emeritus, School of Science

"One of the best things about Neil's association with the Physics Department was that he made it a family-to-family connection."

Ed Bertschinger
Professor of Physics Emeritus and former Department Head

"...it has been incredible to see the impact the Pappalardo family has on the Department. The opportunities this fellowship provides are so transformative, not only for myself personally, but for the support and advancement of physics at MIT that it encourages and enables."

Gillian Kopp
2025-2028 Pappalardo Fellow

"... It was a privilege to be a part of the Pappalardo Fellowships Committee at its inception, and to witness its growth thanks to Neil's continuous involvement."

Mehran Kardar
Francis L. Friedman Professor of Physics

"... [Neil's] memory will be a blessing that continues to ripple outwards, touching so many."

Krishna Rajagopal
William A. M. Burden Professor of Physics; Margaret MacVicar Faculty Fellow

"NEIL WILL BE DEEPLY MISSED AND LONG-REMEMBERED, AND HIS LEGACY WILL CONTINUE TO DRIVE PHYSICS DISCOVERY FAR INTO THE FUTURE."

Tracy Slatyer
Professor of Physics and Director, CTP-LI



ABOVE: Pappalardo Fellowships 25th Anniversary speakers with Neil Pappalardo. From left: Former Pappalardo Fellows and Professors Marin Soljačić (MIT), Ashvin Vishwanath (Harvard), Ben Safdi (UC-Berkeley), Neil Pappalardo, Nitya Kallivayalil (UVA-Charlottesville), Jocelyn Monroe (Oxford), with Cecil & Ida Green Professor of Physics Pablo Jarillo-Herrero (MIT).

"The Pappalardo Fellowship has changed my life for the better, forever."

Jens Hertkorn
2024–2027 Pappalardo Fellow

"We remember Neil Pappalardo as an MIT alumnus whose generosity and vision made a lasting difference to the Physics Department and to the many people whose work and aspirations it has shaped. His support was more than philanthropy; it was an investment in scientific discovery, young talent, and the future of physics. It is especially fitting that this symposium brings together young researchers whose work has been supported by his generosity. Their presence reflects the living character of Neil Pappalardo's legacy: a gift that continues to create opportunities, inspire new ideas, foster collaboration, and prepare new generations of scientists to carry the work forward."

Leonid Levitov
Professor of Physics

Student Honors & Awards: Undergraduate



ABOVE: 2026 Alan H. Barrett Prize winner and 2026 Morse/Orloff Award for Research winner Vinh Tran. Credit: Steph Stevens.

2026 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 or undergraduate student with outstanding research in astrophysics.

Vinh Tran SB '26
Academic advisor: Philip Harris

2026 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.

Julia Li SB '27

Vlad Stefan Oros SB '27

The 2026 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 one or more senior students of high academic standing who plan to pursue graduate studies in physics.

Vinh Tran SB '26
Academic advisor: Philip Harris





The 2026 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 each winner.

SERVICE

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

Felicia Xiao SB ’26
Academic advisor: Tracy Slatyer

SCHOLARSHIP

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

Munich Tripattaranan SB ’26
Academic advisor: Isaac Chuang

RESEARCH

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

Katherine Panebianco SB ’26
Academic advisor: Philip Harris



ABOVE LEFT: 2026 Joel Matthew Orloff Award for Service winner Felicia Xiao. Credit: Steph Stevens.

ABOVE RIGHT: 2026 Joel Matthew Orloff Award for Scholarship winner Munich Tripattaranan. Credit: Steph Stevens.

LEFT: Joel Matthew Award for Research winner Katherine Panebianco. Credit: Steph Stevens.



RIGHT:
2026 Order of the Lepton Award winner Yongao Hu. Credit: Steph Stevens.

The 2026 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.

Yongao Hu SB '26

Academic advisor: Richard Milner

2026 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 21 new members.

Erez Abrams
Emily Albornoz
Kaylee Barrera
Rebecca Chang
Stanley Chen
Erin Cusson
Ne Dassanayake
Evan Erickson
Matson Garza
Aarush Gupta
Yongao Hu
Haedam Im
Teo Lara
David Lee
Oluyinka Lindblad
Lawrence Long
Max Miller
Max Misterka
Emily Neill
Temujin Orkhon
Sam Packman
Katherine Panebianco
Jiwoo Park
Rishab Parthasarathy
Kartik Pingle
Michael Popik
Diego Rivera
Alexander Sherstnev
Minki Shim
Caio Silva
Gordon Su
Lily Sun
Wendy Sun
Kyle Tignor
Munich Tripattaranan
Felicia Xiao
Lana Xu

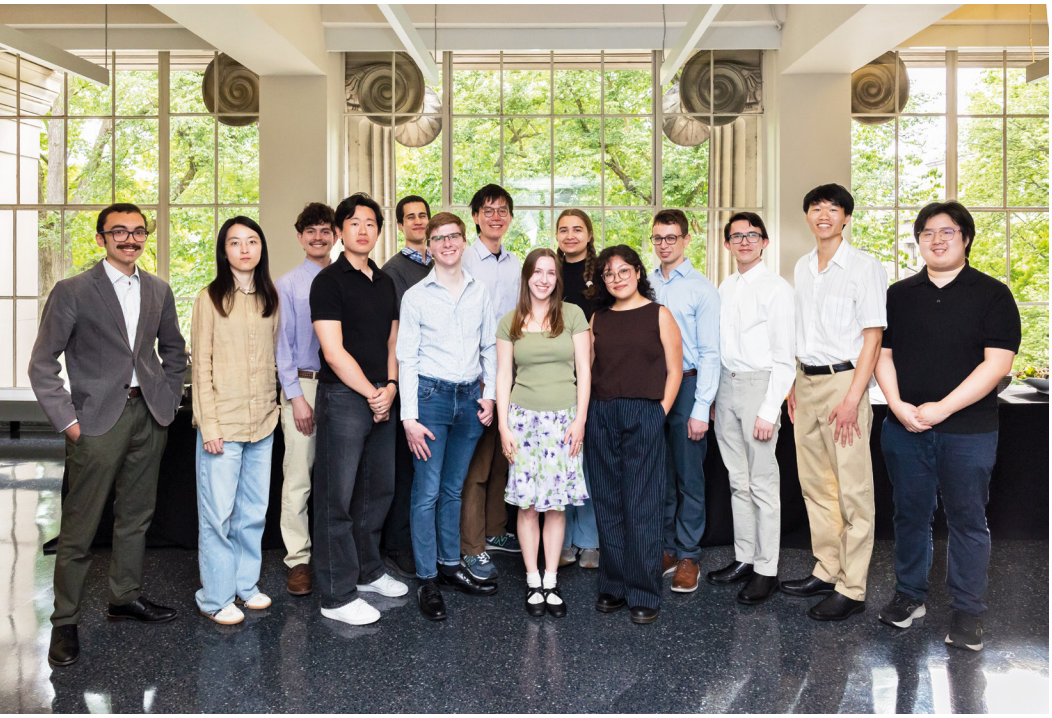


LEFT:
2026 Sigma Pi Sigma inductees. Credit: Steph Stevens.

2026 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 99 members of the Class of 2026, 22 of whom are physics majors, to membership in the Society.

Kaylee Barrera
Henry Bezos
Evan Erickson
Kevin Cheng
Maston Garza
Alex Gu
Yongao Hu
Luke Kelly
Teo Lara
Oluyinka Lindblad
Skipper Lynch
Max Miller
Emily Neill
Sam Packman
Jiwoo Park
Diego Rivera
Caio Silva
Gordon Su
Wendy Sun
Kyle Tignor
Munich Tripattaranan
Lana Xu



LEFT:
2026 Phi Beta Kappa inductees. Credit: Steph Stevens.

2025–2026 Buechner Undergraduate Advising Award

Awarded to faculty members who show exceptional care, mentorship, and guidance for undergraduate students.

Philip Harris PhD '11

Associate Professor of Physics



RIGHT:
Philip Harris PhD '11. Credit: Justin Knight Photography.

Student Honors & Awards: Graduate

The Department's graduate awards winners for the 2024–2025 academic year (listed below) were publicly announced at an on-campus event in September 2025. A listing of all prizes and winners for 2025–2026 will appear in the Fall 2027 issue of *physics@mit*.

2024–2025 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. One thousand dollars is awarded annually to one or more graduate students mid-way through thesis research in any field, with preference for an experimentalist.

Ruixiao Yao
Atomic Physics
Thesis supervisor: Martin Zwierlein

Alexandra Klipfel
Experimental Nuclear & Particle Physics
Thesis supervisor: Peter Fisher

2024–2025 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.

Sal Pace
Theoretical Condensed Matter Physics
Thesis supervisor: Xiao-Gang Wen

Marianne Moore
Center for Theoretical Physics–A Leinweber Institute
Thesis supervisor: Tracy Slatyer

2024–2025 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.

Abdelaziz Hussein

MIT Kavli Center for Astrophysics and Space Research
Thesis supervisor: Lina Necib

2024–2025 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 1962–67.

Bahar Shakerifakher

Departments of Brain and Cognitive Sciences and Physics
Thesis supervisor: Ila Fiete

Rachel Steinhorst

Center for Theoretical Physics–A Leinweber Institute
Thesis supervisor: Krishna Rajagopal

Laurel White

MIT Kavli Center for Astrophysics and Space Research
Thesis supervisor: Michael McDonald

Graduate Degree Recipients 2025–26

(PhD, except as noted)

SEPTEMBER 2025

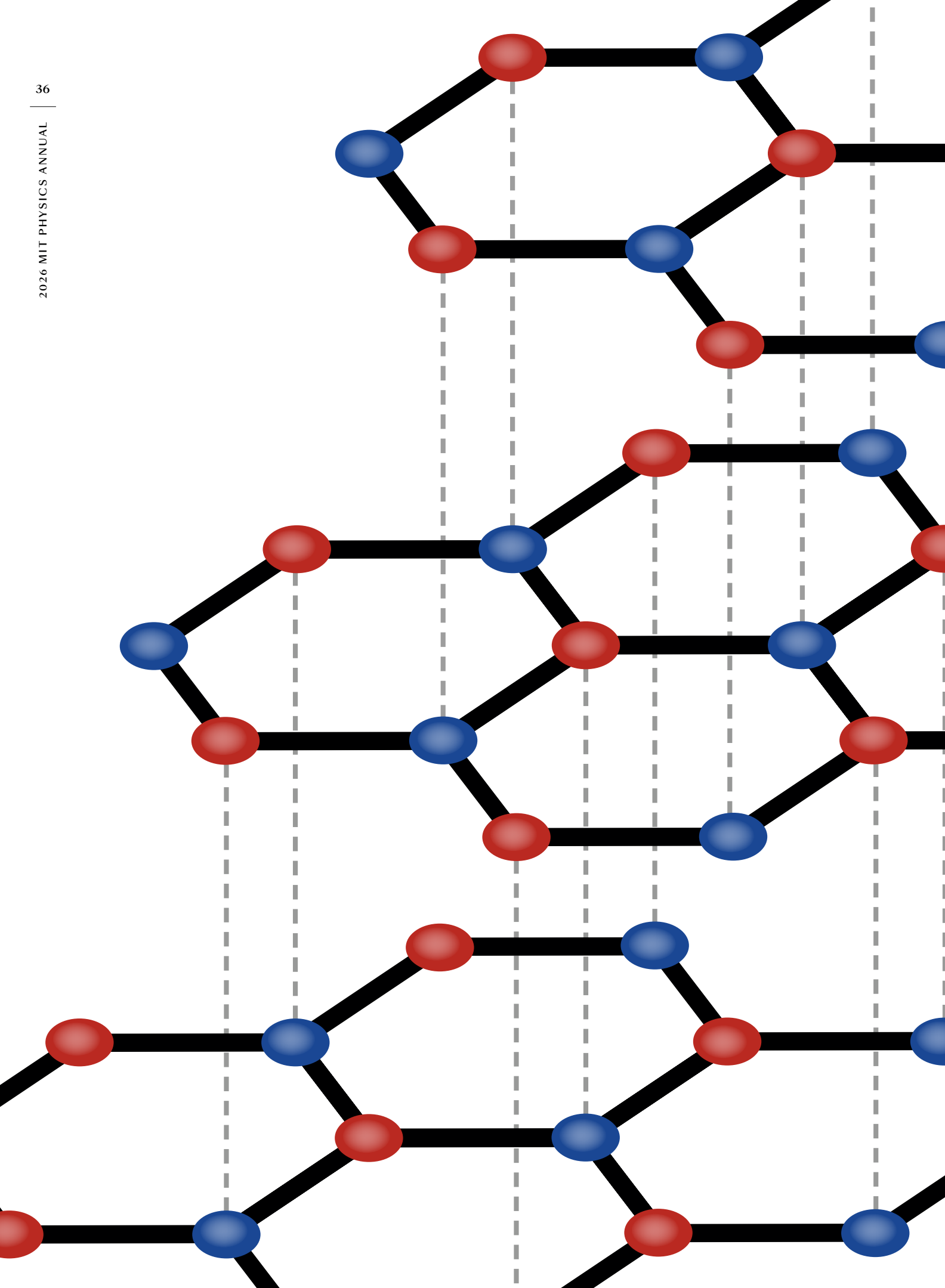
Ryan Abbott
Samuel Aronson
Artur Avkhadiev
Shankar Balasubramanian
Arkya Chatterjee
Anjie Gao
Hugh Higinbotham
Collin Lewin
Joshua Lin
Ziming Liu
James McGreivy SM
Nisarga Paul
Matthew Peters
Zhiquan Sun
Weiran Xu

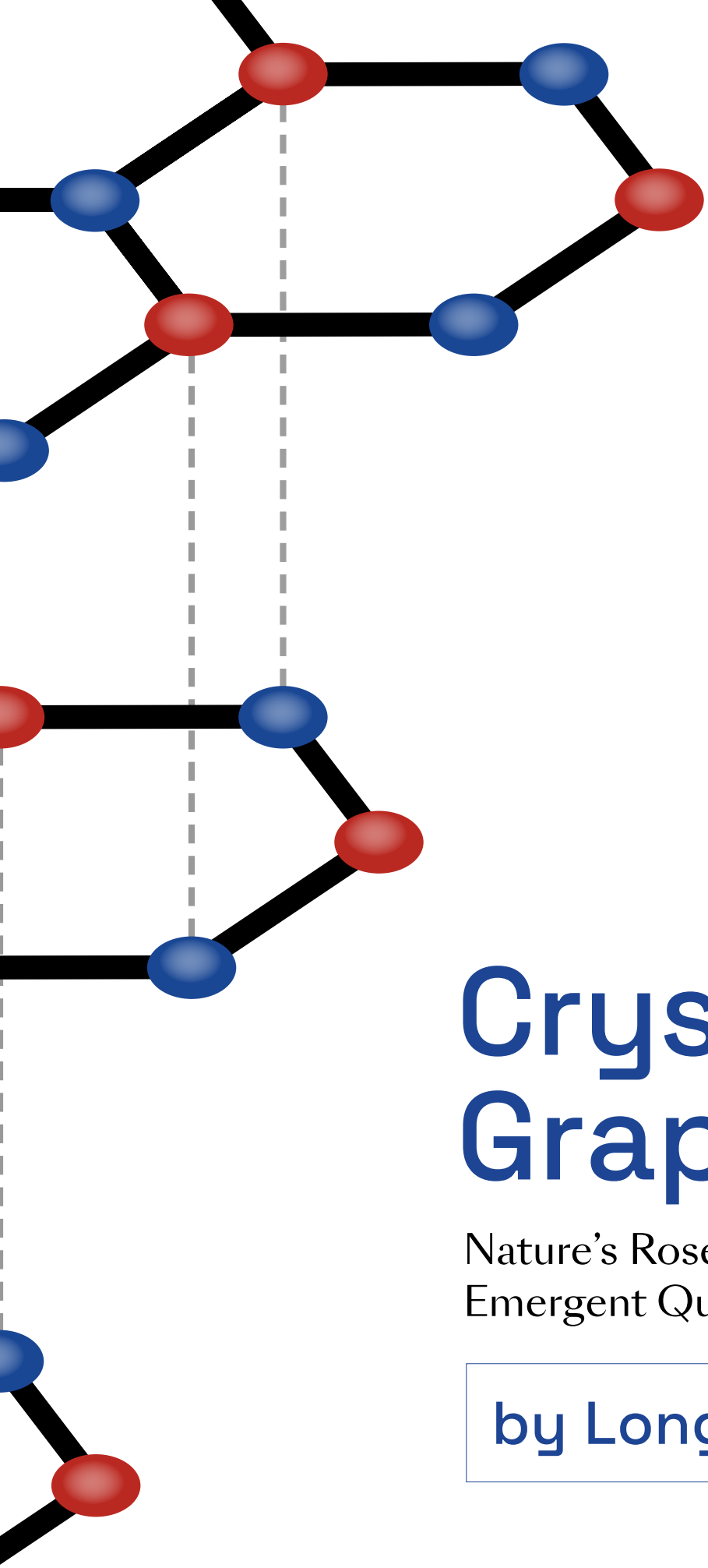
FEBRUARY 2026

Jack Bolster
Eric Michaud
Benjamin Reichelt
Anna Simpson SM
Xirui Wang

MAY 2026

Magdelena Allen
Elba Alonso-Monsalve
Sean Benevedes
Kai-Feng Chen
Zhuo Chen
Chung-Tao Chou
David DePalma
Raymond Diab
Dominika Durovcikova
Tonghang Han
Jack Heinzel
Deepti Kannan
Abijith Krishnan
Boning Li
Daniel Mark
Ethan Marx
Megan Masterson
Marianne Moore
Khachatur Nazaryan
Darcy Newmark
Meredith Neyer
Kyoung Hun Oh
Botond Oreg
Sal Pace
Sangeon Park
Aidan Reddy
Jared Rivera
Tzu-An Sheng
Jasmine Sinanan-Singh
Haochen Wang
Philip Weigel
Laurel White
Jixiang Yang
Yunchao Zhang





Crystalline Graphene:

Nature's Rosetta Stone of Emergent Quantum Phenomena

by Long Ju

More is different–the philosophy of constructionism

If someone asked the question "What is MIT?", most people would agree that the answer should be composed of two key parts: who is at MIT and how do they interact with each other. The individuals define the basic building blocks, while their interactions more often determine the structure and how the community exhibits itself to outside observers. These simple empirical rules apply to any community like MIT, or a state or a nation, and they guide our exploration and understanding of nature as well.

For a long time in scientific history, physicists tried to understand the composition of the material universe by seeking the smallest units of matter. This approach of reducing matter, named as *reductionism* in philosophy, can be traced back to ancient Greece when the word *atom* was coined. The associated natural philosophy, Atomism, proposed that the physical universe is composed of fundamental indivisible components known as atoms. Following this reductionism philosophy, particle physicists have discovered many elementary particles and the Standard Model, which greatly improved our understanding of the universe.

On the other hand, physicists asked if knowing the building blocks is enough to understand matter and nature. There are simple examples to justify this question: both graphite and diamond are composed of the same simple carbon atoms, but they exhibit contrasting properties in almost every sense—soft vs. hard, opaque vs. transparent, conducting vs. insulating. How the building blocks are arranged into crystal structures and interact with each other can lead to dramatically different macroscopic phenomena. This idea is described as the philosophy of *constructionism*, in contrast to reductionism, and it tells us that new and unexpected properties could emerge from the assembly of simple elementary particles.

This philosophy is best explained by Philip Anderson in "More is Different." [1] The early development of the quantum theory of solid-state materials, later coined by Anderson as condensed matter physics, has led to the successful categorizations of metals, semiconductors, and insulators. Some of these materials form the foundation of the electronic and optical industries, which have completely transformed our society. Condensed matter physicists aim to explore and understand such emergent phenomena in various solid-state materials. These materials provide an extremely rich platform to explore emergent quantum phenomena, given their rich chemical compositions and structures.

Electron correlation and topology: pillars of modern condensed matter physics

While condensed matter materials are composed of atoms, which include nuclei and electrons, most of their properties are determined by the behavior of electrons. In the simplest picture to describe electrons in crystals, they are treated as independent particles. This single-particle assumption has proven to be very effective in predicting the basic properties of many metals, semiconductors, and insulators. However, electrons interact with each other through the Coulomb repulsion and Fermi-Dirac statistics rules. When such interactions are strong enough and electrons' behaviors are strongly correlated, completely new phenomena can emerge from the large collection of electrons: a form of constructionism that is specific to electrons,

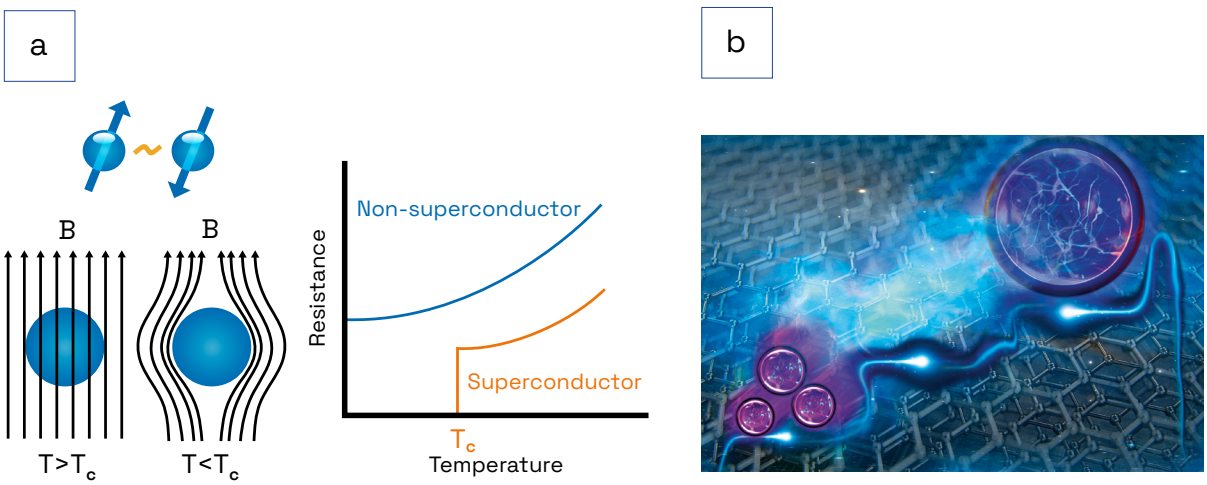


FIGURE 1:
(a) Electron pairs lead to zero resistance and perfect exclusion of the magnetic field in superconductors. (b) Illustration of the fractional quantum Hall effect, in which interacting electrons effectively break into fractions. Credit: Ju Group, MIT.

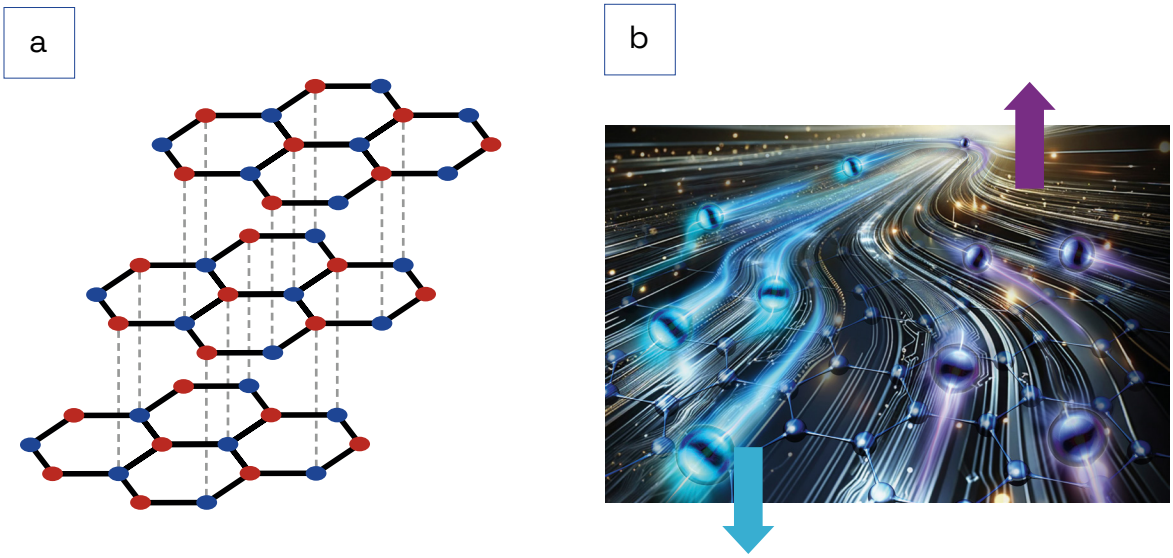


FIGURE 2:
(a) Layers of carbon forming the rhombohedral stacking order, as part of natural graphite. Credit: Ju Group, MIT. (b) Illustration of IQAHE, which spatially separates traffic of forward- and backward-moving electrons to avoid colliding. Credit: Sampson Wilcox, MIT RLE and Ju Group, MIT.

which is one of the most well-understood of elementary particles. These phenomena are the central topics of modern condensed matter physics, and their underlying principles are much more awe-inspiring than the simple principles that distinguish metals from insulators.

Two famous examples best represent these two principles. In 1911, the first superconductor was discovered when mercury was cooled down to about -269° Celsius. The microscopic understanding was not available until four decades later, which suggests that, remarkably, electrons attract each other and form pairs in superconductors. The properties of superconductors are effectively determined by these pairs, as if the pairs are the elementary particles instead of the constituent electrons! Since then, many superconductors, including some at much higher temperatures, have been discovered. Phenomenologically, superconductors appear as just perfect metals that have zero electrical resistance, but soon they were found to be a completely new phase of interacting electrons that also perfectly expels magnetic field. This field expulsion, known as the Meissner Effect, is observed widely in superconductors, regardless of the specific superconducting material.

In another case, the electrical resistance of certain materials is measured to be perfectly quantized. In early 1980s, physicists measured some very clean materials based on silicon and gallium arsenide, in which electrons are confined in a quasi-two-dimensional plane. When subjected to a high magnetic field, the so-called Hall resistance was shown to be exactly the same value as defined by $h/\nu e^2$, where h and e are fundamental constants in physics, and ν is either an integer [2] or fraction [3]. These phenomena, known as *integer and fractional quantum Hall effect*, revealed for the first time perfect quantization of a physical quantity in condensed matter materials. The implication is deep and profound: if real materials have defects and disorders and are far from perfect, why would the collection of electrons decide to exhibit perfectly quantized resistance that is accurate down to nine zeros after the decimal point? It was later found that the underlying principle is rooted in topology of the electronic band structure, much like the difference between a donut and an orange: the former has one hole, while the latter has zero, so they each have a distinct topology, unless a violent operation transforms one to another.

The Rosetta stone of emergent quantum phenomena?

Apart from the examples given above, condensed matter materials have exhibited various emergent quantum phenomena driven by electron correlation and topology, sometimes with the two mechanisms intertwined. Given that there are more than 100 elements in the periodic table, and one can combine pretty much an arbitrary number of them to assemble into crystals, the power of constructionism to enable a plethora of emergent phenomena seems to be well-justified and expected.

However, instead of synthesizing many complex materials, our group at MIT focuses on a particularly simple material that is a few layers of carbon atoms, known as *rhombohedral graphene (RG)*. We start with

ordinary graphite, which is pencil lead, that can be exfoliated into thin layers by peeling with ordinary tape. Within the exfoliated thin layers, we find that regions of RG exist. Although extremely simple in its chemical composition and structure, by early 2023 RG has already exhibited very interesting properties that are both within and beyond the single-particle picture. Thanks to the collective efforts by several groups in the U.S. and U.K., we already knew that RG can be a metal, semiconductor, insulator, and even a superconductor, depending on the experimental conditions. In particular, we at MIT observed a so-called *integer quantum anomalous Hall effect (IQAHE)*, which effectively demonstrated an electronic highway along which electrons propagate without energy dissipation [4].

Given these initial rich observations, we wondered if RG could be a model system to explore, engineer, and understand various emergent quantum phenomena in condensed matter physics? In the history of deciphering ancient Egyptian literatures, the Rosetta Stone played the key role, as it provides a dictionary for translation. Given the vast variety of condensed matter materials with different chemistry and structures, and the wide range of emergent phenomena, can we use RG as the Rosetta Stone to understand existing phenomena, for which theories are still being developed? And even better, can we use it as the crystal ball to predict unprecedented phenomena, which are beyond theoretical expectations?

Unprecedented and unpredicted duo

The real excitement in RG for emergence started in the summer of 2023, when we observed the fractional quantum anomalous Hall effect (FQAHE) [5]; "anomalous" means at zero magnetic field. It shows the same perfectly quantized Hall resistance as the Nobel Prize-winning fractional quantum Hall effect, but this time at zero magnetic field. Our device contains a five-layer RG flake and another flake material called hexagonal boron nitride (also known as "white graphene"). They form a moiré superlattice, kind of a spatial beating between two atomic patterns that have slightly different periods. Our observed FQAHE was made in the absence of any theoretical predictions, and happened shortly after a similar effect was reported the same summer in a very different material of twisted MoTe2. FQAHE was predicted for twisted MoTe2, but the same theory does not seem to work for graphene. Even after three years of heavy investigations by theorists all around the world the underlying mechanism is still under debate and remains a central problem in the field.

To understand the mechanism of FQAHE in graphene, we further explored a device in which RG and hBN form a very large twist angle, which was known to suppress or eliminate the moiré effect. This time there is no FQAHE, but instead superconductivity [6].

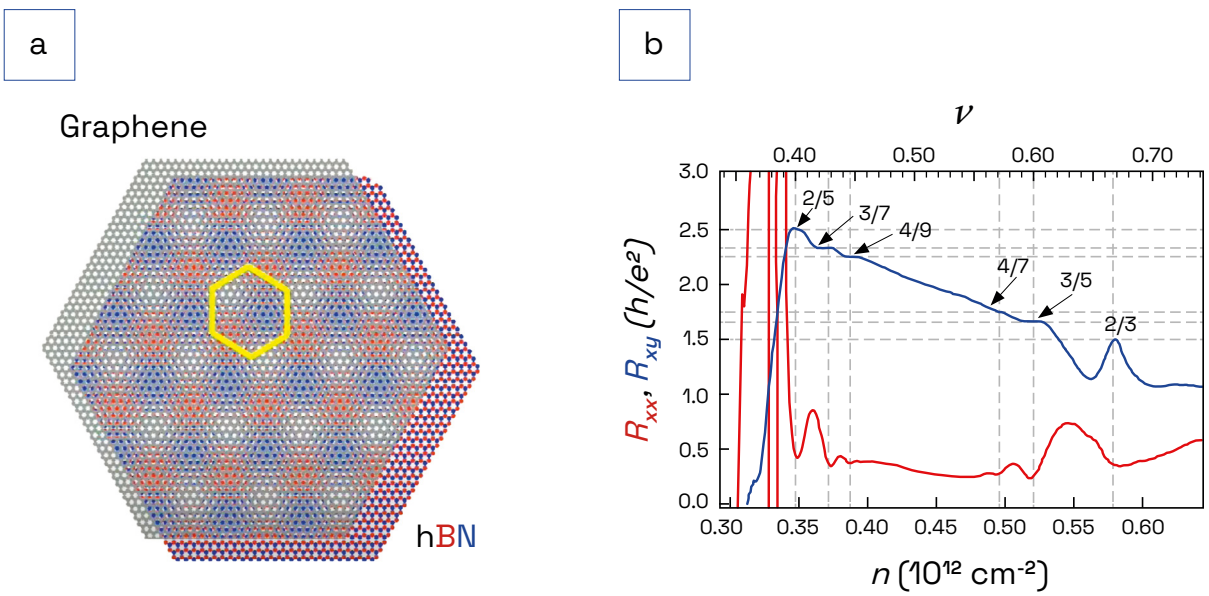


FIGURE 3: (a) Moiré superlattice formed between graphene and hBN as a spatial beating pattern. (b) FQAHE with plateaus of the Hall resistance (R_{xy}) precisely quantized at $h/\nu e^2$, where ν takes fractional values. Credit: Guorui Chen/ Shanghai Jiao-Tong University.

Surprisingly, this superconductor exhibits some very exotic phenomena not observed in any other superconductors since 1911: when the external magnetic field is swept, the resistance of the superconductor goes from zero to finite to zero and shows a delay between forward and backward scanning. Such kind of magnetic field dependence, known as *hysteresis*, indicates that the superconductor is itself a magnet! This directly challenges the conventional understanding that superconductivity and magnetism are mutually exclusive. A direct consequence is that the superconductor spontaneously picks up chirality, which usually describes the left- and right-hand-like structures in chemical molecules. Here the pairs of electrons do not harbor structural chirality, instead they circle around clockwise or counter-clockwise, corresponding to left- or right-handedness.

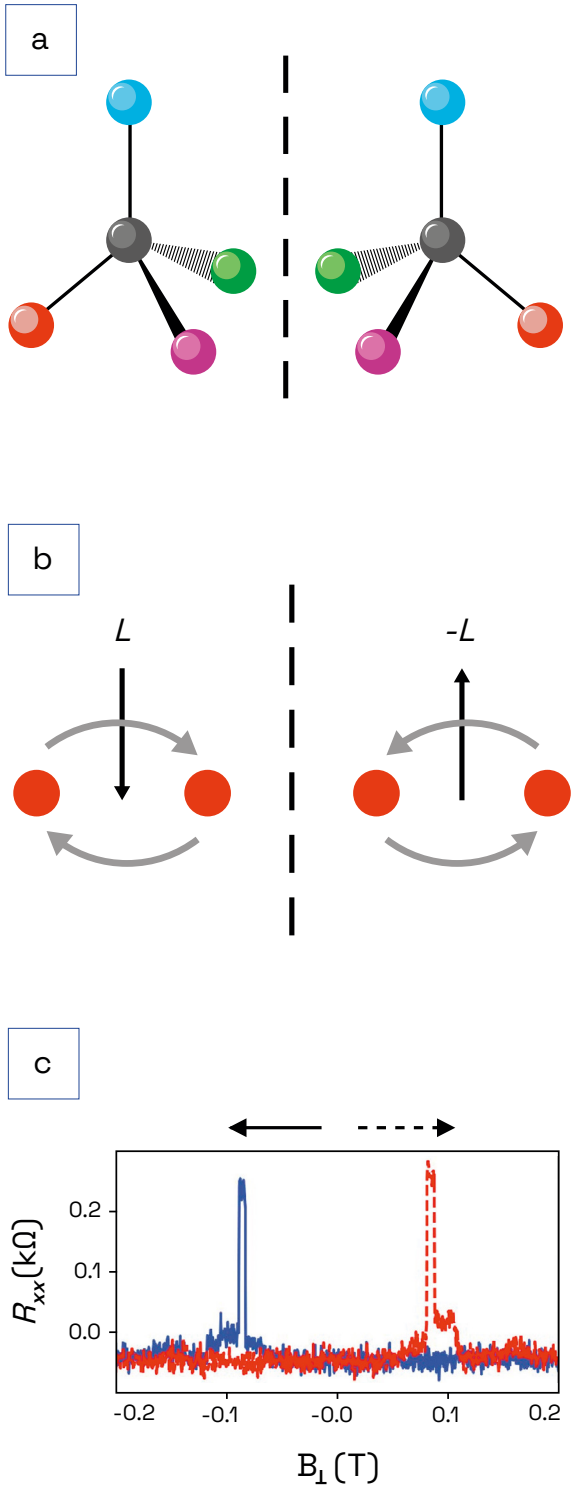


FIGURE 4:
(a) Structurally chiral molecules that form mirror images. (b) and (c) Chiral superconductor with electron pairs winding clockwise and counter-clockwise (forming mirror images), resulting in opposite angular and magnetic moment states that are connected by hysteretic resistance curve under scanning magnetic field. Credit: Ju Group, MIT.

Both the FQAHE and chiral superconductivity are unique quantum states of interacting electrons, and neither of them was predicted in RG by theory before our experiments. They both exhibit new features that distinguish from the conventional quantum Hall materials and superconductors. The most surprising thing is that the duo of these unprecedented and unpredicted emergent quantum phenomena co-exist in simple crystalline graphene, which is the gift by nature.

A new paradigm of quantum many-body physics

One might ask how can a single material exhibit so many different properties? The truth is that we are not just dealing with what nature invented; we can control the properties of RG by tuning a range of experimental knobs. For example, we can apply electric voltages through the so-called gates near the two-dimensional RG flake. This allows us to add or withdraw electrons from RG and change the energy of states, independently. In addition, we can proximitize RG by other materials such as hBN and semiconductors, to endow new flavors to electrons in RG, such as the so-called spin-orbit coupling, which is usually very weak in carbon atoms, and the moiré superlattice effect, which modulates the electric potential in addition to that from the carbon atom itself. Through these operations, we can transform RG into effectively a million different conventional materials, each of which has its own interesting properties. We note that the most important factor underscoring the majority of the observed phenomena is the so-called flat electronic band. Electrons in this condition behave as though they are very heavy and move slowly so that they have enough time to interact

with each other and co-ordinate behaviors in a strongly correlated way. This is much like two persons sitting down to chat to make a plan in a relaxed environment, instead of rushing past each other quickly.

We tune all the experimental knobs and study RG in our lab at MIT, practicing a new paradigm of condensed matter physics. Compared to synthesizing materials with complex chemistry and structure, this new and controlled paradigm allows us to separate the effects of different factors and identify the key one that is responsible for an observed phenomenon. It demonstrates a deep and intriguing unification of the reductionism and constructionism: the simplest components can be tuned to interact strongly and generate the most complex phenomena—a new philosophical way of understanding condensed matter physics and nature.

Into the future

This new paradigm opens up exciting opportunities for further exploring quantum emergence and constructionism. For example, the FQAHE state is expected to host the so-called anyons—entities that have fractional charge and obey fractional statistics rules that are different from fermions or bosons. Anyons are not real particles, as they only emerge as a consequence of interactions between electrons. However, they exhibit measurable experimental effects which are the same as if they are real particles.

On the other hand, chiral superconductivity is expected to host Majorana zero modes—a quasiparticle that is its own anti-particle and with memory of the history of being exchanged with other Majorana particles. This is different from fermions and bosons, the two categories that all real particles belong to, for which exchanging two particles merely results in an additional phase factor of wave function. The memory effect of exchanging Majorana zero modes can be utilized to engineer quantum bits, which could resist perturbations from the environment and improve the performance of quantum computers.

Regardless of applications, our observations point to exploring constructionism at a fresh new level: given the various states of crystalline graphene, which already host intriguing emergent phenomena, one can envision constructing completely new devices to place these phenomena at close proximity and exploring what could emerge from their interactions. What to expect? Only time can answer it. Right now, we are collaborating with several condensed matter physics groups at MIT to explore this frontier—those of Professors Ray Ashoori, Liang Fu, Senthil Todadri, and Xiao-Gang Wen.

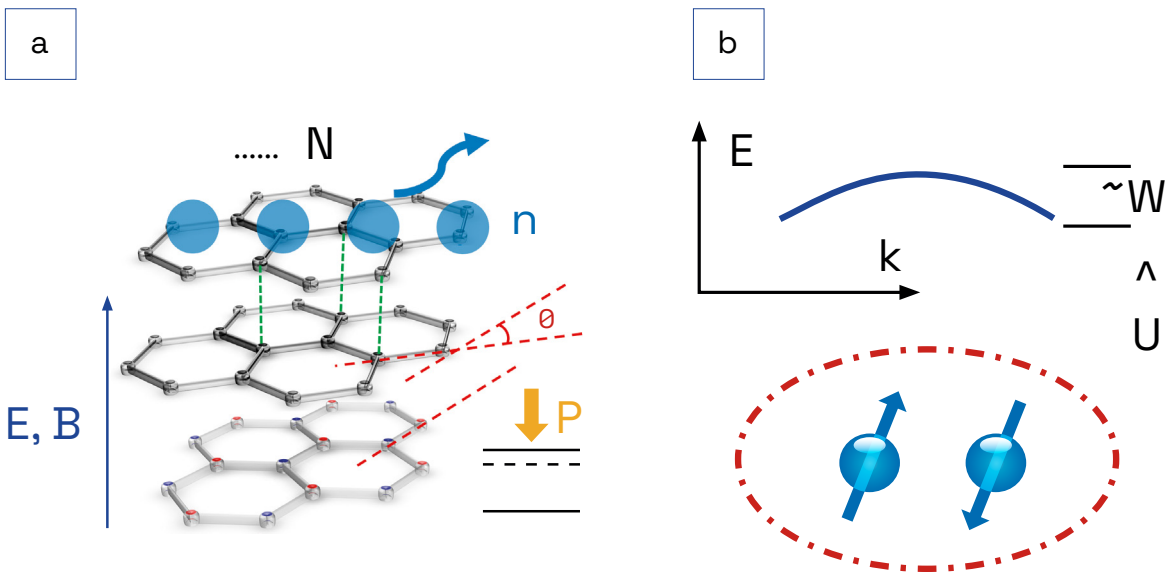


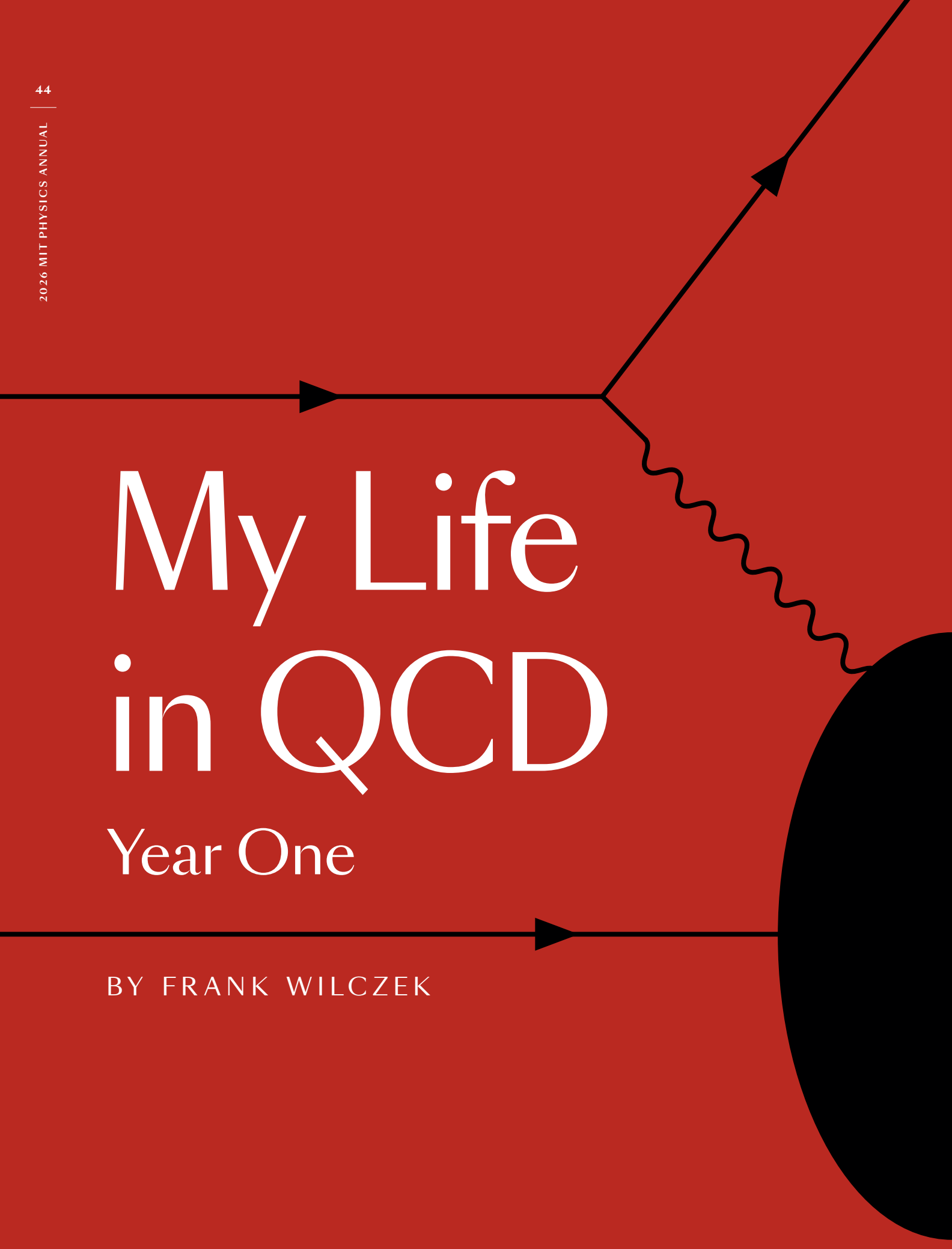
FIGURE 5:
(a) Multiple knobs to enrich RG: layer number *N*, twist angle *θ*, electric field *E*, magnetic field *B*, electron density *n* and pressure *P*. (b) Flat band promotes electron correlation effect when the kinetic energy *W* is dwarfed by the interaction energy *U*. Credit: Ju Group, MIT.

LONG JU is the Lawrence C. (1944) and Sarah W. Biedenharn Associate Professor of Physics at MIT. His research group focuses on understanding light-matter interactions and electron transport in novel quantum materials. Of particular interest are atomically thin materials and their van der Waals hetero-structures. These materials host a variety of fascinating electronic and optical properties individually, and they offer exciting opportunities to explore possibilities enabled by controlling the stacking order and electrically tuning the band structure and charge doping. Especially, such materials provide a new platform to design and engineer more exotic quantum phenomena when electron correlations and topology are included. The Ju Group develops problem-oriented experiments by employing various optical spectroscopy and microscopy tools in a broad spectrum range from UV to THz, as well as DC transport measurements. Ultrafast optical techniques and scanning probe optical microscopy will be utilized to study dynamical properties on a time scale down to femtoseconds and a spatial resolution of nanometers. Most importantly, device fabrication and application of electric and magnetic fields will be combined to achieve external control of material properties.

Long Ju joined the MIT Physics Department as an assistant professor in January 2019. He received his BS in Physics in 2009 from Tsinghua University, China, and his PhD in Physics in 2015 from the University of California, Berkeley. He then moved to Cornell University, where he was a Kavli postdoctoral fellow until December 2018. Long Ju's honors and awards include a Sloan Research Fellowship, the OCPA Outstanding Young Researcher Award (Macronix Prize), and *MIT Technology Review*'s Innovators Under 35.

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My Life in QCD

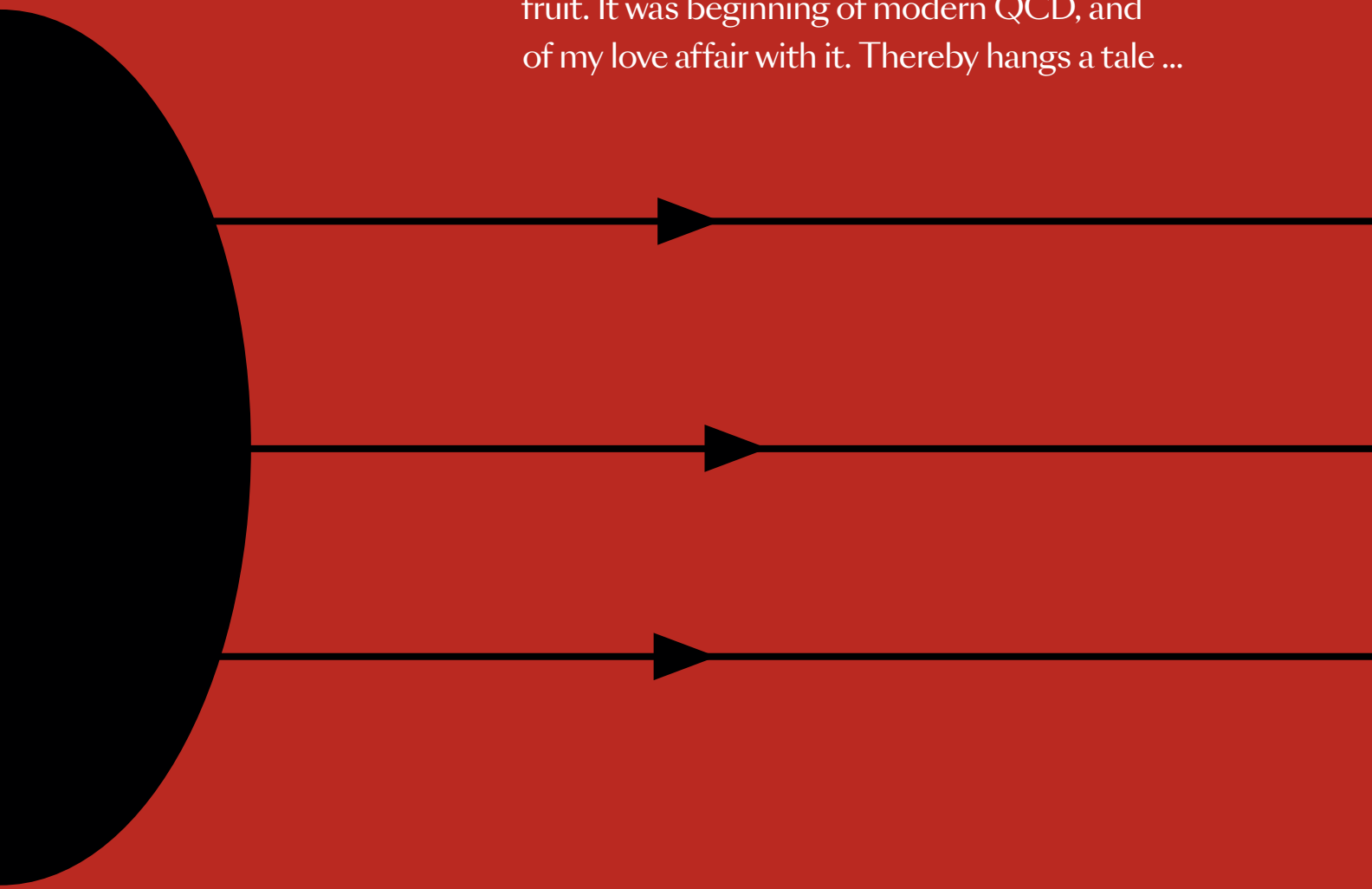
Year One

BY FRANK WILCZEK

In the winter of 1972 I was a struggling, lonely graduate student at Princeton, in the process of converting from pure mathematics to physics. I had spent two years "in the wilderness" after graduating from the University of Chicago, during which I lacked clear direction.

That summer and fall, two miracles occurred. In the summer I met Betsy Devine. Wandering in the wilderness ceased to be an acceptable option. (A year later, on July 3, 1973, Betsy and I got married. We recently celebrated our golden anniversary.)

The second miracle was the beginning of an intense collaboration with David Gross, my new thesis advisor. This work soon bore spectacular fruit. It was beginning of modern QCD, and of my love affair with it. Thereby hangs a tale ...



Asymptotic freedom as a theoretical discovery

David and I considered many possible projects to pursue. We converged on a problem area that was both fundamentally interesting and relevant to his program of showing that quantum field theory could not describe the strong interaction. (More on that shortly, below.)

There were two big recent developments in theoretical physics that were not yet widely known, nor fully digested, in the research community. They offered new approaches to fundamental problems—and, crucially for me, lots of potential thesis fodder. These were the renormalization group, on the one hand, and non-abelian gauge theories on the other.

The renormalization group is a collection of methods for investigating what a mathematical model predicts for physical behavior in extreme circumstances. Ken Wilson had recently injected powerful new ideas into the subject, for which he eventually (in 1982) was awarded the Nobel Prize. He gave a brilliant series of lectures about his new ideas at Princeton, that both David and I attended.

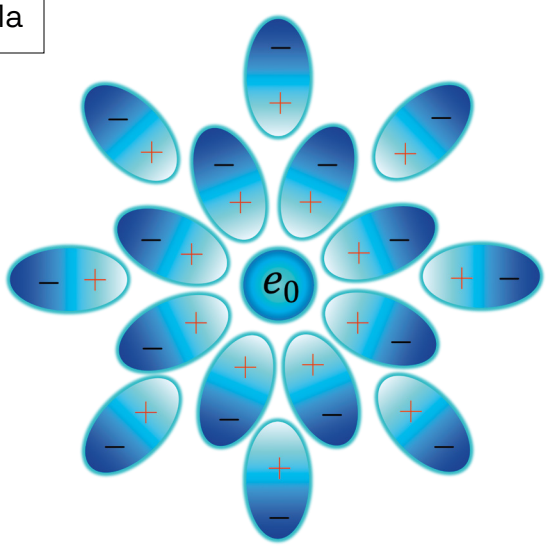
Non-abelian gauge theories are a specific way of constructing equations that are consistent with the basic principles of special relativity and quantum mechanics. Those principles are quite constraining, so such constructions are few and far between. Non-abelian gauge theories are mathematically elegant—the equations display a tremendous amount of symmetry—but they are challenging to work with. Adequate tools for the job became available around 1970, mainly through remarkable work by Gerard 't Hooft and Martinus Veltman, for which they eventually (in 1999) were awarded the Nobel Prize.

It was, then, a natural and attractive problem to investigate whether and how one could bring those two developments, the renormalization group and non-abelian gauge theory, together. It offered fresh perspectives on a profound issue that, for arcane reasons, is known as "the Landau ghost." Here I'll describe the problem in a way that doesn't bring in spooks.

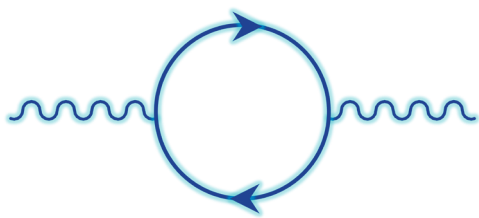
Figure 1a shows how screening works in a dielectric material. A positive test charge, by attracting negative and repelling positive charges, distorts the surrounding molecules in such a way that it is, in effect, surrounded by a cloud of negativity that reduces the field it would otherwise generate. We say that the test charge is (partially) screened. A version of this effect also occurs in empty space. In that case you have to imagine the picture to be a snapshot in time, and the molecules to be quantum fluctuations or, in more vivid language, virtual particle-antiparticle pairs. Each fluctuation—

FIGURE 1:
(a) A test charge inserted into a dielectric medium polarizes the surrounding molecules. As a result its influence is diminished (screened) far away. An analogous screening effect, known as vacuum polarization, arises from the polarization of virtual particle-antiparticle pairs (and other quantum fluctuations). (b) Vacuum polarization can be calculated using Feynman graphs. It becomes singular at short distances, leading to catastrophic screening.

1a



1b



$$e_0 < \infty \Rightarrow e_\infty = 0$$

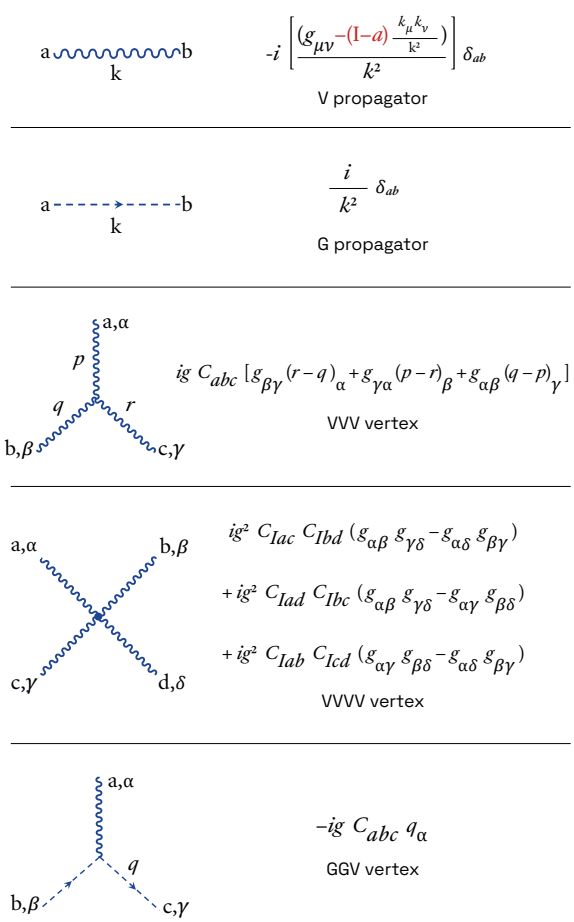


FIGURE 2:
The Feynman rules for a pure Yang-Mills theory (all momenta flow into the vertices). Non-abelian gauge theories introduce new kinds of quantum fluctuations, and it gets complicated to calculate vacuum polarization. This partial inventory of its building-blocks gives some impression of that complexity.

or, alternatively, each virtual pair—is short-lived, but new ones constantly arise to replace them. These vivid, dynamic effects in space-time are difficult to visualize or to work with directly, but fortunately they correspond to a simple calculation with Feynman graphs, displayed in Figure 1b. That calculation, translated back into our pictures, reveals that the density of virtual pairs toward the center gets very large. In fact, it gets so large that any test charge we insert gets *completely* screened. Any finite "bare" test charge e_0 results in vanishing observable charge e_∞.

Landau and his school investigated this phenomenon in a wide variety of quantum field theories, as did Zee and, most systematically, Coleman and Gross. All known theories exhibited the same sort of catastrophic screening. It disturbed Landau so badly that he wrote:

> *We are driven to the conclusion that the Hamiltonian method for the strong interaction is dead and must be buried, although of course with deserved honor.*

I had encountered that quote in my reading, and it made a big impression on me.

None of those existing calculations of screening used the new non-abelian gauge theories. Taking them on posed both practical and conceptual challenges. If those challenges could be overcome, the renormalization group would tell us whether or not the new theories, like the old, had catastrophic screening—in other words, whether they were haunted by the Landau ghost. If so, the popular electroweak theories had a serious problem. If not, we could calculate how they behaved at short distances. Either answer would be interesting, and help me to get my degree.

The main practical challenge was, simply, algebraic complexity. You can get a glimpse of that challenge from a glance at Figure 2. There you see displayed the basic building-blocks of the minimal non-abelian gauge theory. These building-blocks had to be combined into more complex expressions, which then go into integrals, according to the rules for Feynman graphs. The resulting integrals are, on the face of it, both infinite and gauge dependent. (In order to do practical calculations in gauge theories one must do something analogous to choosing a coordinate system, which here we call choosing a gauge. But physically meaningful results cannot depend on how you choose the gauge, just as geometrically meaningful results cannot depend on your choice of coordinate system.)

We had hand-waving arguments that the renormalization group was consistent with gauge independence, but no reliable proof. This was a big conceptual challenge. Sidney Coleman, a masterful Harvard physicist and fast friend who was on leave at Princeton, took great interest in what we were doing. He emphasized it to me. I felt compelled to answer his questions experimentally, so to speak, by doing the calculations using several different kinds of test charges using several different ways of choosing a gauge. In other words, I took on many different complicated calculations that I hoped—and expected—would all give the same final answer. That, to me, would be more convincing than any abstract formal proof. (The abstract proof could, and did, come later.) To be safe, I also tested my processing procedures—

which were unconventional but streamlined the calculations—in all the older theories, where we already knew the right answer.

The calculations were "straightforward in principle." But over time, as we followed through on them, that phrase (which we often used) became something of a joke between David and me. After several weeks of labor, anxiety, and de-bugging, all my calculations finally did converge on the same answer, as we had hoped. And that answer, as summarized in Figure 3, was a thing of beauty. The new theories escaped the screening catastrophe. Instead, they had the opposite property: anti-screening. With anti-screening, a finite observable charge at large distance corresponds to an infinitesimal bare charge at small distances.

$$\beta(g) = -\frac{g^3}{16\pi^2}\left(\frac{11}{3}N_c - \frac{4}{3}\frac{N_f}{2}\right)$$



FIGURE 3:
The central result of the calculation is the formula displayed here, taken from the poster for the 2004 Nobel Prize. It gave anti-screening, as opposed to screening, and thereby eliminated the "Landau ghost." The photos are contemporary pictures of (from left) David Gross and me.

Anti-screening is a much healthier situation than screening, theoretically, since we build up the theory starting from the primary interactions that occur at short distances, and therefore involve bare charges.

Following Sidney's suggestion, we called the phenomenon that the basic interactions in non-abelian gauge theories become feeble at short distances, and ultimately turn off, "asymptotic freedom."

Asymptotic freedom as an experimental reality

The Geiger-Marsden experiment of 1912, pictured in Figure 4a, was a milestone event for modern physics. When alpha particles from a radioactive source impinged on a gold foil, they were sometimes deflected through large angles. Ernest Rutherford, who had suggested the experiment, quickly supplied a convincing interpretation of its result. From the observed distribution of deflection angles you can infer the forces that caused them, as indicated in Figure 4b. Rutherford deduced, from the observed pattern of deflections, that most of the mass of gold atoms was concentrated in a small heavy nucleus, that contained most of the atom's mass and all of its positive electric charge. The required force could then be ascribed to ordinary electrical repulsion between the alpha particles and the gold nuclei.

The model of atoms that emerged from this experiment, featuring a small, positively charged nucleus surrounded by a cloud of (negatively charged) electrons, was taken up by Bohr, who introduced rules suggested by the nascent ideas of quantum theory. For several years, the application of quantum ideas involved a lot of guesswork. A mature version of quantum theory, based in unambiguous equations and algorithms, emerged in 1924–1925, primarily through the work of Heisenberg and Schrödinger. Though many refinements came in later, their ideas laid the foundation for the theory of atoms we still use today.

The frontier of exploration in fundamental physics moved inward, to the atomic nuclei. Their very existence was evidence for a new force, beyond the previously known forces of electromagnetism and gravity. The electrical repulsion among like charges wanted to blow them apart, and gravity was much too feeble to hold them together. The new force would have to be very powerful, so it got called the strong force. Apart from its name, however, almost everything about this force remained mysterious for many years. Study of the strong force led to discovery of many interesting phenomena and insights, notably including the transmutation of elements, the source of stellar energy, nuclear weapons, and the existence of many new particles. But a fundamental theory remained elusive. In 1970, at the dedication of Fine Hall in Princeton, Freeman Dyson opined that no such theory would emerge for a hundred years.

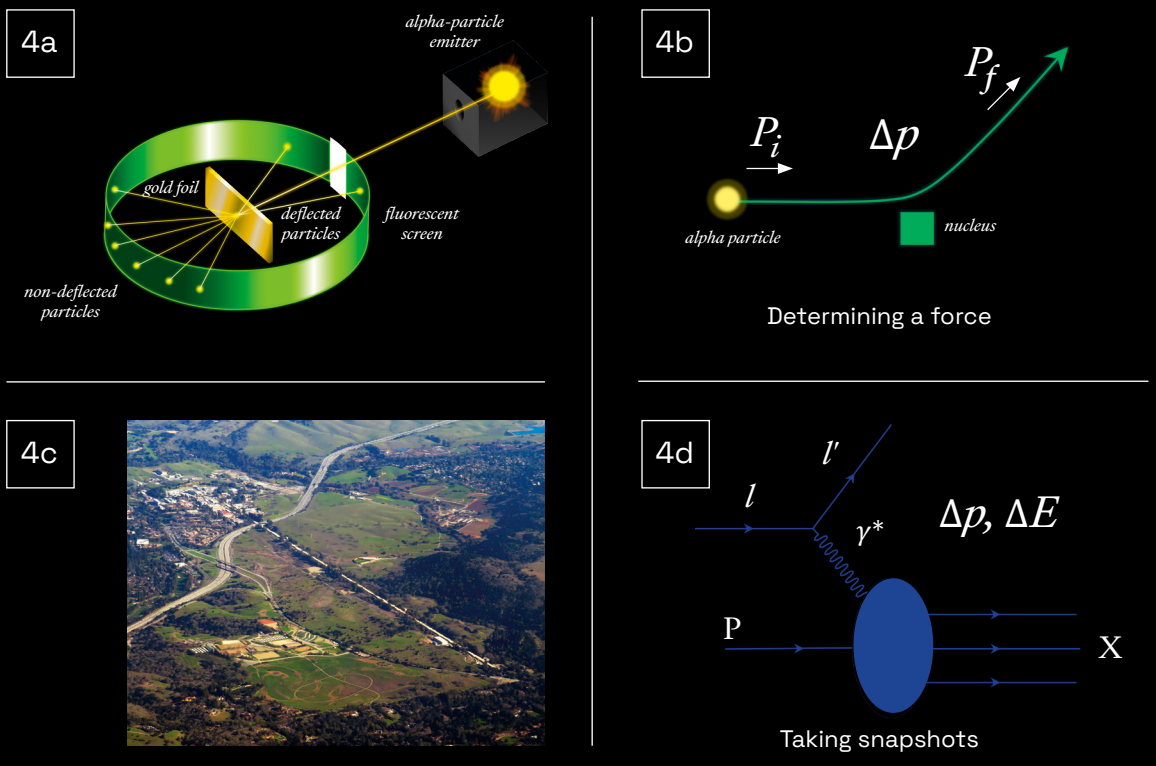
In hindsight, we can see that the crucial experiment was a beautifully logical follow-up to the work of Geiger, Marsden, and Rutherford. It was done by a team led by Jerome Friedman, Henry Kendall, and Richard Taylor starting in the late 1960s, and led to a Nobel Prize in 1990. The new work featured two innovations. The first was simply to work at much higher energies, using ideally simple particles as projectiles—electrons, in the original experiments. Geiger-Marsden was a table-top experiment, but Friedman-Kendall-Taylor was a job

for the Stanford Linear Accelerator (SLAC), shown in Figure 4c, which is two miles long. High energy is necessary due to the wave nature of electrons, which implies that good resolution in space requires large changes in momentum. The second was to study not only the angles of deflection, but also the pattern of energy losses—what physicists call inelastic scattering. Whereas changes in angle correspond to changes in momentum, which empowers good spatial resolution, changes in energy empower good resolution in time, as indicated in Figure 4d. This turns out to be crucial, because things move very fast inside protons. The translation from scattering cross-sections to snapshots of proton interiors is a sophisticated exercise in image processing, but straightforward in principle.

FIGURE 4:
(a) The original Geiger-Marsden experiment, a table-top experiment that revealed the existence of atomic nuclei but did not resolve their structure. (b) The principle behind the experiment: by measure the deflections of projectiles, one can infer the forces that caused them. (c) The Stanford Linear Accelerator (SLAC), a two-mile long device that produced beams of high-energy electrons. Credit: Pi.1415926535, CC BY-SA 3.0 <*https://creativecommons.org/licenses/by-sa/3.0*>, via Wikimedia Commons. (d) By keeping track of both deflection and energy losses of the projectile electrons, one resolves their causes in both space and time.

Strikingly clear pictures of proton interiors emerged from this work. They revealed that protons are built up out of simpler particles. The existence of some of those particles—quarks—was not entirely surprising, since phenomenological models using quarks had been helpful in other connections. But there had to be some additional electrically neutral "dark matter" inside protons, since the observed quarks gave only about half of the total energy stored in protons (according to $m = E/c^2$), but all of their charge. The most surprising and paradoxical aspect of the pictures, however, was precisely their clarity. Since quarks participate in the strong interaction, we might anticipate that they would exchange energy and momentum with each other, and, presumably, with the subnuclear "dark matter." Such exchanges would distort the changes in energy and momentum of the electron of the scattered electron in Figure 4d. In effect, the electron wouldn't be viewing the quark itself but only its image as processed through a medium.

That heuristic argument could be made mathematically precise, as shown by Callan and Gross. If the strong interaction was always strong, you could not understand the Friedman-Kendall-Taylor pictures. David suspected that any quantum field theory would make strong interactions observed at nuclear distances even stronger forces at subnuclear distances: the screening effect we



discussed earlier. Had that been the case it would have vindicated Landau's call for a burial, and a fresh start.

But asymptotic freedom revealed a profoundly simple, radically conservative alternative. If the strong interaction was governed by an asymptotically free theory, it would not always be strong. In fact good resolution in space and time would begin to reveal the bare charges, which interact feebly and therefore *can* be imaged sharply. We could hope to understand the pictures in quantum field theory, after all—but only if we assume that the theory of the strong interaction is asymptotically free.

The theory of the strong interaction

Asymptotic freedom pointed us toward a specific *kind* of theory for the strong interaction, but it wasn't immediately clear to us that it pointed to a specific theory. It had to be a non-abelian gauge theory, and (based on the SLAC pictures) it had to contain quarks. Those ingredients were necessary, but were they sufficient? David and I explored many alternatives, but all of them were ugly, physically flawed, or both. They generally predicted new features in the pictures, and new particles, for which there was no evidence. We soon convinced ourselves that the minimal theory was likely to be the right one. It is the theory we now call quantum chromodynamics (QCD)—and it proved to be the right one.

Our failed attempts to find viable alternatives to QCD for the theory of the strong interactions were not entirely fruitless, though. Through those explorations, we expanded the repertoire of quantum field theory. The more general models can be, and have been, repurposed. They supply adventurous models that promise to augment and unify our account of fundamental interactions, and to give new perspectives on the early universe.

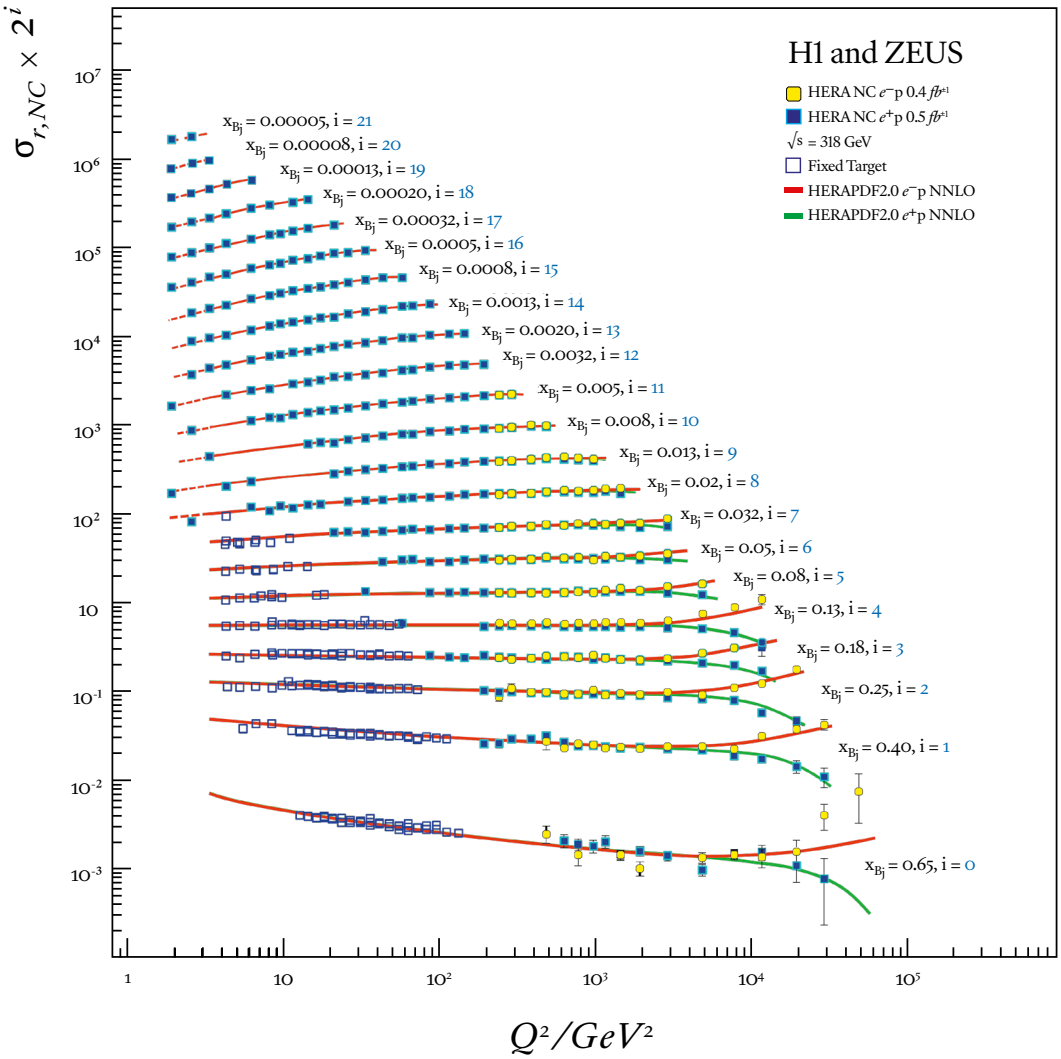
The emergence of QCD as a uniquely attractive realization of asymptotic freedom transformed the problem of the strong interaction. In place of the broad research programs and fragmentary insights that had characterized earlier work, we now had a single, specific candidate theory—a theory that could be tested, and perhaps falsified, but which could not be fudged. Even now, when I re-read our declaration:

> *Finally let us recall that the proposed theories appear to be uniquely singled out by nature, if one takes both the SLAC results and the renormalization-group approach to quantum field theory at face value.*

FIGURE 5:
(a) Mickey Rooney's Downingtown Inn, the site of my first physics conference. (b) This sign "No boring people allowed" inspired a performance by Feynman. He made a show of studying it, strode through, and gave a challenging stare to his entourage, before waving them in, deadpan.



5a | 5b



I relive the mixture of exhilaration and anxiety that I felt at the time.

Having settled on specific, well-motivated candidate equations for a complete, definitive theory of the strong interaction, we were faced with the challenge of drawing out testable, quantitative consequences. We hoped, of course, that our theory would be right, but also—and to me, at least equally important—that it would be fruitful.

In the early days, our ability to draw out testable predictions was very limited. We could calculate how the strong interaction worked at short distances and very high energies, but most experiments in particle physics bring in a complicated mixture of distances and energies. The outstanding exception was deep inelastic scattering à la Friedman-Kendall-Taylor where you could focus on short distances and, with more powerful accelerators, higher energies. We worked hard, using asymptotic freedom and the renormalization group, to calculate what the theory predicted for those kinds of experiments.

FIGURE 6:
The quantitative comparison of theory and experiment for our non-abelian gauge theory of the strong interaction was very crude at first, but after a few years it came to look like this. Credit: Abramowicz, H., Abt, I., Adamczyk, L. *et al.* Combination of measurements of inclusive deep inelastic scattering cross sections and QCD analysis of HERA data. *Eur. Phys. J.* C 75, 580 (2015). *https://doi.org/10.1140/epjc/s10052-015-3710-4.*

The results brought both good news and bad news. The good news, was that we got very specific predictions. Testing them was "straightforward in principle." The bad news, was that it appeared that in practice they would be extremely difficult to test. We predicted that certain quantities—technically, moments of structure functions—would vary as powers of logarithms as you change the energy. The problem is that it takes big changes in energy to make small changes in its logarithm. Sam Treiman, a wise and experienced friend and professor at Princeton, told me "People never

measure logarithms." Though he said it with a smile, that sobering thought brought me down to earth.

A few weeks later, thought, I got a big boost. It was at my first-ever conference, a small workshop on high energy physics at the Downingtown Inn, in the Philadelphia suburbs (Figure 5). Feynman was there, and he gave the closing summary talk. But instead of simply summarizing the workshop—which was all over the map—he devoted half his talk to describing our predictions and urging the experimentalists to take them seriously! He said our theory was probably wrong, but maybe not, and it deserved to be tested, even though that would be tough. Feynman had long been a big hero for me, and for him to focus on my work was, to me, an almost incredible affirmation.



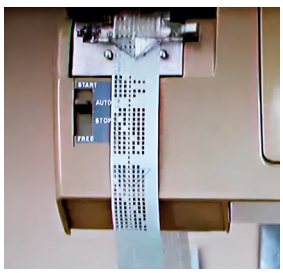


FIGURE 7:
Using computers was a very different experience in the early 1970s. My early versions of the theory calculations that go into Figure 6 were done in late night and early morning sessions on Val Fitch's PDP-11.

And the experimental community did rise to the challenge, way beyond anything I anticipated. Within a few years, we had results like what's shown in Figure 6. The measured results agreed beautifully with the output I coaxed out of Val Fitch's PDP-11 (Figure 7) in early morning sessions on borrowed time. It turned out that sufficiently determined people could measure logarithms, after all.

Over the remainder of the twentieth century, and continuing to this day, theorists learned how to calculate many more consequences of QCD than we drew initially, and experimentalists learned new ways of organizing their data. A key idea, generalizing the lesson of SLAC, was to focus on flows of energy and momentum ("jets"), rather than individual particles.

During QCD's childhood, success was uncertain but progress was rapid. The sessions of high energy physics conferences devoted to "Testing QCD" were, consistently, exciting and well-attended highlights.



FIGURE 8:
A wise fortune cookie.

Eventually, though, people got tired of testing the theory. The novelty of success had worn off; it had become a routine expectation. Nowadays the same kind of work that used to be called "Testing QCD," but now carried out with much greater sophistication and accuracy, is called "calculating backgrounds." That can be an important activity, enabling new discoveries. Notably, the discovery of the Higgs boson was powered by QCD. Still, maturity is a bittersweet experience.

Hopeful calculation

Looking back, it seems remarkable to me how much we learned by following the strategy of *hopeful calculation*. Plowing ahead, we postponed many hard technical issues involving infrared divergences, confinement, gauge invariance, and experimental feasibility. We calculated what we could and learned by doing. My all-time favorite Chinese fortune cookie (Figure 8) contained this gem:

> *The work will teach you how to do it.*

That gets it right.

FRAMING

This piece is based on the first quarter of my David M. Lee lecture "My Life in QCD: A Fifty-Year Love Affair, Still Going Strong," at Harvard University, April 9, 2024. Related material appeared in my Nobel lecture: *https://www.nobelprize.org/prizes/physics/2004/wilczek/lecture/*, in my keynote "QCD at 50; Golden Anniversary, Golden Insights, Golden Opportunities," at the 2023 Erice summer school, *https://arxiv.org/pdf/2403.06038*, and "Triumph, Window, Clue, and Inspiration: The Higgs Particle in Context," by Frank Wilczek. physics@mit 2013; 36–45. These contain extensive references. All figures provided by Frank Wilczek and Juliana Baena Rodriguez.

PROFESSOR FRANK WILCZEK is considered one of the world's most eminent theoretical physicists. When only 21 years old and a graduate student at Princeton University, in work with David Gross he defined the properties of color gluons, which hold atomic nuclei together. This earliest research included the discovery of asymptotic freedom and the formulation of quantum chromodynamics, as discussed in this article. Later highlights include the invention of axions and discovery of their potential role in cosmology, and the discovery and exploitation of new forms of quantum statistics (anyons), the discovery and investigation of color-flavor locking, and the proposal of time crystals. "Axions," "anyons," "color-flavor locking," and "time crystals" are all terms that he introduced. They have come to define major topics in physics research.

Frank Wilczek received his BS degree from the University of Chicago and his PhD from Princeton University in 1974. He remained at Princeton through 1980, rising to Professor. During 1981–1988, he was the Chancellor Robert Huttenback Professor of Physics at the University of California at Santa Barbara, and the first permanent member of the National Science Foundation's Institute for Theoretical Physics. In the fall of 2000, he moved from the Institute for Advanced Study (1989–2000), where he was the J.R. Oppenheimer Professor, to the MIT Department of Physics, where he is now the Herman Feshbach Professor of Physics, Post-Tenure, and where he used to have an office. He is now tenured as the Wager Professor of Physics at Arizona State University (ASU). He has also been Professor at Stockholm University and NORDITA since 2016. In recent years Wilczek has also been active in China. During 2017–2022, he served as Founding Director of the T. D. Lee Institute in Shanghai. Since 2016, he is Chief Scientist at the Wilczek Quantum Center, sponsored by Shanghai Jiao-Tung University (STU) and University of Science and Technology in China (USTC).

Wilczek has been a Sloan Foundation Fellow (1975–1977) and a MacArthur Foundation Fellow (1982–1987). He has received UNESCO's Dirac Medal (UNESCO), the Lorentz Medal (Netherlands Academy of Sciences), the American Physical Society's Sakurai and Lilienfeld Prizes, and several others. In 2004 he received the Nobel Prize in Physics, and in 2005 the King Faisal Prize. In 2022, he was honored with the Templeton Prize. In 2022, Wilczek gave the initial Steven Weinberg Memorial lecture at the University of Texas, Austin. He is a member of the American Academy of Arts and Sciences, and the U.S., the Netherlandish, the Swedish, and the Chinese Academies of Sciences, among others.

In 2015, he co-founded the Quantum Connections international summer school near Stockholm, and in 2025, its sister winter Quantum Connections in Sanya, China. Since 2018, the Jagellonian University (Krakow) has awarded a biannual "Wilczek Prize" for young Polish physics researchers. These institutions continue to thrive.

During 2015–2023, Wilczek wrote a monthly "Wilczek's Universe" column for the *Wall Street Journal*; this evolved into an ongoing "Wilczek's Multiverse" series at the *South China Morning Post*. He has authored several well-received books for the public that are published by leading commercial publishers and widely translated, notably including "Longing for the Harmonies" (with Betsy Devine) (WW Norton & Co, 1988), "A Beautiful Question" (Penguin, 2015), and "Fundamentals" (Penguin, 2021). Presently he is working on "Futures" (Penguin, expected 2027), an examination of how science, by defining possible futures, can inform the search for purpose. He is also editor-in-chief of "The Princeton Companion to Physics" (Princeton University Press, expected 2029).



MIT AND THE

NOVEMBER REVO

ESTABLISHING THE STANDARD MODEL OF PARTICLE PHYSICS



LUTION

by Peter Fisher & David Kaiser

FIFTY YEARS AGO, the worldwide community of particle physicists rapidly converged on what we now call the "Standard Model." Since that time, the Standard Model has passed every experimental test, and it continues to guide our investigations of three of the four fundamental forces of nature: electromagnetism, the weak nuclear force, and the strong nuclear force—encompassing all physical interactions except gravity. Over the years, theoretical physicists have used the Standard Model to calculate predictions for specific quantities, and in some cases those predictions match the latest high-precision experimental measurements to parts-per-trillion accuracy. In short, the Standard Model is the single most quantitatively precise scientific theory in human history. The banality of its title belies the grandeur of the accomplishment.

One of the most significant milestones in building the Standard Model occurred early in November 1974, when physicists announced the discovery a new particle, known as the "J/ψ," an event that was quickly dubbed the "November Revolution." That breakthrough, and several others along the way, has strong ties to MIT. These efforts exemplify the power of open-ended, basic research—and underscore the need to remain open to surprises.

THE BACKDROP: Suggestive Symmetries in the Sixties

At the close of the Second World War, when physicists in many parts of the world hoped to return from war-related projects to basic research, the set of known subatomic particles numbered just seven: electrons and positrons, protons and neutrons, photons, and positive and negative mesons (soon dubbed "muons"). Some theorists entertained notions of other possible particles—Wolfgang Pauli had reluctantly introduced the idea of a "neutrino" in a now-famous letter to colleagues in 1930, apologizing for his "desperate" attempt to make sense of the energy carried off by electrons in radioactive decays, among other puzzles—but no solid evidence supported such speculations.

The situation changed rapidly soon after the war. In the United States, the brand-new federal Atomic Energy Commission—successor to the wartime Manhattan Project—financed the rapid-fire construction of new particle accelerators: thirteen new accelerators came online between 1946 and 1954 alone, including MIT's own synchrotron, completed in 1950. These new machines operated at considerably higher energies than their prewar counterparts, probing interactions with energies of hundreds and soon thousands of MeV [million electron volts], well above the typical binding energies of nuclear matter. Nearly as soon as these new accelerators came online, physicists began finding a flood of new particles. In 1953, theorist Freeman Dyson quipped that hardly a month went by without the announcement of a new particle discovery. Around that same time, Edward Teller felt moved to versify:

There are mesons π *and there are mesons* μ
The former ones serve us as nuclear glue
There are mesons τ*, or so we suspect*
And many more mesons which we can't yet detect [1].

By 1960, experiments around the world had yielded more than one hundred new particles, in a dizzying mishmash dubbed the "particle zoo."

Physicists sought patterns amid the outpouring. Some of the new particles only seemed to be produced in combination with others—a phenomenon quickly designated "associated production." Theorists wondered if perhaps there were additional properties of the particles, analogous to familiar charge and spin, which might account for these patterns. For example, the new K mesons always seemed to appear with Λ particles or Σ particles. Just a few years past his doctoral studies, Murray Gell-Mann (MIT PhD 1951), along with Abraham Pais, wondered if a new quantum number, which they called "strangeness," needed to be conserved, much as electric charge was conserved. If the K mesons had equal and opposite "strangeness charge" to the Λs and Σs, maybe they always came careening out of particle scatterings together because then the net "strangeness" of such interactions would remain zero.

Within a few years, Gell-Mann and (separately) Yuval Ne'eman found that certain combinations of these new "charges" could account for even larger patterns. In 1960, Gell-Mann introduced his "Eightfold Way"—the name a playful homage to Buddhists' path to nirvana—by which he could arrange clusters of the new particles in simple patterns, by assigning each of them various properties (baryon number, strangeness charge, isospin, and so on). Dozens of seemingly independent particles suddenly snapped into place when plotted in abstract mathematical planes like "hypercharge" versus "isospin," all governed by discrete symmetry groups.

Emboldened by the patterns, Gell-Mann famously predicted at a conference at CERN in July 1962 that a new particle would be found with specific properties, based on a gap in an otherwise-full grouping of nine other new particles. The new particle, Gell-Mann declared, should have hypercharge -3 and isospin 0, with a mass around 1680 MeV/c^2—and about eighteen months later, experimentalists at Brookhaven National Laboratory identified exactly such a particle, which Gell-Mann had named the Ω^-, with a mass within 0.4% of Gell-Mann's prediction.

Inspired by such successes, Gell-Mann (by then a professor at Caltech) and George Zweig (a postdoc at CERN) independently proposed—within 13 days of each other, early in January 1964—that the symmetries among nuclear particles could be associated with three constituent particles. Citing James Joyce's notoriously obtuse novel *Finnegans Wake* among his brief set of just eight references, Gell-Mann called these new hypothetical particles "quarks"; Zweig named them "aces." By carefully assigning values of hypercharge, strangeness charge, isospin, and electric charge to each of these three hypothetical constituents, Gell-Mann and Zweig could account for all of the symmetric groupings among particles in Gell-Mann's "Eightfold Way." A proton, for example, could be mapped to two "up" quarks and one "down" quark, while a neutron could be associated with two downs and an up. A positive pion could be associated with an up quark paired with an anti-down quark (the antimatter cousin of a down quark). Particles with strangeness charge, like the K meson, included at least one "strange" quark, while the Ω^- could be represented as a bound state of three strange quarks.

"It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities). ... A search for stable quarks at the highest energy accelerators would help to reassure us of the non-existence of real quarks."

—MURRAY GELL-MANN

Although the quark idea may seem routine today, it was by no means an obvious suggestion back in the 1960s. For starters, Gell-Mann and Zweig had to assign fractional electric charges to the quarks—even though no fractional charges had ever been observed. The dynamics of how such particles might interact with each other also remained a complete mystery. Gell-Mann himself hedged, calling his brief article "A *schematic* model of baryons and mesons." In the conclusion he wrote, "It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities). ... A search for stable quarks at the highest energy accelerators would help to *reassure us of the non-existence of real quarks*." Zweig found out even more dramatically just how unrealistic his colleagues considered the new idea: neither of his 1964 papers on "aces" was accepted for publication. To this day, they exist as unpublished preprints on the CERN server [2].

Even as most physicists remained skeptical that quarks were real, several were impressed by the power of discrete symmetries to bring order to the jumble of new particles. Over the course of the 1960s, Sheldon Glashow, Steven Weinberg, and Abdus Salam each independently introduced models that combined the weak nuclear force with electromagnetism into a single "electroweak" force. In these models, the interactions remained symmetrical—that is, unchanged—even if various particles were swapped for one another in a pattern that could vary across time and space. Such models are known as "local gauge theories."

The theorists hypothesized that some new, force-carrying particles skittered among the known particles, enforcing the overall symmetry. Like the familiar photon from electromagnetism, the new particles would each carry one unit of spin; but unlike the photon, three of them (which Weinberg labeled the W^+, W^-, and Z^0 particles) would need to be massive, to account for the short-range nature of the weak force. Weinberg wrote his landmark 1967 article, "A model of leptons," while on sabbatical at MIT, before joining the MIT faculty.

By the time Weinberg (and, separately, Salam) wrote their articles on electroweak theory, they could incorporate recent work on spontaneous symmetry breaking. This last step was critical, since their model required the force-carrying W and Z particles to be massive; but if they simply assigned masses to these particles from the start, the mass terms would break the very symmetries that the new particles were meant to preserve.

So Weinberg and Salam borrowed a trick that several others had recently worked out: they incorporated yet another hypothetical field, this one with zero spin, whose self-interaction potential allowed for multiple, degenerate ground states at non-zero values of the field. When the field settled into one of these lowest-energy states, the motion of any other particles that interacted with it, such as the W and Z particles, would be affected. In particular, their interactions with the molasses-like spin-0 field would make them lumber through space as if they were massive. Building on critical work by Jeffrey Goldstone from 1961, Peter Higgs, François Englert and Robert Brout, and Gerald Guralnik, Carl Hagen, and Thomas Kibble introduced versions of this spontaneous symmetry-breaking mechanism in 1964, tailored to local gauge theories in which forces were governed by so-called "non-Abelian" symmetry groups [3]. (Goldstone joined the MIT faculty in 1977, and Guralnik had completed his undergraduate studies at MIT in 1958.) A few years later, Benjamin Lee dubbed this mass-bestowing spin-0 particle the "Higgs boson."

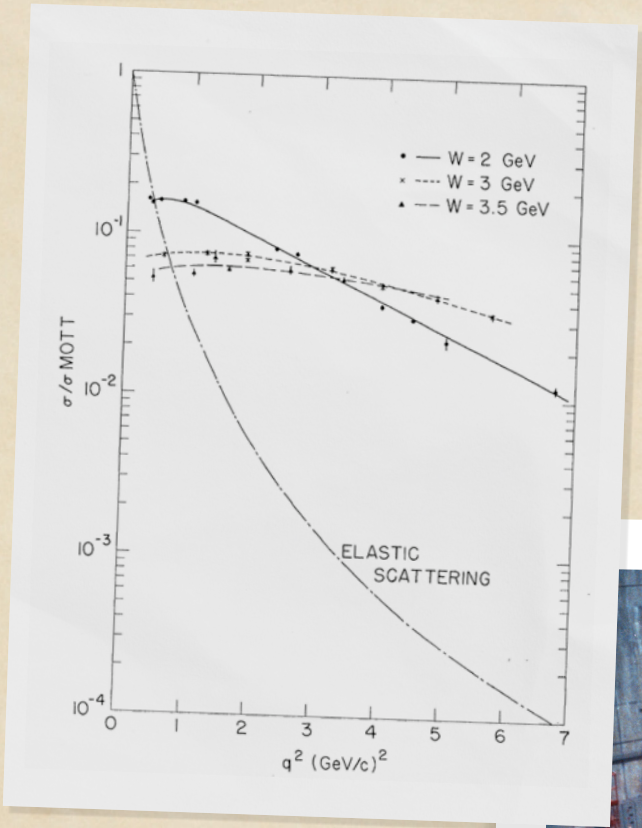
By the late 1960s, several suggestive hints were in hand about the basic constituents of the microcosmos. Perhaps particles like protons and pions were actually composites, built out of quarks; maybe nuclear forces like the weak force were mediated by spin-1 particles like the Ws and Z; perhaps an all-pervasive Higgs field made these (and other) particles behave as if they were massive. But there was no consensus about any of these hints. Nor was it clear that the theoretical framework even made sense: it all appeared to break down when applied to high-energy phenomena, and the analogy to electromagnetism decidedly failed for particles that interacted strongly with each other, even at low energies.

SEEKING DEEPER STRUCTURE:

The SLAC-MIT Deep Inelastic Scattering Experiments

Beginning in 1962, the U.S. Atomic Energy Commission began construction of an even larger particle accelerator in the hills near Stanford University in California. Unlike most of the previous generation, the new machine would string a series of powerful electromagnetic cavities along a straight line—stretching for two miles—to accelerate electrons to unprecedented energies before smashing them into fixed targets. The





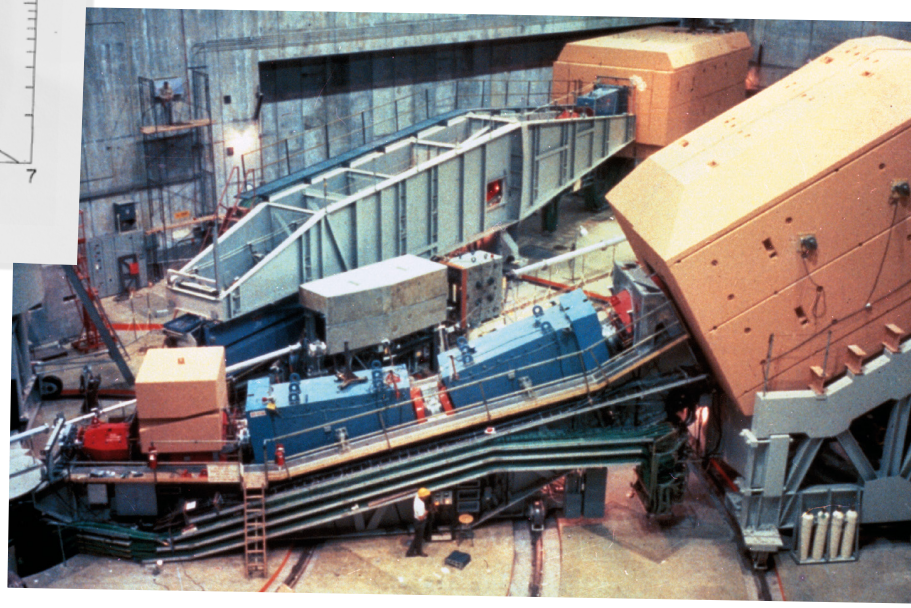


Figure 1.

TOP: The two-mile "linac" (linear accelerator) at SLAC. Electrons accelerated down the linac are directed by magnets into experimental stations housed in buildings near the bottom of the image. CENTER: Data from one of the group's first papers, showing the prediction (dashed curve) of interaction strength as a function of momentum transfer from the electron to the proton, if the proton were a smooth, spherical ball of charge. The data points indicate much higher interaction strengths, indicating the presence of concentrated scattering sites—internal structure—within the proton. BOTTOM: One of the spectrometers for the deep inelastic scattering experiments. The target—a small tube, about 7 cm in diameter and 14 cm long, containing hydrogen gas—is beyond the left edge of the image. The scattered electrons' momenta were measured as they traveled through the two blue magnets and into the detectors inside the orange shielding. Each spectrometer rode on circular rails so they could measure electrons at different angles from the incident beam. SOURCES: (top and bottom) © SLAC National Accelerator Laboratory; (middle) M. Breidenbach *et al.*, "Observed behavior of highly inelastic electron-proton scattering," *Physical Review Letters* 23, no. 16 (20 October 1969): 935–939, on 935, © American Physical Society.

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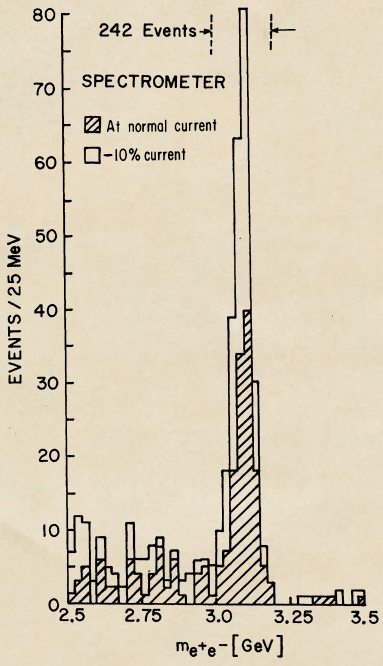


Figure 2.

The MIT-Brookhaven experiment, 1974. TOP LEFT: Photograph of the twin-arm spectrometer used to measure the energies and momenta of the electrons and positrons produced by protons hitting the beryllium target, which lies below the image. ABOVE RIGHT: Annotated photograph of the spectrometer, showing each arm containing magnetic and position sensors to measure each particle's momentum, followed by detectors to identify the particle as an electron or positron and measure its energy. BOTTOM LEFT: Publication histogram of the electron-positron events as a function of energy, showing a sharp peak around 3.1 GeV, indicating the decay of a *J* particle of that mass. SOURCES: Courtesy Professor Samuel Ting; Samuel C. C. Ting, "The discovery of the *J* particle: A personal recollection," *Reviews of Modern Physics* 49, no. 2 (April 1977): 235–249, on 241, © American Physical Society; J. J. Aubert *et al.*, "Experimental observation of a heavy particle *J*," *Physical Review Letters* 33, no. 23 (2 December 1974): 1404–1405, on 1404, © American Physical Society.

Stanford Linear Accelerator Laboratory, or SLAC, began operation in 1966.

One of the first experiments at the new accelerator was directed by MIT's Jerome Friedman and Henry Kendall, along with Richard Taylor at SLAC. The group's original proposal, submitted in January 1966, was to scatter high-energy electrons off of liquid hydrogen targets. They aimed to measure the "form factors" of the protons inside the target nuclei when subjected to high-energy bombardment by electrons; these form factors described how magnetization and electric charge were distributed within a proton.

Their expectation was that the proton could be treated as a smooth, spherical ball of positive electric charge with a radius of around one fermi. (A fermi, also known as a femtometer, is 10^{-15} m.) In that case, the fast electrons from the accelerator should have been slightly deflected in their passage through a proton's sphere of charge. That would correspond to proton form factors that varied in a smooth way as a function of the electron's incoming energy and angle of scatter. Occasionally the electron-proton interaction would produce secondary particles, causing the electron to lose some energy, known as an "inelastic" process. In those cases, the types of particles produced could be determined by comparing the electron's energy before and after the scattering. The effort became known as the SLAC-MIT Deep Inelastic Scattering experiments. (See Figure 1.)

Between 1967 and 1969, the SLAC-MIT team carefully measured how the scattering rates varied with energy and angle with enormous magnetic spectrometers. Each spectrometer included powerful magnets to bend an electron's path following a collision, directing it toward detectors that could measure its momentum. One spectrometer was sensitive to energies up to 8 billion electron volts, while the other—which weighed more than 3,000 tons—could measure the scattered electrons' energies up to 20 billion electron volts. Each spectrometer was mounted on circular rails, like a railroad car, so it could be swiveled to take measurements at various scattering angles.

While the experimental group was still collecting data, neighboring theorists James Bjorken (MIT SB 1956, then based at SLAC) and Richard Feynman (MIT SB 1939, then a professor at Caltech) predicted that *if* a proton had internal, point-like structure—rather than behaving like a smooth blob of charge—then electron-proton scattering at high energies should depend only on the ratio of the momentum transfer between the electron and proton and the electron's energy loss, but not on either quantity separately. Feynman argued that from the point of view of the speeding electron, racing toward the proton target, the proton would undergo relativistic length contraction, appearing to squeeze into a narrow pancake. Moreover, any internal forces occurring within the proton would essentially freeze from the electron's point of view, since (thanks to relativistic time dilation) the electron would "see" the proton's internal clock tick very slowly. Hence whatever complicated jumble of interacting, moving parts might live inside a proton would act, to the electron, as essentially free (non-interacting), stationary, point-like targets.

The SLAC-MIT experimental data showed exactly this scaling: protons really *do* have internal structure. In 1990, group leaders Jerome Friedman, Henry Kendall, and Richard Taylor shared the Nobel Prize in Physics.

Tellingly, Feynman dubbed the scattering sites inside protons "partons"—not "quarks." Gell-Mann's and Zweig's idea about constituent quarks concerned low-energy phenomena and required that the quarks (if real) interact very strongly with each other to remain bound inside particles like protons. Feynman's partons, on the other hand, served as high-energy scatterers that hardly interacted with each other at all. The dramatic results from the SLAC-MIT experiments, combined with Bjorken's and Feynman's clever analyses, quickly convinced the community that protons have internal structure, but *not* necessarily that quarks are real. Indeed, as late as 1972, Gell-Mann himself still referred to quarks as "fictitious." That would soon change.

THE NOVEMBER REVOLUTION: A New Particle and New Clarity

In 1970, Sheldon Glashow (of electroweak-theory fame, on the Harvard faculty) collaborated with two younger Harvard postdocs, John Iliopoulos and Luciano Maiani, to clarify a puzzling pattern from different experiments. They focused on weak-force decays of unstable particles like the K mesons. The original Gell-Mann–Zweig quark model had included three "flavors" of quarks: up, down, and strange.

Combined with the Glashow-Weinberg-Salam electroweak theory, the three-quark model suggested that K mesons should rapidly undergo radioactive decays known as "flavor-changing neutral currents": the strange and anti-down quarks within a K meson would decay (via emission of *W* particles) into a pair of positive and negative muons. Yet such transitions appeared to occur about ten thousand times less frequently than predicted by these models.

Glashow, Iliopoulos, and Maiani demonstrated that if there existed a fourth flavor of quarks—akin to the up quark, but more massive—then there should be a near-perfect cancellation of the quantum-mechanical amplitudes governing such flavor-changing neutral currents. That near-cancellation would suppress the likelihood that K mesons would decay into pairs of muons.

Strikingly, the "GIM mechanism" suggested something even deeper: perhaps there existed a symmetry linking the known leptons (the electron, electron-neutrino, muon, and muon-neutrino, which do not "feel" the strong nuclear force) with the still-hypothetical quarks (which do). Upon incorporating the new "charm" quark, the trio argued, each lepton might be paired with a corresponding quark. The particles could be grouped in "generations": the electron and its neutrino paired with the up and down quarks in the first generation; the muon and its neutrino paired with the charm and strange quarks in the second.

As Glashow, Iliopoulos, and Maiani completed their calculations, two new experiments began to take form. Neither had been pitched or planned with quarks in mind, let alone a possible fourth flavor. Rather, both experiments had been developed to test the interaction of light with matter. But in November 1974, when both groups announced their discovery of a new particle called the "J/ψ," the implications for quarks seemed clear.

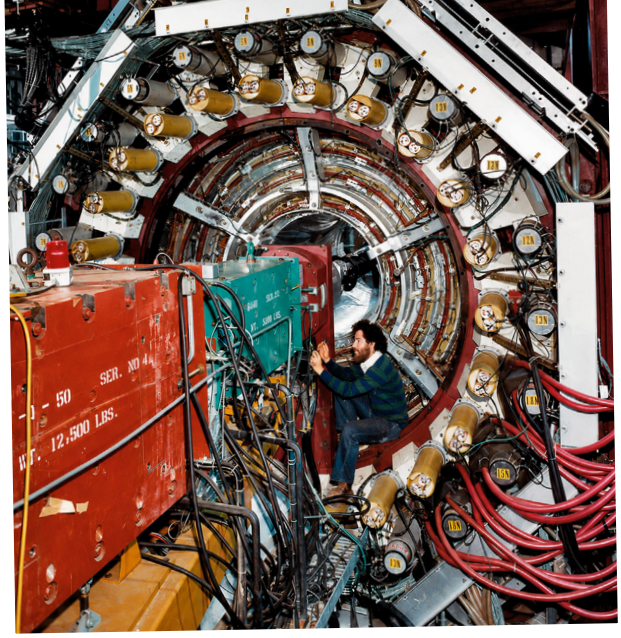
One of these experiments was based at Brookhaven National Laboratory on Long Island, New York, and led by MIT professor Sam Ting. Ting's driving question concerned the conversion of photons into heavy nuclear particles, along with MIT junior faculty Ulrich Becker and Min Chen. Throughout the 1960s, physicists had measured such conversions into three new particles: the ρ meson, the ω meson, and the ϕ meson. Each carried the same quantum numbers as the photon (for example, each had one unit of spin and zero electric charge); but unlike massless photons, each "heavy photon" (also known as "vector mesons") had a large mass, comparable to that of a proton. The new particles decayed rapidly into pairs of electrons and positrons, by means of which physicists could measure how strongly ordinary photons interacted with the heavy photons—measurements that Ting and his group had performed during the late 1960s.

By 1971, Ting had grown puzzled: could there really only exist three heavy photons, each with around the same mass? Since the ρ, ω, and ϕ had been produced in proton-proton scattering experiments, he proposed to seek new members of the set in higher-energy proton collisions. He submitted a proposal to Brookhaven to use the Alternating Gradient Synchrotron, which could produce high-intensity beams of very energetic protons, with energies up to 30 billion electron volts. When the protons interacted with a beryllium target, they could produce new particles with masses up to about four times the mass of a proton. So many energetic particles would be produced that the target had to be segmented into ten plates, each around 1 cm^2 and spaced about 10 cm apart, to allow for heat dissipation.

Downstream from the target, Ting and his group designed and installed a double-arm spectrometer with which they could measure the energy and momentum of electrons and positrons. (See Figure 2.) The very high rate of particles entering the spectrometer meant that the data had to be recorded on a computer—a very early application of microcomputers in such experiments—and then analyzed on mainframe computers over the months after the data had been acquired. In addition to Ting, Becker, and Chen, the group included ten other physicists from MIT.

By late summer 1974, the team had identified a sharp, narrow peak at around 3.1 GeV: at that energy, the number of electron-positron events spiked, indicating that the energetic proton scattering had produced a new particle which quickly decayed into electron-positron pairs. Ting and his group decided to call the new particle "*J*," since they had been inspired to search for such "heavy photons" by thinking about the electromagnetic current (typically denoted "*j*") that couples matter to photons.

Over the same period, an experimental team at SLAC, led by Burton Richter (faculty member at Stanford University, MIT SB 1952, MIT PhD 1956), developed a



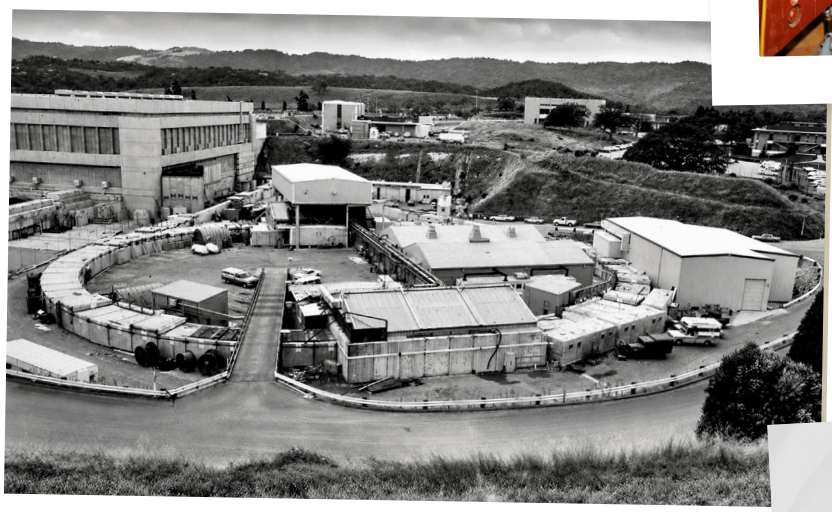




Figure 3.

TOP LEFT: The Stanford Positron Electron Asymmetric Ring (SPEAR) storage rings. Electrons were injected via the beam pipe visible tangent to the ring in the upper left; a second beam was injected from a location behind the building in the upper left. Within the ring, electrons circled counterclockwise and the positrons circled clockwise. Magnets focused the electrons and positrons into collisions in the building to the right, at a point surrounded by the Mark I detector. TOP RIGHT: The Mark I detector. The red focusing magnet in the foreground enclosed the beam pipe and the intersection point. The octagonal structure measured 3.5 m across and consisted of a 2 m diameter inner detector that measured charged particle momentum and trajectory, a 3 m diameter scintillator detector that measured particle velocity, the 3.3 m diameter solenoidal magnet, which created the magnetic field for the momentum measurement, and more scintillators that measured penetrating particles. BOTTOM RIGHT: Data display showing four particles emanating from the intersection point. The different symbols show the different measurements of each particle. Combining or "reconstructing" these data indicated they came from the decay of a ψ particle at the intersection point [4]. SOURCES: each image courtesy SLAC National Accelerator Laboratory.

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new kind of accelerator and detector. (Joining Richter on the SLAC team were several other MIT graduates, including Martin Breidenbach SB 1965, PhD 1970, and Roy Schwitters SB 1966, PhD 1971.) For the new detector, the SLAC group worked in collaboration with colleagues at nearby Lawrence Berkeley Laboratory to design the first comprehensive, cylindrically symmetric detector, which could register particles at nearly any angle from the beam direction—a big change from previous instruments that could only detect particles within narrow angles. The novel SLAC-LBL detector became known as the "Mark I" detector. The accelerator included a storage ring about 100 meters in radius that would be filled with particles from the 2-mile linac. The Stanford Positron Electron Asymmetric Ring (SPEAR) could hold high-energy electrons traveling in one direction, while positrons traveled within the same circular beam pipe in the opposite direction, each guided by a magnetic field. The electrons and positrons would counter-rotate for several hours, made possible by a very high vacuum within the machine. At one point on the ring, the Mark I detector surrounded the beam pipe. At that location, focusing magnets brought the electrons and positrons into collision.

When an electron-positron collision occurred, it yielded a spray of up to about ten particles that the Mark I detector could measure. (See Figure 3.) The large number of particles, whose momenta were measured across several channels, required that the Mark I detector—like the MIT-Brookhaven experiment—use a computer to record the data for subsequent ("off-line") analysis. Much like the MIT-Brookhaven effort, the original proposal for the SLAC experiment did not mention anything about quarks; the focus had been on measuring properties of photons produced in electron-positron annihilation.

The SLAC team faced a different challenge than the MIT-Brookhaven group. Any new, short-lived particle that might be produced from the annihilation of a counter-rotating electron and positron would have an energy exactly twice that of the electron. Since the SLAC team did not know with any precision what the mass of the new particle might be, they had to adjust the electron beam in steps to "scan" the energy, working first in steps of 100 MeV. By summer 1974, the team found that runs in the vicinity of 3.1 GeV were giving statistically inconsistent results. A software glitch first seemed to be the likely culprit; by that autumn, some team members suspected hardware problems and undertook a more fine-grained energy scan, using steps of just 1 or 2 MeV. The team did not yet know that the new particle—which their group dubbed the "ψ" meson, based on the arrangement of particle trajectories in their experiment—could only be produced when the electron-positron collision energy was within 0.05 MeV of the ψ particle's mass, corresponding to just 1/20th of their step size. Fortunately for the group, imperfections in the SPEAR storage ring introduced a spread of 1 MeV in the beam energy, creating a small signal that physicists could then home in on.

The two groups completed their analyses around the same time in autumn 1974, and Ting and Richter announced their groups' findings on November 11. Ting also shared a preview of his group's results with colleagues at the Frascati Laboratory in Italy. With a clear indication of what energy to focus on, the Italian group was able to replicate the results within two days. All three groups published their results just three weeks later, in the same issue of *Physical Review Letters*. The dramatic announcement of the J/ψ discovery was quickly dubbed the "November Revolution."

Even before the experimentalists' papers had appeared in print, several theorists (including Glashow) submitted articles demonstrating that the J/ψ particle could be described as a bound state of a charm quark with an anti-charm quark, a state of matter soon known as "charmonium." This interpretation gained traction when the SLAC group found evidence of an excited state of the ψ particle—which they dubbed the ψ'—about two weeks after they first identified the ψ. Just two years later, Sam Ting and Burton Richter shared the 1976 Nobel Prize in Physics for their groups' discoveries.

FRAMING AND NAMING THE STANDARD MODEL

Beginning in 1972—while the MIT-Brookhaven and SLAC-SPEAR experiments were still under construction—Murray Gell-Mann and colleagues developed a new dynamical theory of the strong nuclear force. Cast in analogy to local gauge theories like electromagnetism and electroweak theory, the new model described quarks interacting by exchanging "gluons" [5] (analogous to photons and the W and Z weak-force carriers). They posited that each quark carried a new kind of charge, which, unlike electric

charge, could have three different values. Much as the three primary colors (red, green, and blue) can combine to yield white light, Gell-Mann and his colleagues dubbed the new feature "color" charge, and their new dynamical theory "quantum chromodynamics," or QCD. Total color charge, they argued, must remain conserved in any interaction. Within months, Harvard PhD student David Politzer and, separately, Princeton PhD student Frank Wilczek and his advisor David Gross, demonstrated that the strength of the QCD interaction should fall at high energies—an effect they called "asymptotic freedom," as Professor Wilczek describes in his contribution to this issue. Politzer, Wilczek, and Gross shared the Nobel Prize in 2004 for this work.

In July 1974, just a few weeks before the big announcement of the J/ψ discovery, Jean Iliopoulos (who had co-authored the GIM mechanism) delivered a plenary address at the 17th annual International Conference on High Energy Physics, held in London. His talk on "Progress in Gauge Theories" offered the first review of an emerging consensus on how various puzzle pieces might fit together. The "ultimate model," he announced, could consist of the GIM-inspired fourth quark and resulting symmetry among lepton and quark generations, with forces governed by the Glashow-Weinberg-Salam electroweak theory and by QCD. He concluded with a flourish: "I am ready to bet now a whole case [of wine] that [...] the entire next Conference will be dominated by the discovery of the charmed particles." [6] He won the bet.

Iliopoulos spoke of the "ultimate model"; Steven Weinberg casually referred to a "standard model" at conferences around that same time. At the 7th International Symposium on Lepton and Photon Interactions, held in August 1975 at SLAC—the first major conference after the November Revolution—participants readily adopted the new framework. The following month, Abraham Pais and Sam Treiman wrote of "a certain four-quark [electroweak] gauge model that we shall refer to here as the 'standard' model." [7]

At the 1975 SLAC conference, some physicists went further, proposing that a third generation of particles might exist: new "top" and "bottom" quarks paired with a tau meson (akin to an electron but more massive) and an accompanying tau-neutrino. In rapid order, experimentalists announced evidence for the tau lepton in 1975 and the bottom quark in 1977. Evidence for the other particles predicted by the Standard Model trickled in more slowly—the W and Z bosons detected in 1983, the top quark in 1995, the tau-neutrino in 2000—capped by the remarkable detection of the long-elusive Higgs boson in 2012.

Open questions remain. As treated by the Standard Model, for example, neutrinos should be massless. Yet experiments since the late 1990s—for which several MIT physicists have played key roles—demonstrate clearly that neutrinos must have very tiny, nonzero masses. Perhaps even more urgent: a welter of astrophysical and cosmological evidence indicates that our universe is filled with some strange "dark matter," which contributes about five times more to the cosmic energy balance than all of the Standard Model particles combined. Dark matter appears to nudge the motion of ordinary objects via gravity, while remaining impervious to all three of the forces (electromagnetism plus the weak and strong nuclear forces) described in such impressive detail by the Standard Model.

In the intervening fifty years, the Standard Model has withstood thousands of experimental tests that sought to find discrepancies and thereby drive a new theoretical advance. None have succeeded, despite forty years of advances in accelerator and detector technology. The latest accelerator, the Large Hadron Collider (LHC)—which is now undergoing a three-year upgrade to increase the amount of data collection tenfold—might reveal physics Beyond the Stand Model (BSM). Yet nothing is guaranteed, and CERN is studying a possible Future Circular Collider (FCC) that could come online in the 2040s.

No matter what comes next, the J/ψ era will stand as a unique time for many years. The teams that discovered real constituents inside protons, and new states of matter like the J/ψ, had not gone looking for such things. Each discovery required serendipity, an openness to surprise, as well as prepared minds. Fifty years ago, particle physics underwent a paradigm shift—following a playbook set forth by historian and philosopher of science Thomas Kuhn (MIT faculty 1979–91)—that changed our understanding of nature forever.

ACKNOWLEDGMENTS

We are grateful to Samuel Ting, Martin Breidenbach, and Robert Jaffe for helpful discussions.



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PETER FISHER, the Thomas A. Frank (1977) Professor of Physics, was appointed associate provost and associate vice president for research in October 2022. He also serves as head of MIT's newly established Office of Research Computing and Data. Fisher served as head of the Department of Physics from 2013 to 2022 and led the Experimental Nuclear and Particle Physics Division from 2002 to 2013.

Fisher has extensive experience in classical and quantum electrodynamics, including carrying out the most precise tests of the theory, and has over 300 publications in the field. He has also served as an expert witness in court cases related to electromagnetism. He has led a DARPA study of wireless energy transmission between spacecraft as part of the System F6 program, and is a founder of WiTricity, a startup developing wireless energy transmission for commercial use. He also serves as Vice Chair of the JASONs.

He has taught electromagnetism at both the undergraduate and graduate levels and was an instructor for the MIT Physics Undergraduate Laboratory, which includes several components related to electromagnetic radiation. Fisher serves as a referee for several journals, including *Physical Review*, *Physical Review Letters*, and *Nuclear Instruments and Methods*. He served on several national panels and advisory groups, including the Particle Physics Program Prioritization Panel that defined the roadmap for experimental particle physics over 10 years, encompassing about $8 billion in research funds from the Department of Energy and National Science Foundation.

His research interests are the experimental detection of dark matter, the development of new kinds of particle detectors, and large scale classical and quantum computing systems. He carried out one of the first dark matter searches and since then has searched for dark matter on Earth and in space, including inventing a new kind of detector, the Dark Matter Time Projection Chamber. He recently published a book, *What is Dark Matter?*, with Princeton University Press. Peter Fisher received a bachelor of science in engineering physics from the University of California at Berkeley in 1983 and a PhD in physics from Caltech in 1988.

DAVID KAISER is Germeshausen Professor of the History of Science and Professor of Physics at MIT. He is the author of several award-winning books about modern physics, including *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (2005), *How the Hippies Saved Physics: Science, Counterculture, and the Quantum Revival* (2011), and *Quantum Legacies: Dispatches from an Uncertain World* (2020). In MIT's Physics Department, Kaiser is based in the Center for Theoretical Physics—A Leinweber Institute, where he focuses on early-universe cosmology, primordial black holes, and foundations of quantum theory. He is Fellow of the American Physical Society and member of the Board of Trustees of the American Institute of Physics Foundation, and he has received MIT's highest honors for excellence in teaching. His work has been featured in *Science*, *Nature*, the *New York Times*, and the *New Yorker* magazine. His group's efforts to conduct a "Cosmic Bell" test of quantum entanglement, together with MIT's Alan Guth and Nobel laureate Anton Zeilinger, were featured in the documentary film, *Einstein's Quantum Riddle*.

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[1] Dyson and Teller quoted in David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: University of Chicago Press, 2005), 198.

[2] Murray Gell-Mann, "A schematic model of baryons and mesons," *Physics Letters* B 8 (1 February 1964): 214–215; George Zweig, "An SU(3) model for strong interaction symmetry and its breaking," CERN preprints TH-401 and TH-412 (January 1964).

[3] A "non-Abelian" symmetry group is one in which the order in which symmetry transformations are applied affects the final state of the system. The discrete Lie group SU(2), at the heart of the Glashow-Weinberg-Salam electroweak theory, is an example of a non-Abelian group.

[4] The story is that ψ was chosen because the particle "signed its own name" on the event display shown in Figure 3 (right).

[5] Ting and his group went on to discover evidence of gluons in 1979 with the Mark J experiment at the PETRA accelerator at DESY in Hamburg, West Germany.

[6] Jean Iliopoulos, "Progress in gauge theories," in *Proceedings of the XVII International Conference on High Energy Physics*, ed. J. R. Smith (Chilton, UK: Rutherford Laboratory, 1974), III-89–116, on 100.

[7] Abraham Pais and Samuel Treiman, "How many charm quantum numbers are there?," *Physical Review Letters* 35 (8 December 1975): 1556–1559, on 1556; their article was submitted on September 8, 1975.

Alumni Notes

'60

Richard L. Greene (SB) was elected to the National Academy of Sciences (2026).

'61

Stephen N. Salomon (SB. Thesis advisor: Wayne B. Nottingham) thought his 65th MIT Reunion in June 2026 was excellent. The fusion lecture reminded him of a technology assessment paper he wrote ~40 years ago while a Littauer Fellow at Harvard University, wherein he compared a world run with fusion reactors vs. liquid metal fast breeder reactors. A principal concern was containing tritium, so DNA in people would not be a problem. Tritium combines with oxygen to become radioactive water!

'64

L. David Roper (PhD. Thesis supervisor: Bernard T. Feld) recently co-authored two papers: "Universal mass equation for equal-quantum excited-states sets I," L. David Roper and Igor Strakovsky, *Eur. Phys. J. A* (2025); "Universal mass equation for equal-quantum excited-states sets II," L. David Roper and Igor Strakovsky, *Eur. Phys. J. A* (2025); and *Acta Physica Polonica B* 57 (2026) No. 2, Special Volume was dedicated to him.

'65

Benjamin Rouben (PhD) continues to be active since his 2007 retirement from Atomic Energy of Canada. He remains an adjunct professor in nuclear energy at McMaster Ontario Tech Universities, where he teaches several courses on reactor physics, nuclear power plant operations, and in-core nuclear fuel management. He is also Secretary/Treasurer of UNENE (University Network of Excellence in Nuclear Engineering), where he also teaches in UNENE's MEng program.

'66

Howard A. Smith (SB; PhD University of California, Berkeley. Thesis advisor: Charles H. Townes) recently published *Secrets of Creation: Mysticism Meets Art and Science* (Ben Yehuda Press), which examines recent discoveries in physics and astronomy (dark matter, gravitational waves, exoplanets, quantum entanglement, black holes, and more), comments on the mystical picture, and shows why a truer understanding of reality emerges best by using both spiritual and scientific insights. (This work is separate from Howard's regular journal articles in astronomy and astrophysics.)

'68

Owen Franken (SB) Photography had always been Owen's passion, including working for John Mattill, at *Technology Review*. His project during the past academic year was continuing to co-write and illustrate a food and travel book proposal, *Around the World in Eighty Meals*. It is based on many worldwide travels and the foods discovered.

Ian S. Glass (PhD; SM '64. Thesis supervisors: George Clark, Frank Scherb) retired from the South African Astronomical Observatory in 2006, where he specialized in infrared astronomy. His current main interest is writing astronomical history. In March 2026 he completed "Grubb Dublin and Grubb Parsons," a history of the famous Anglo-Irish telescope company. Ian continues to enjoy mountain walking and traveling.

'70

Alan Goldberg (SB. Thesis advisor: Hale Bradt) finally retired this past year, after 35 years at MITRE Corp. advising various government agencies on technical aspects of spacecraft acquisition, sensors and data processing. His last gig was advising on improved data and metadata formats. While Alan proved in industry to be a better engineer than scientist, the first principles he learned in courses 5 (and 6, 14, and 18) at MIT helped throughout. He and his wife Pamela ('74) relocated to Maryland, where he has a dark sky to once again be an amateur astronomer, along with time to spend collecting and restoring old phones.

'72

Stephen Perrenod (SB; PhD '77 Harvard University) is Vice Director for the Scientific Bitcoin Institute (SBI), which he co-founded in early 2026 with Italian physicist Giovanni Santostasi. SBI (*scientificbitcoin institute.org*) engages in econophysics and network science research, as well as educational activities related to the Bitcoin blockchain and ecosystem; research partners include the Politecnico di Torino. He and Santostasi recently published their first scientific paper from SBI, "A Mechanistic Derivation of the Bitcoin Price Power Law." Preprint available at *zenodo.org/records/19387099*.

'76

Eric Bogatin (SB. Thesis advisor: John King) After 40 years working in industry, starting his own company and having it acquired by Teledyne, Eric is now on the ECEE faculty of the University of Colorado, Boulder. He teaches the senior design capstone course and some grad classes in signal integrity. Eric has two research groups, one of which focuses on developing a curriculum around hands-on electronics labs for pre-college engineering. He remains a Fellow at Teledyne LeCroy.

'78

Paul Edelman (SB) continues his work with family enterprise and family office leaders on high-stakes decisions, succession, and rising-generation development. Highlights included articles in *International Family Offices Journal*, *FFI Practitioner*, and *familybusiness.org*; a *Family Wealth Report* interview on decision-making and family dynamics; several conference presentations; and continued advisory work with families and advisory teams facing complex transitions. Paul's MIT physics training remains a deep influence on his approach to defining and solving problems systematically.

Edward Charles Sittler, Jr. (PhD. Thesis advisor/supervisor: Stanislaw Olbert, Herbert Bridge) successfully launched a tech demo of his Tandem Ion Mass Spectrometer (TIMS) in February 2026 by auroral sounding rocket at Poker Flat Alaska to altitude > 300 km. He gave a talk at the March 2026 APS Meeting about TIMS and its ability to measure heavy interstellar ions within our heliosphere, for mass A > 56 amu, and by using superconducting magnets A > 200 amu to test models of core-collapse supernovae for mass peaks A ~ 50 and 80 amu r-process nuclei and Binary Neutron Star (BNS) mergers r-process nuclei for mass peaks A ~ 130 and 195 amu.

André-Marie Tremblay (PhD. Thesis supervisors: Bruce Patton, Paul Martin) retired this year from the physics faculty of the University of Sherbrooke, Canada, but is still supervising PhD students and doing research. They made progress on the front of high-temperature superconductivity in cuprates. See *PRX* 15, 021071 for material-specific predictions and *PRL* 136, 256503 on the dynamics of pairing.

'79

Jeffrey H. Hunt (SB; PhD University of California, Berkeley. Thesis advisor: Michael Feld) gave two invited talks this past year: September 2025 at the EU Graphene Week conference in Vincenza, Italy ("Graphene applications in aerospace platforms: Why would a seemingly academic curiosity be of interest to an industry that manufactures massive mobile airborne structures?"), and May 2026 at the UK Integrated Quantum Networks Hub in Bristol, UK ("Actualization of a Quantum Network: What pieces are in Place? A Review of Quantum Patent Portfolio"). Jeff is an Executive Technical Fellow at Boeing and fellow of the APS and Optica.

'80

Leon Tabak (SB) retired in May 2026. He taught computer science at Cornell College in Iowa for 37 years. A longtime educational counselor for MIT, he will continue interviewing students for MIT. On July 1, 2026, he marked 4,000 consecutive days of practice on Duolingo.

'82

Lawrence M. Krauss (PhD) continues his role as president of the Origins Project Foundation, and host of The Origins Podcast (*originsproject.org/origins-podcast/*), in addition to his physics activities. Guests on the podcast during the 2025–26 academic year included Nobel Laureate Alvin Roth, physicist Sabine Hossenfelder, Noam Chomsky, Richard Dawkins, and many others.

'91

Maha Achour (PhD. Thesis supervisor: Barton Zwiebach) A January 2026 *Nature* paper revealed that the branching of neurons follows the exact same mathematical structure proposed in a 1989 MIT paper by Maha and his advisor Barton Zwiebach. It is Maha's strongest conviction: describe something with sufficient mathematical precision, and reality will eventually catch up. He feels he continues to bring a rare combination of frontier physics, applied mathematics, deep engineering across key industrial sectors, commercial fundraising, and board governance to UK-based AI startup Kodamai.

'92

Cameron Miner (SB. Thesis advisor: Bruno Coppi) This past year brought several changes for Cameron. He left MIT Lincoln Laboratory, where he founded the Digital Twin Working Group, to focus full-time on advisory and board work. He is advising Fareon, a neurotech startup raising its Series A; Frontier Industries on AI/SMR nuclear infrastructure strategy; and Cortheon, an MIT spinout on 3D-printing materials for investment casting. This is alongside the MIT Engine's Blueprint Program and MITdesignX, as well as guest lecturing in Ken Zolot's course and the D-Lab. Cameron also recently gave a TEDx Portsmouth talk, "AI Is Everywhere. Except Where Needed Most."

'98

Karen (**Thibault**) **Bodnar** (SB) took an unconventional path after MIT, serving in the U.S. Air Force before becoming a pediatrician. She now serves as medical director of the Breastfeeding and Lactation Medicine clinic at Inova Health System. Karen helped found the North American Board of Breastfeeding and Lactation Medicine (NABBLM), which develops standards for physician training and certification in this emerging specialty, and currently serves as its president.

'08

J. Colin Hill (SB *Physics, Mathematics*. Thesis advisors: Claude Canizares, Kenneth Rines) received a 2026 New Horizons in Physics Prize from the Breakthrough Prize Foundation for advances in cosmic microwave background cosmology. He is an associate professor in the Department of Physics at Columbia University.

'19

Kiriakos Hilbert (SB. Academic advisors: David Kaiser and Alan Guth) works at Amplified Industries, an MIT-alumni-founded startup in Boston that builds automation technology for oilfield operations. He works at the intersection of numerical physics simulation and machine learning, building more accurate methods to model real-world well conditions and optimize their control. Kiriakos would be interested in connecting with fellow alumni who have branched out into deep-tech fields.

Hang Yu (PhD. Thesis supervisors: Nevin Weinberg, Matthew Evans) is an assistant professor of physics at Montana State University, recently receiving a National Science Foundation CAREER Award. The award will support research on constructing theoretical models describing the inspiral and post-merger oscillation of binary neutron stars, an important type of source for gravitational wave observations.

'22

Kylie Yui Dan (SB) is a PhD candidate in astronomy at the University of Maryland (UM), under Sylvain Veilleux. This past year Kylie published an article in *ApJ* presenting JWST MIRI/MRS results of the ULIRG F10565+2448. They found warm molecular, warm ionized, and hot coronal outflows, as well as signs of shocks. Kylie also earned the astronomy master's degree at UM, passing the thesis proposal defense.

Patrons of Physics Fellows Society

The personal stories of graduate fellowship recipients were shared at the Society's annual dinner.

by Danielle Forde

Eleanor Richard is a first-year graduate student and recipient of a Frank Fellowship

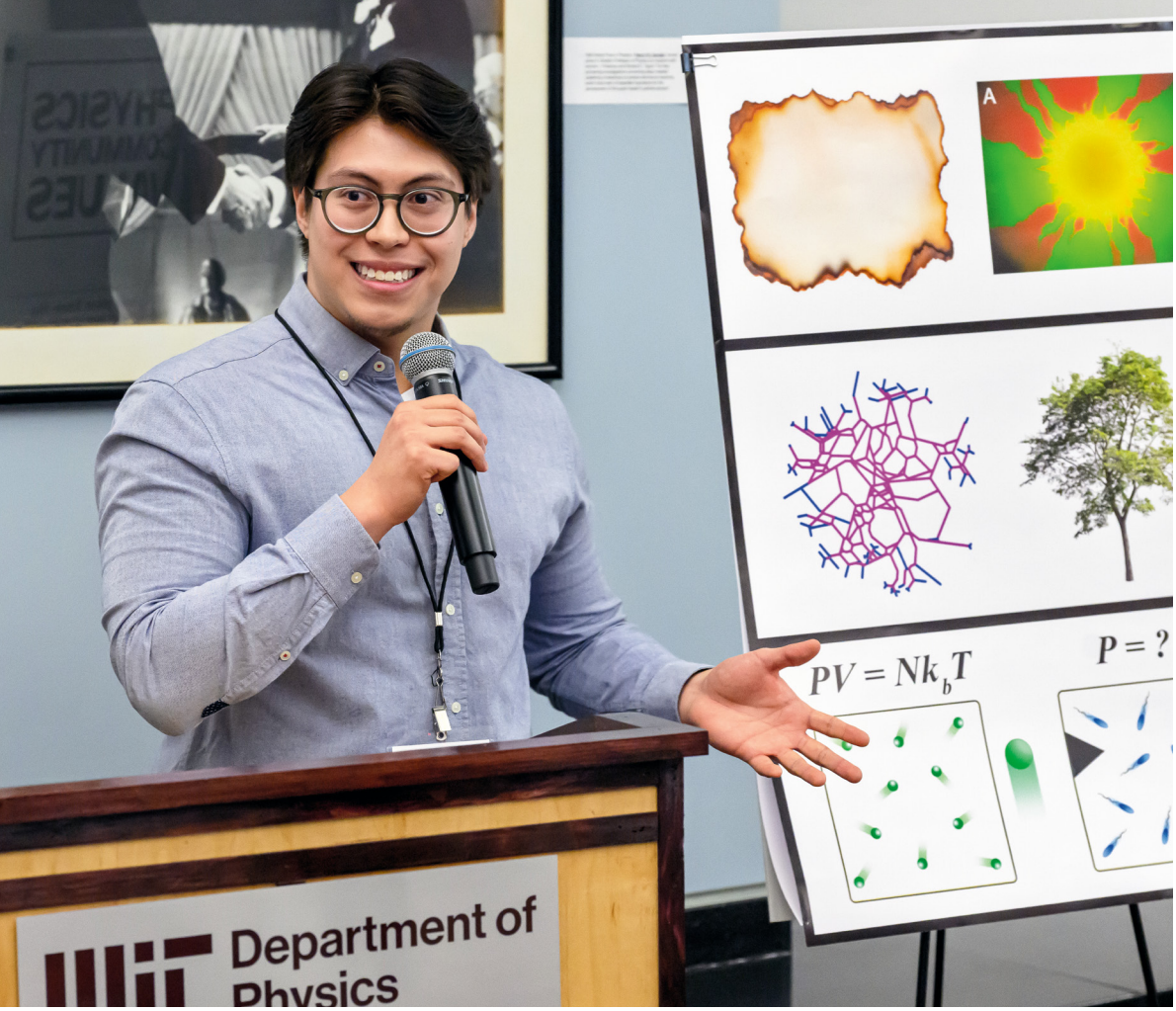
Thank you very much for your kind and generous sponsoring of my fellowship. I am extremely grateful for the opportunity to attend MIT without financial concern during my first year. Your support has allowed me to immerse myself in a research group whose work truly excites me, without the distraction of funding uncertainty.

I have joined the condensed matter experiment division, where I study the out-of-equilibrium properties of two-dimensional materials using ultrafast electron diffraction. In our experiments, we excite materials with light and track their lattice and charge dynamics by recording electron diffraction patterns as a function of time. This approach allows us to probe how materials respond on ultrafast timescales and move toward controlling material properties on demand. I believe this capability will be essential for accessing and stabilizing phases of matter that have not yet been observed experimentally. As an undergraduate at Cornell University, I also studied out-of-equilibrium material properties using complementary techniques such as terahertz spectroscopy, which is sensitive to low-energy excitations. I am excited to continue building on this foundation during my PhD and to contribute to our understanding of how we can control materials with light.

The flexibility provided by my fellowship has also allowed me to be involved more broadly in the MIT community. I joined the Physics Graduate Students Advising Graduate Admissions organization where I mentored two senior undergraduate students applying to physics PhD programs. I really enjoyed meeting other passionate students and sharing insights from my own graduate



Eleanor Richard, Frank Fellow. Credit: Justin Knight Photography.



Sergio Eraso, Thomas Fellow. Credit: Justin Knight Photography.

application process. Outside of academics, I joined the MIT triathlon team and have loved exploring the beautiful Boston area through running and biking!

Thank you again for your generosity and support. This fellowship has made my first year at MIT truly exceptional. I am grateful for all that I have learned so far and am excited for the opportunities that lie ahead!

Sergio Eraso is a third-year graduate student and recipient of a Thomas Fellowship

I am writing this to express my gratitude for your generous support in enabling me to pursue my PhD in Physics at MIT. When I was seven, I immigrated to the United States with my mom, leaving behind familiar life in Colombia. We spent the next decade moving between various different neighborhoods and schools in the search of better opportunities. Each time we moved, the classrooms, teachers, and classmates changed, but the symbols written on the board stayed mostly the same. Math became a constant anchor in my education, something that transcended school systems and countries. From a young age, I enjoyed the puzzles math provided and learned to take ownership of my education as a result of the instability of switching schools so often. I spent much of my free time reading textbooks and watching YouTube videos on math and science. By the time I got to college, I supplemented all of my classes with the MIT OpenCourseWare versions. I used to joke that at least a third of my undergraduate degree came from MIT long before I received my acceptance letter.

Now, as a PhD student at MIT, I have the privilege of studying a wide range of questions at the interface of physics and biology. Currently, I am studying the collective behavior of active matter, self-propelling particles such as bacteria or molecular motors, that do not obey many laws in the established physics canon. Better understanding of these systems can provide insight into how biological systems self-aggregate into cohesive structures. Thanks to your generous support, I have also been able to submit two manuscripts for publication in my PhD: one on computational immunology studying how our body repartitions energy upon infection, and the other on



Thomas Barbera, Whiteman Fellow. Credit: Justin Knight Photography.

evolutionary dynamics and connections to well-known results in the field of nonequilibrium statistical physics. Your aid has greatly facilitated my contributions to these two drastically different fields.

Beyond research at MIT, I am also passionate about mentorship and outreach. I have spent much of my free time tutoring students in our Physics Department and providing support to students applying to graduate school from underrepresented backgrounds. Your investment not only represents hope in students like me, but it extends to the students that I serve as well, whose paths to places like MIT were not always straightforward. I am sincerely thankful for your generosity and for the role you have played in making my education possible.

Thomas Barbera is a first-year graduate fellow and recipient of a Whiteman Fellowship

I have always had a passion for learning. Math was my first love; for something that seemed simple at first glance, there was so much complexity under the surface. It harnesses the ability to describe everything. But I found myself desiring a more tangible career; something more concrete, where I could point to a discovery or invention and say "We found it." However, growing up in a single-parent household with a mother who works in education and two older siblings, I was not in a very privileged financial position. I was hard-pressed to find opportunities to gain research experience in high school, and was blessed to earn merit scholarships to cover my undergraduate studies at the University of Notre Dame.

I began my college career as a chemistry major, as it seemed to me that chemistry was the most tangible science. In my second semester, I remember sitting in an organic chemistry lecture, following complex reaction mechanisms across the board, when it occurred to me that there was something more to all of this; a hidden structure beneath the web of arrows and bonds. I began to notice patterns, hints of a deeper logic beneath the molecules themselves. And I realized I wasn't just fascinated by how reactions occurred; I was drawn to the underlying rules—the invisible framework that governed all matter. At that moment, I became fascinated by the power

of physics to explain the universe at every level, starting from the smallest fundamental particles and building to entire galaxies. Physics is the foundation for the world of science; it is where our understanding of the universe begins and ends. After that semester, I switched my major to physics and never looked back.

It was a dream come true to be accepted to the PhD program at MIT. As a Massachusetts native, I always dreamed of returning home for my career. MIT was the school I visited every summer, walked around campus, and said "This is where I want to be." So, when I opened that acceptance letter sitting on my floor, expecting nothing but disappointment, it hit me—everything I spent 22 years working for had finally come to fruition.

Throughout my first year at MIT, I have worked with Prof. Brooke Russell on a variety of fundamental particle physics projects surrounding dark matter detection and the properties of neutrinos. Currently, I am actively probing several unverified predictions related to both. For neutrinos, I contribute to hardware and simulation efforts for the Deep Underground Neutrino Experiment (DUNE) Near and Far Detector systems, which aim to measure neutrino flavor oscillations and explore potential differences between neutrinos and antineutrinos. I am also heavily involved in a novel dark matter direct detection experiment at the Kamioka Cryolab in Japan, where I spent this past summer building and installing readout electronics to commission a cryogenic refrigerator that I will use to detect nuclear recoils in superfluid helium—possible signatures of low-mass dark matter interactions.

All of my success would not have been possible without your kindness and generosity. I have been able to fulfill a lifelong dream of studying at MIT, and can continue to strengthen my understanding of physics over the next several years. I want to thank you both, from the bottom of my heart, for the opportunity you have given me to be here. I look forward to the years ahead, where I can grow as a student, physicist, and individual. Truly, thank you.

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The MIT Department of Physics strives to be at the forefront in every field where new physics can be found. By constantly pushing the limits, we have a chance to observe new general principles and to test theories of the structure and behavior of matter and energy.

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Attracting the best graduate students to work with our faculty continues to be our highest priority. We have established the Patrons of Physics Fellows Society to recognize friends of the Department who have made it possible for us to recruit the very best graduate students. A commitment of $70,000 or higher will make you a member of this society. You will receive updates from the named graduate student you are supporting and be invited to the annual Patrons of Physics Fellows Society dinner.

With your help, we will continue to understand the deepest aspects of nature, perhaps even the origins of space, time and matter. To make a gift, or for more information on making a gift, please contact:

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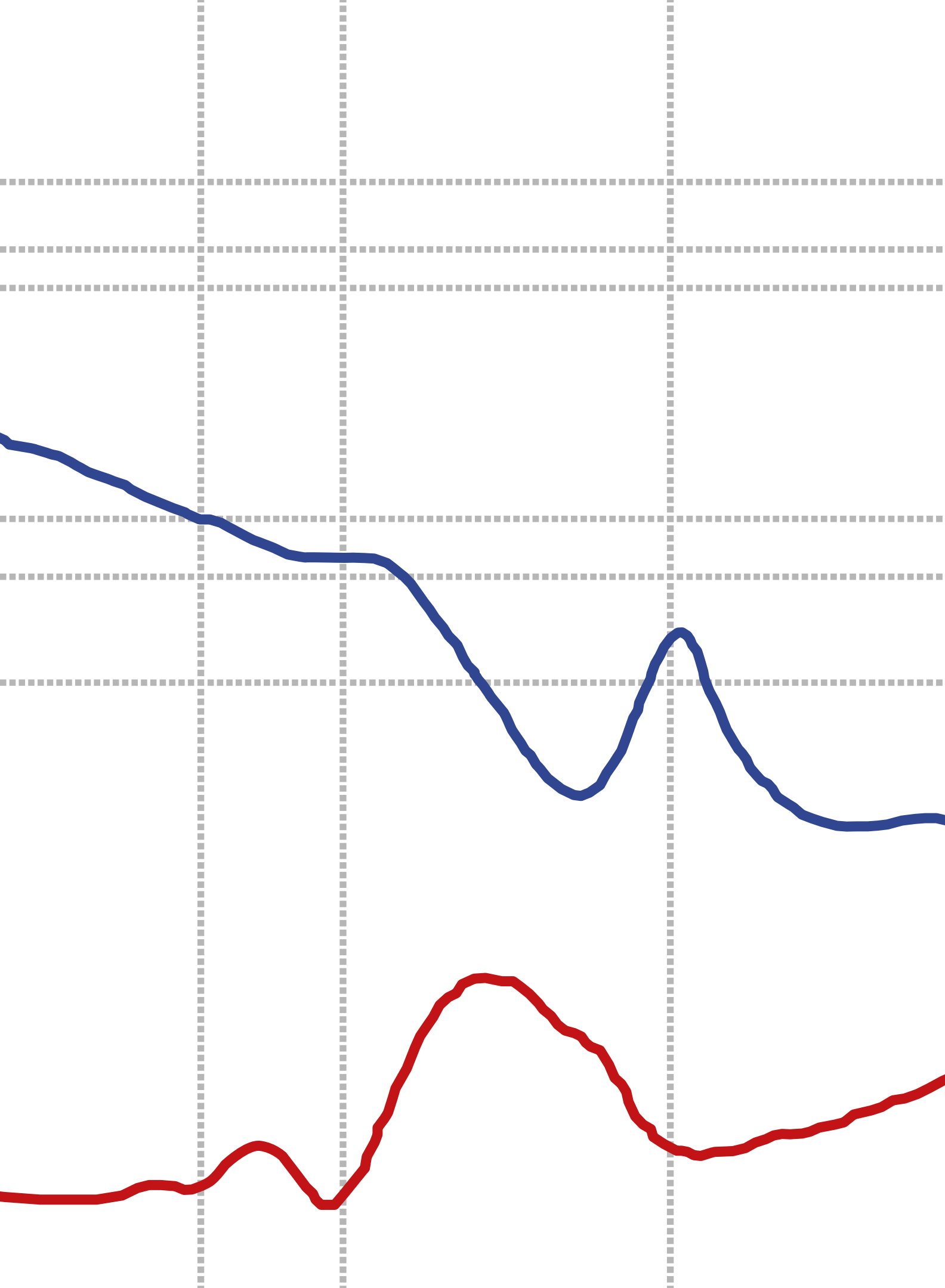
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