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DEPARTMENT OF PHYSICS
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Cover designs adapted from figures in Prof. Robert Simcoe's (exterior front cover), Profs. Mike Williams' and Jesse Thaler's (inner front cover) and Prof. Netta Engelhardt's (inner back cover) feature articles on pages 32, 50 and 42, respectively.

Message from the Department Head

DEAR MIT PHYSICS COMMUNITY MEMBERS,

This is my first Department Head letter for *physics@mit*. It was my honor to succeed **Prof. Peter Fisher** as Department Head last September after his nine years of distinguished service. A few months later, **Sally Kornbluth** was appointed as the new President of MIT, and she has moved quickly to affirm a sense of possibility, mission and partnership across the MIT community. It is an exciting time of transition and renewal!

I am an undergraduate alumnus of the Physics Department (Class of 1988), and received my PhD at Caltech before returning to MIT as a postdoc in 1996, then joining the Physics faculty in 1999. My research in astrophysics uses X-ray observations from orbiting telescopes to study neutron stars and black holes, most recently using NASA's *NICER* X-ray instrument on the International Space Station. Previously, I served as Head of our Department's Astrophysics Division for 10 years (2008–2019), as co-lead faculty of our Physics 8.01 freshman mechanics course for eight years (2011–2018), and as Associate Department Head for two years (2020–2022).

I am greatly aided in my new role by our (also new) Associate Department Head **Prof. Lindley Winslow**, and by the other members of Physics Council: **Profs. Ray Ashoori**, **Joe Formaggio**, **Anna Frebel**, **Mehran Kardar**, **Rob Simcoe**, **Tracy Slatyer**, **Iain Stewart**, **Vladan Vuletić**, and **Bolek Wyslouch**, as well as Director of Administration and Finance **Matt Cubstead**.

As usual, this issue of *physics@mit* details a number of important comings, goings and stayings in the Department. We have had a big transition in the Physics Academic Programs Office: our long-time Academic Administrator, **Cathy Modica**, retired this June after 13 years of service. She will be very much missed. We welcome her successor, **Shannon Larkin**, who brings extensive experience from other academic programs at MIT. We also welcome several new faculty members:

Profs. Anna-Christina Eilers, **Mikhail Ivanov**, and **Eluned Smith**. You can read more about them in *New Faculty*. This July, partially owing to a pandemic-related backlog, a record number (ten!) of our faculty received promotions, including awards of tenure to **Profs. Riccardo Comin**, **Netta Engelhardt**, and **Or Hen**. On a sad note, we mourn the passing of two distinguished emeritus faculty members, **Profs. George Clark** and **Roman Jackiw**.

This issue also features several exciting scientific developments within the Department. First, Francis L. Friedman Professor and MIT Kavli Institute Director **Rob Simcoe** describes early science results from NASA's *James Webb Space Telescope*, launched in December 2021, exploiting *JWST*'s revolutionary ability to probe the early Universe using deep infrared observations. Second, Biedenharn Career Development Associate Professor **Netta Engelhardt** describes her breakthrough efforts to resolve the black hole information paradox, a 50-year-old puzzle first identified by Stephen Hawking. Third, **Profs. Mike Williams and Jesse Thaler**, Deputy Director and Director, respectively, of the Institute for Artificial Intelligence and Fundamental Interactions (IAIFI), describe this new Institute, which is an MIT-led, NSF-funded multi-institutional collaboration that seeks to infuse artificial intelligence with "physics intelligence," simultaneously driving AI innovation and attacking challenging problems in fundamental physics with powerful new tools.

Speaking of artificial intelligence, the sudden and wide public availability of ChatGPT and other large language models has captured the world's attention. These tools are remarkably good at generating polished and plausible text (and computer code) in response to prompts, but the content is not reliably correct. Yet, used properly, these tools could be transformative in how we work and learn. In July, Pappalardo Fellow **Kevin Burdge**, MIT Kavli Institute postdoc **Josh Borrow** and Prof. **Mark Vogelsberger** organized an MIT workshop, *The Impact of ChatGPT and Other Large Language Models on Physics Research and Education*, where nearly 200 attendees discussed how these tools can be used (or abused). This fall, several of our faculty will experiment with ways to use these tools in their courses to help students learn.

Our success as a department is due to the people who work here. We are very lucky to be able to recruit, and retain, some of the best physicists in the world to be our students, postdocs and faculty. The tools that enable this—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 helpful. 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
Professor of Physics
Head, Department of Physics

New Faculty

January 2023

Eluned Smith

Assistant Professor of Physics, Laboratory for Nuclear Science

Research Interests

Professor Eluned Smith's research uses rare beauty decays, measured with the LHCb detector at CERN, to search for new fundamental particles at mass scales above the collision energy of the LHC.

The Standard Model (SM) of particle physics describes all known fundamental particles and their interactions. However, there are many aspects of our universe that the Standard Model fails to explain, pointing to the existence of physics Beyond the Standard Model (BSM).

Heavy BSM particles can mediate known Standard Model decays, altering their properties. Comparing the decay properties of these known particles to their predictions therefore provides sensitivity to BSM effects. This approach probes very heavy BSM energy scales, which would otherwise be inaccessible at the LHC.

Smith's research uses rare decays of particles containing beauty quarks (B hadrons). These decays are referred to as electroweak penguin decays, named after their dominant Feynman diagram.

Over the last decade, significant tensions with the SM have been seen in rare electroweak penguin decays, in a phenomenon referred to as the Flavour-Anomalies. However, these decays are also sensitive to poorly described QCD effects, which could mimic BSM signatures. Smith and her group specialize in using novel high-dimensional fits to data to both constrain the properties of the potential BSM signatures behind these anomalies and to isolate and constrain the magnitude of possible QCD contributions. In doing so, her work aims to resolve whether the Flavour Anomalies are misunderstood QCD or the first sign of BSM physics at the LHC.

Biographical Sketch

Eluned Smith completed her undergraduate degree and PhD (2017) at Imperial College London. She did her first postdoc at RWTH Aachen before winning an Ambizione Fellowship from the Swiss National Science Foundation at the University of Zürich. Since 2021 she has led the Rare Decays physics program within the LHCb experiment. Smith joined the faculty of the MIT Physics Department as an assistant professor in January 2023.

For a list of Prof. Smith's selected publications, please visit her faculty web page at *physics.mit.edu/faculty/eluned-smith/*.

July 2023

Anna-Christina Eilers

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

Research Interests

Professor Anna-Christina Eilers is an observational cosmologist leading the Cosmic Dawn Group (*mit.edu/~eilers/*) at the MIT Kavli Institute for Astrophysics and Space Research. Her research focuses on the formation of the first galaxies, quasars and supermassive black holes in the early universe, during an era known as the Cosmic Dawn. In particular, Eilers is interested in the growth of the first supermassive black holes which reside in the center of luminous, distant galaxies known as quasars, to understand how black holes evolve from small stellar remnants to billion solar mass black holes within very short amounts of cosmic time. The question of how black holes accrete sufficient matter from their surrounding accretion disk and grow very rapidly has been an open puzzle for decades and challenges the current understanding of supermassive black hole growth and accretion physics.

In her research, Eilers develops new methods to study the timescales of quasar activity and supermassive black hole growth phases. She aims to understand how galaxies and their central supermassive black holes evolve through cosmic time, how the accretion physics might change in the early universe, and what the nature of the seeds of these early black holes could be.

She uses a combination of multi-wavelength observations from telescopes around the world and in space; cosmological simulations; and new machine learning models. She is heavily involved in multiple programs using NASA's newly launched James Webb Space Telescope, which is piercing deeper than ever before into the distant past of our universe. Eilers is also passionate about making science more accessible through public outreach.

For a list of Prof. Eilers' selected publications, please visit her faculty web page at *physics.mit.edu/faculty/anna-christina-eilers/*.

Biographical Sketch

Anna-Christina Eilers is originally from San Francisco, CA, but grew up in Germany. She received a BS in Physics from the University of Goettingen with a focus on neuroscience. After an internship at the European Space Agency in The Netherlands she decided to study astrophysics at the University of Heidelberg, where she obtained her MS and completed her PhD at the Max Planck Institute for Astronomy. During her thesis Eilers worked with Profs. Joe Hennawi and Hans-Walter Rix on both high-redshift quasars and the early growth phases of supermassive black holes, as well as on data-driven models of stars within our own Galaxy, the Milky Way. In 2019 she was awarded a NASA Hubble Fellowship and the Pappalardo Fellowship to continue her research at MIT. In July 2023 she joined the MIT Department of Physics as an assistant professor.

Mikhail Ivanov

Assistant Professor of Physics, MIT Center for Theoretical Physics

Research Interests

Professor Mikhail Ivanov's research has developed at the interface of theoretical physics and data analysis, bridging state-of-the-art theoretical ideas with observational data. The overarching aim of his research is to use Effective Field Theory in combination with astrophysical data to resolve fundamental challenges of modern physics, such as the nature of dark matter, dark energy, inflation and gravity.

Ivanov has been creating first-principle theories and statistical techniques for cosmological analysis of data from large-scale structure surveys. He specializes in the extraction of information from correlation functions of the galaxy and matter distribution on cosmological scales. This information is then used to seek signals of new physics beyond the standard cosmological model, which may shed light on dark energy, dark matter and the early universe. This program has already produced many unique results, such as the first-ever measurements of the Hubble constant and other properties of the universe from the galaxy power spectrum shape. These results set the stage for analyzing new cosmological data from upcoming high-precision large-scale structure surveys. Ivanov's research in large-scale structure unites fundamental cosmology, formal field theory and galaxy formation physics.

Ivanov also works on aspects of black hole physics relevant for gravitational wave astronomy. In particular, he studies black hole perturbations, and specifically how their symmetries are connected to the mysterious behavior of their tidal deformations (Love numbers). In addition, Ivanov is broadly interested in using novel theoretical tools, such as gravitational effective field theories and scattering amplitudes, to interpret gravitational wave observations and to understand the origin of spacetime.

Biographical Sketch

Mikhail obtained his PhD from the École Polytechnique Fédérale de Lausanne (EPFL) under the supervision of Sergey Sibiryakov in 2019. During his PhD studies, he spent one year at the Institute for Advanced Study (IAS) at Princeton University as a Fellow of the Swiss National Science Foundation. Thereafter he was a postdoctoral associate at New York University before returning to the IAS as an NASA Einstein Fellow. In 2021 he was awarded the Second Buchalter Cosmology Prize. Ivanov joined the MIT Physics Department as an assistant professor in July 2023.

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

Faculty & Staff Notes

Honors + Awards

Edmund Bertschinger, Professor of Physics, received the 2023 MIT Physics Doc Brown Award and 2023 Buechner Special Prize Award.

Yi Chen, Postdoctoral Associate, Roland Group, received the 2022 Wu-Ki Tung Award for Early Career Research on QCD.

↓ **Soonwon Choi**, Assistant Professor of Physics, received a 2023 National Science Foundation CAREER Award.

Netta Engelhardt, Associate Professor of Physics, was awarded the 2023 Gribov Medal.


Soonwon Choi


Ronald Fernando Garcia Ruiz

↑ **Ronald Fernando Garcia Ruiz**, Assistant Professor of Physics, was awarded a 2023 Sloan Research Fellowship; received the American Physical Society's 2022 Stuart Jay Freedman Award; and was awarded the 2022 IUPAP Young Scientist Prize in Nuclear Physics.

Nuh Gedik, Professor of Physics, was named a Fellow of the American Physical Society (2022).

Or Hen, Associate Professor of Physics, was named a Fellow of the American Physical Society (2022).

Arthur Hennequin, Postdoctoral Associate, Williams Group, was awarded a 2023 CERN Fellowship.

Pablo Jarillo-Herrero, Cecil and Ida Green Professor of Physics, was named the APS Kavli Symposium Speaker (2023); named the 2022 Dresselhaus Lecturer (MIT); and named the 2022 Max Planck Lecturer, MPI for Solid State Physics (Germany).

↓ **Nicholas Kern**, 2020–2023 Pappalardo Fellow, was awarded a NASA Hubble Fellowship (2023).

Peter Kosec, Postdoctoral Associate, Kara Group, was awarded a NASA Hubble Fellowship (2023).

↓ **Marissa LaFleur**, IAIFI Project Manager, received a 2023 Infinite Mile Award, MIT School of Science.

↓ **Kiyoshi Masui**, Associate Professor of Physics, was awarded the 2023 Harvey B. Richer Gold Medal, Canadian Astronomical Society.


Nicholas Kern


Marissa LaFleur


Kiyoshi Masui


Lina Necib


Phiala Shanahan


Marin Soljačić

Debbie Meinbresse, Program Coordinator, MIT Kavli Institute for Astrophysics and Space Research, received a 2023 Infinite Mile Award, MIT School of Science.

↑ **Lina Necib** PhD '17, Assistant Professor of Physics, was awarded the American Physical Society's 2023 George E. Valley Prize.

Gunther Roland, Professor of Physics, was awarded the 2023 Heraeus Foundation Endowed Visiting Professorship at Goethe University, Germany.

↑ **Phiala Shanahan**, Class of 1957 Career Development Associate Professor of Physics, was awarded the 2022 Ruby Payne-Scott Medal, Australian Institute of Physics; received the 2022 University of Adelaide James McWha Distinguished Alumni Award; and named the 2023 South Australian Woman of the Year.

↑ **Marin Soljačić**, Professor of Physics, received Optica's 2023 Max Born Award; and was named a 2023 Highly-Cited Researcher, Web of Science.

Jesse Thaler, Professor of Physics and Director, NSF IAIFI, was named a Fellow of the American Physical Society (2022).

↓ **Senthil Todadri**, Professor of Physics, was named a 2022 Highly-Cited Researcher (Cross-Field Category), Web of Science; and elected to the American Academy of Arts and Sciences (2023).

Vladan Vuletić, Lester Wolfe Professor of Physics, was named a 2022 Highly-Cited Researcher, Web of Science; and received the 2023 Tesla Spirit Award, Tesla Science Foundation.

Shane Wilkins, Postdoctoral Associate, Garcia Ruiz Group, was awarded the 2023 Institute of Physics Early Career Prize on Nuclear Physics.

Dakota Wyne, Financial Coordinator, received a 2023 Infinite Mile Award, MIT School of Science.

↓ **Boleslaw Wyslouch**, Professor of Physics and Director, Laboratory for Nuclear Science, was elected to the American Academy of Arts and Sciences (2023).

Senthil Todadri

Boleslaw Wyslouch

Riccardo Comin

Netta Engelhardt

Or Hen

Promotions

↑ **Riccardo Comin** to Associate Professor of Physics with tenure.

William Detmold to Full Professor of Physics.

↑ **Netta Engelhardt** to Associate Professor of Physics with tenure.

Philip Harris to Associate Professor of Physics without tenure.

↑ **Or Hen** to Associate Professor of Physics with tenure.

Kiyoshi Masui to Associate Professor of Physics without tenure.

Maxim Metlitski to Associate Professor of Physics without tenure.

Tracy Slatyer to Full Professor of Physics.

Michael Williams to Full Professor of Physics.

Lindley Winslow to Full Professor of Physics.

News & Events in Physics

Pappalardo Distinguished Lecture

On October 6th, 2021, the Department held its annual Pappalardo Distinguished Lecture Series. The host for the evening, **Or Hen**, Class of 1956 Career Development Associate Professor of Physics, introduced the speaker, Dr. **Brian Nord** of Fermilab. Nord is a scientist in Fermilab's AI Project Office and Cosmic Physics Center. He is also a CASE Scientist in the Department of Astronomy and Astrophysics, The University of Chicago, and Senior Member of the Kavli Institute for Cosmological Physics (KICP). Nord spoke on "Imagining scientific advancement in the era of AI: implications for discovery and community." At the honorary dinner following the lecture, Physics Department Head Professor **Deepto Chakrabarty** '88 thanked **Neil and Jane Pappalardo** for supporting this lectureship. *(D. Forde)*

2023–2026 Pappalardo Fellowships in Physics Competition

The Department's flagship postdoctoral fellowship program, the Pappalardo Fellowships in Physics, completed its 24th annual competition in January 2023 with the appointment of two Fellows arriving in Fall 2023: astrophysicist **Juliana García-Mejía** and condensed matter experimentalist **Kevin Nuckolls**.

Juliana García-Mejía is bringing a Heising Simons Foundation 51 Peg Fellowship to MIT for a combined, five-year appointment with her Pappalardo Fellowship. She is broadly interested in developing novel astronomical instrumentation to enable the study of exoplanets, their atmospheres and their low mass stellar hosts.

García-Mejía is the principal investigator of The *Tierras* Observatory, a new 1.3-m ultra-precise fully-automated photometer located atop Mt. Hopkins, Arizona. Having spent her entire graduate career building *Tierras*, she is currently focused on using the facility to uncover temperate terrestrial planets, search for moons around exoplanets, and study their low mass stellar hosts.

She is also pursuing the design of a high throughput, extremely-high resolution pathfinder spectrograph to enable narrow-wavelength atmospheric structure and velocity dynamic studies of exoplanets, and to expand cosmochronological and magnetic field studies of stars of varied spectral types. In the future, this instrument could enable the detection of molecular oxygen in a terrestrial exoplanet atmosphere.

Kevin Nuckolls is an experimental condensed matter physicist interested in the electronic and magnetic properties of quantum materials. His research interests broadly center around two major themes of quantum materials research: electronic correlation effects and topologically protected properties.

Juliana García-Mejía

Kevin Nuckolls

Correlation effects result from interactions among an Avogadro number (~10^{23}) of electrons, which produce complex collective phases of matter. Topological properties are immutable qualities of materials that are derived from geometric qualities of their electronic energy bands. Nuckolls' research focuses on how these two effects can together give rise to new and unusual material properties, some of which may be useful for next-generation quantum technological applications.

For the first two years of his PhD, Nuckolls and his teammates designed and built a millikelvin-temperature scanning tunneling microscopy facility, capable of studying quantum materials with atomic-scale spatial resolution and unmatched energy resolution. He then used this facility to identify microscopic mechanisms for many exotic electronic phases in magic-angle twisted bilayer graphene (MATBG), a tunable correlated electronic material that hosts unusual insulating, magnetic, and superconducting states. Most recently, his work has established key signatures of unconventional superconductivity in MATBG that are irreconcilable with conventional theories.

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)*

21st Annual Pappalardo Fellowships in Physics Symposium

On March 16, 2023, the Physics Department's Pappalardo Fellowships program celebrated the return of its annual symposium to the traditional live, in-person format, after a four-year online hiatus.

The event's five featured presenters were Pappalardo Fellows **Christina Eilers**, **Benjamin Lehmann**, **Aviram Uri**, **Joshua Foster** and **Rohan Naidu**, with introductory remarks by experimental atomic physicist and MIT Physics faculty member **Richard Fletcher**, a 2016–2019 Pappalardo Fellow.

Leading the speaker roster, astrophysicist **Christina Eilers**, a 2022–2024 Pappalardo Fellow and 2019–2022 NASA Hubble Fellow, spoke on recent insights learned from "Peeking into the Distant Past of Our Universe with the JWST." Eilers will join the Department in Fall 2023 as an assistant professor, based in the MIT Kavli Institute for Astrophysics and Space Research. Next up was high energy and particle theorist **Benjamin Lehmann**, a 2022–2025 Fellow, with a lively discussion of his original and broad-ranging "New Tools for Dark Matter Physics." Following was 2021–2024 Fellow **Aviram Uri**, a condensed matter experimentalist, speaking on his recent, exciting discoveries related to "Superconductivity in an Engineered Moiré Quasiperiodic Crystal." Theoretical nuclear and particle physicist **Joshua Foster**, a 2021–2024 Fellow, then discussed his work within the realm of "Dark Matter at the Wave Frontier." Wrapping up the event was astrophysicist and 2022–2025 Hubble Fellow and 2025–2027 Pappalardo Fellow **Rohan Naidu**, sharing the most recent revelations on new classes of galaxies with "The First Glimpse of the First Galaxies with the JWST."

Neil Pappalardo (1964) and his 2022–2023 Pappalardo Fellows. Credit: C. Breen

Joining Physics Department Head Professor **Deepto Chakrabarty** '88 and members of the MIT Physics community in the audience were program founder and benefactor **Neil Pappalardo** and his wife **Jane**, son **Michael Pappalardo** and daughter-in-law **Didi O'Brien**, daughter **Sheila Lemke** and husband **Todd**, grandson **Declan Pappalardo**, and longstanding Department friend and supporter alumni **Curt Marble**. Videos of each talk are available on the Department's YouTube page at *youtube.com/playlist?list=PLKemzYMx2_OtoHxp4grN1mvdI6wPcJ3Qm*. *(C. Breen)*

California Trip

Physics Department Head **Deepto Chakrabarty** '88 traveled to Palo Alto, CA, in March 2023. Alumnus **Paul Swartz** introduced Professor Chakrabarty at a breakfast reception at the Sheraton Palo Alto Hotel. Fifty-two alumni and friends gathered to welcome him and to learn the most recent updates on the Physics Department. *(D. Forde)*

Physics Department Head Deepto Chakrabarty ’88 (VIII) with Curtis Marble ’63 (VI). Credit: Justin Knight Photography

(FROM LEFT) Physics Department Head Deepto Chakrabarty, Anita Busquets, Professor of Physics Emeritus Lee Grodzins, and Bill Ladd. Credit: Justin Knight Photography

Patrons of Physics Fellows

This year the Department celebrated its 18th annual Patrons of Physics Fellows event in person on April 7, 2023. Professor **Deepto Chakrabarty** ’88 welcomed everyone to his first Patrons Dinner as Department Head. The following students gave talks: **Gefen Baranes, Peskoff Fellow**; **Dasol Kim, Whiteman Fellow**; and **Wenjie Gong, Frank Fellow**. **Tom Frank** concluded the evening with remarks on the incredible work the students are doing and thanked the donors for their continued support of the Department. Also in attendance were **Alex Hastings**, **Neil Constable**, **Paul Swartz**, **Curt Marble**, **Theodore Sung**, **Bill Ladd** and **Anita Busquets**. Faculty in attendance included **Nikta Fakhri**, **Joseph Checkelsky**, **Long Ju**, **Soonwon Choi**, **Emeritus Lee Grodzins**, **Emeritus Hale Bradt**, **Marin Soljačić**, and **Krishna Rajagopal**. *(D. Forde)*

Academic Administrator Cathy Modica with her students at the Department's 2022–2023 Undergraduate Awards dinner. Credit: Justin Knight Photography

Physics Academic Administrator Cathy Modica retires after 24 years of service to the Institute

by Sandi Miller

Academic Administrator Catherine "Cathy" Modica joined the MIT Physics Department in Fall 2009, after ten years in Health Sciences and Technology as the Student Life and Admissions Coordinator. She has worked with three Physics department heads, four associate heads and several acting associate heads. She concluded her time with the Department, and MIT, in mid-June 2023.

Cathy graduated from Tufts University with an undergraduate degree in English and Theater, later useful when enhancing her writing and public speaking skills in Physics. She also received her EdM from Harvard University's Graduate School of Education.

Cathy's office in 4-315 is warm and inviting, filled with Tibetan prayer flags and photos of her grandchildren, and designed to be a calming space for the often highly-stressed students who have met with her over the years. Physics students are often deeply concerned about grades and getting into graduate school, but over the years Cathy also worked to help students who were hungry and impoverished, victims of assault and racial hatred, and struggling to work from home while isolated from their peers during the pandemic's extended lockdown.

Cathy channeled her feelings to become active in the Department and Institute community, including a key role developing the Physics Values Committee; helping launch and co-chairing Accessing Resources at MIT, a clearinghouse for information for low-income students; co-founder of "When Support Gets Personal," a training program for student-facing MIT administrators; co-chairing the Graduate Administrators Roundtable; search committee member for Student Support Services (S3) and the MIT Chaplain; and joining the Student Privacy Policy and MIT Memorial Planning committees. Her recognitions include the 2013 School of Science Infinite Mile Award, the 2003 Laya Weisner Community Award, and several School of Science "Spot Awards."

physics@mit: Over the years, you responded to changes in how universities were working with students and discovered new ways to meet the needs of Physics students, especially those in need of economic and emotional support. How did your role as academic administrator evolve to meet these shifts to help students?

Cathy Modica: Supporting the well-being of students was always one of my main goals, one that I felt I could make a real contribution to—unlike, say, teaching them quantum field theory, which is not in my skillset! Focusing on this took a variety of forms. From my first years at MIT, I made efforts to learn about all the many resources available when students are experiencing problems that are not just academic, and I developed a network of contacts around the Institute that I felt confident referring our students to. Within Physics, I was a founding member of the Physics Values Committee (PVC), the genesis of which was serious concerns about the climate in the Department for any kind of "untraditional" student. Over time, the PVC, and more importantly, the Physics Community Values statement, became embedded in the life of the Department.

In parallel to my work in the Department, I served as co-chair of the Accessing Resources at MIT Coalition (ARM) for several years. ARM aims to foster and promote the many types of financial and material support that are available to MIT's low-income students, on campus and in the Cambridge area. And, of course, I spent a lot of time just talking privately with students about whatever was on their minds. There's little that shocks me and almost nothing I haven't heard over time.

p@m: What will you miss most?

CM: Oh, the people in this wonderful community, of course! I've been privileged to work with some of the very best students in the world, to watch them grow as scientists, and to make a modest contribution to their growth as people. I keep in touch with many alums and have attended a number of weddings and baby showers! I already know how hard it is to miss seeing our students on a daily basis from our experience during the extended lockdown, and I expect missing the students will be the hardest thing about leaving.

Our Department staff is creative, hard-working and fully energetic in supporting our students. Staff seldom entirely get their due in universities, but I've been satisfied to see the kind of respect that our Department administration and our faculty have always shown towards the Academic Programs Office staff.

And I will miss the faculty! To get to see their important work close up, and simultaneously to have them as my partners in caring for our students, has been nothing short of amazing. I feel so lucky in our faculty; they are student-centered, education-driven, and endlessly kind-hearted—in addition to being world-class scientists—and many of them have become my close friends. A particularly happy memory was the day the LIGO breakthrough was announced. To be able to see my faculty colleagues with tears in their eyes at the excitement of this event was incredibly moving, something I'll always remember.

p@m: What are your post-retirement plans?

CM: At first I'm just going to chill out at home, tend my garden, do a lot of reading, catch up on sleep, and play with my granddaughters. My one goal for this summer is to wake up one morning and not be already thinking about work when I open my eyes! Later, when being a person of leisure feels a bit more normal, I expect to do some traveling, take classes (one goal is to relearn the French I used to be almost fluent in, a million years ago) and do volunteer work. I think learning anything new is about the most fun there is, so I'm looking forward to seeing where my interests take me.

"Cathy is the person to talk to about a problem when you don't know who to talk to about a problem."

Joseph Smolsky
PhD Candidate

"Cathy was a wonderful person to work with over the past year. She always advocated for others and was a great person to admire."

Paige DiMatteo
Student Payroll Coordinator

"Cathy is always ready with a listening ear and an open heart. Whether you came in tears or in triumph, she would always be there for you. I can't imagine my own journey without her support, and it is hard to imagine MIT Physics without her."

Makinde Ogunnaike
PhD Candidate

"Cathy Modica is truly a one-of-a-kind person. She has brought a unique guidance, warmth and kindness to the community that will be greatly missed. It's people like Cathy that really make the world a better place."

Caolan John
PhD Candidate

"Cathy is one of the most thoughtful and considerate people I know. Her personal note at the beginning of each week's student newsletter was always full of, and inspiring more, reflection on what it is that we strive to achieve here. Her dedication to the Physics Department is a major part of what keeps this place running."

Simon Grosse-Holz, PhD '23

"Cathy helped in so many ways through these hectic four years, and always went far and beyond to help, with empathy and determination unmatched. I hope she has a fantastic next phase of her life, and makes sure to visit us."

Orisvaldo Salviano Neto, SB '23

"For fourteen years, Cathy has been at the heart of our department. Thousands of students, more than a hundred faculty, and all of her team, have been warmed by her empathy, have learned from her wisdom, and have benefitted from her judgment. It's hard to see how we could have navigated the past few years without all three."

Krishna Rajagopal
William A. M. Burden Professor of Physics

"I've sat down and tried to write something three times now over the past few weeks and nothing comes out. No words I can come up with properly capture Cathy's presence in our community. I suppose that's grief. So all I can manage to say is, 'Much thanks, Cathy, job well done, and best wishes for the future.'"

Sean Robinson, SB '99, PhD '05
Lecturer and Associate Director, Junior Lab

"Cathy has provided a nurturing environment for our students and a collegial atmosphere for the APO staff. I wish her all the best for her retirement."

Sydney Miller
Graduate Academic Program Coordinator

"Cathy believes in the good in every person that she encounters, and is one of the kindest people I know."

Michal Holland
Undergraduate Program Coordinator

"Cathy has made Physics a place where all of our undergraduate and graduate students feel supported, seen, heard and respected. She has accomplished this from policy implementation, but primarily from her actions. Our students trust her and see her as a source of information and support. She will be missed!"

Matt Cubstead
Administrative Officer

"Cathy Modica was a constant source of inspiration and comfort for our Department. She always had time for the important conversations and, I am sure, many, many of our students and faculty owe their teaching success to Cathy's support."

Peter Fisher
Thomas A. Frank (1977) Professor of Physics;
Director, MIT Office of Research Computing and Data

"Cathy always went above and beyond to provide support and encouragement to those of us in the APO, whether offering a listening ear during a difficult project or providing encouragement during a challenging time—her office door was always open. She will be sorely missed."

Kim Heatley
Web/Database/Course Administrator

"My wife Jaymi and I frequently attend the annual Physics Fall Reception, and although she doesn't know many people there, Jaymi looks forward to the event mainly because of one person, Cathy. Cathy is able to connect with people at such a deep level that they instantly feel welcome. Along with doing an exemplary job in the APO, Cathy brings beauty, grace and poetry to the everyday."

Joseph Formaggio
Professor of Physics; Division Head, Experimental Nuclear and Particle Physics

"Cathy has been at the center of so much in our department's education program that I can't really express what she has meant: she has been the chief supporter, advocate and listener-in-chief to generations of undergraduate and graduate students, and to a pretty substantial fraction of MIT physics faculty as well."

Scott Hughes
Professor of Physics

"Gosh, so many MIT graduate students have relied on Cathy. How many students showed up in her office with problems they did not know how to solve? I was one of them, and for me, as for so many, Cathy's sage advice showed there was a way forward. MIT Physics will miss her greatly."

Michael Austin DeMarco, PhD '22

"Cathy Modica has been a phenomenal supporter, resource and friend to the members of our community. She has uplifted student group efforts to build a more inclusive department and has worked tirelessly to create support structures for our students through periods of turbulence. I feel lucky to have lived through a version of MIT Physics with Cathy at the helm!"

Pamela Stark, SB '23

"The best advice I've found to give to new faculty colleagues is to get to know Cathy Modica, because she knows everything about how the department works, and she's incredibly generous with her time and advice. She will be very much missed!"

Tracy Slatyer
Professor of Physics

"Over the past four years, it's been an incredible experience working with Cathy in my various student leadership roles. She has always been kind, helpful and receptive to student needs—and willing to hear us out when we think things aren't going well. She'll be sorely missed, but I'm certain that she'll continue to do great things after her time here at MIT."

Rahul Jayaraman
PhD Candidate

"Cathy was there during each step of my academic path at MIT. But what means the most to me is Cathy's support when the war in Ukraine started. Cathy attended numerous events, spoke often with students and gave endless sympathy and help. She created warm and beautiful memories through the darkest of times."

Margarita Davydova
PhD Candidate

"Cathy has been a pillar of the Physics Department and it will be impossible to imagine it without her. She supported me as a student, and now as junior faculty, with kindness, efficiency and expertise that we cannot find anywhere else. Personally, I will struggle not having her around next year."

Lina Necib, PhD '17
Assistant Professor of Physics

"From research challenges to personal upheavals to a global pandemic, Cathy's warm smile and kind words have never failed to comfort me. I'll miss her dearly, and am so grateful for the masses of often invisible work that she and other departmental administrators do to keep the Physics Department running."

Adam Trebach, PhD '23

"When you walk into Cathy's office, you aren't just a physicist, but a whole human being. Whether you are a stressed-out student or a frazzled faculty member, Cathy is there with sage advice and an open heart."

Jesse Thaler
Professor of Physics; Director, NSF AI Institute for Artificial Intelligence and Fundamental Interactions

"Cathy has been our North star, guiding us calmly and consistently in the right direction."

Anna Frebel
Professor of Physics; Division Head, Astrophysics

Student Honors & Awards: Undergraduate

2023 Alan H. Barrett Prize winner Hillary Diane Andales.
Credit: Justin Knight Photography

2023 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.

Hillary Diane Andales SB '23

Academic Advisor: Erin Kara
Research Supervisor: Anna Frebel

2023 Malcolm Cotton Brown Award

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

Aidan Chambers SB '23

Academic Advisor: Jeff Gore
Research Supervisor: Philip Harris

2023 Malcolm Cotton Brown Award winner Aidan Chambers.
Credit: Justin Knight Photography

2022 & 2023 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.

Antti Eero Asikainen SB '25
Kylee Carden SB '22
Keaten Ciarno SB '22
Iana Ferguson SB '24
Tenzin Jampa SB '23
Catherine Ji SB '22
Benjamin Lou SB '25
Joy Ma SB '24
Ananda Santos Figueiredo SB '25
Felicia Xiao SB '25
Clara Xu SB '23

The 2023 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.

Sanjay Raman SB '23

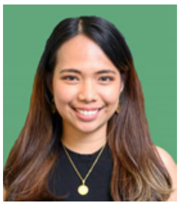
Academic Advisor: Washington Taylor
Research Supervisor: Iain Stewart

The 2023 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 winners in three categories.

SERVICE

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



Hillary Diane Andales SB '23

Academic Advisor: Erin Kara

Pamela Stark SB '23

Academic Advisor: Jacqueline Hewitt

TOP/BOTTOM: 2023 Joel Matthew Orloff Award for Service winners (*from top*) Hillary Diane Andales, Pamela Stark. Credit: Justin Knight Photography

SCHOLARSHIP

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

Xiangkai Sun SB '23

Academic Advisor: Jeff Gore
Research Supervisors:
Soonwon Choi, Martin Zwierlein

RIGHT: 2023 Joel Matthew Orloff Award for Scholarship winner Xiangkai Sun. Credit: Justin Knight Photography

RESEARCH

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

Luis Bariuan SB '23

Academic Advisor:
Netta Engelhardt
Research Supervisor:
Tracy Slatyer

RIGHT: 2023 Joel Matthew Orloff Award for Research winner Luis Bariuan. Credit: Justin Knight Photography

2023 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 24 new members.

Faisal Alsallom
Hillary Diane Andales
Derek Baldwin
Thomas Bergamaschi
Kylee Carden
Yu-Che Chien
Laura Cui
David Fang
Jiahai Feng
Dhyey Gandhi
Catherine Ji
Lauren Li
Richard Luhtaru
Ilan Mitnikov
Sahil Pontula
Sanjay Raman
Aden Rothmeyer
Jonathan Shoemaker
Richard Sollee
Xiangkai Sun
Archer Wang
Charlotte Wickert
Brian Xiao
David Xiong

2023 Sigma Pi Sigma Inductees. Credit: Justin Knight Photography

The 2023 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.

Hillary Diane Andales SB '23

Academic Advisor: Erin Kara

2023 Order of the Lepton Award winner Hillary Diane Andales.
Credit: Justin Knight Photography

2023 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 101 members of the Class of 2023, 13 of whom are physics majors, to membership in the Society.

Hillary Diane Andales
Vincent Bian
Kylee Carden
David Fang
Jiahai Feng
Catherine Ji
Sanjay Raman
Aden Rothmeyer
Bryan Sperry
Archer Wang
Wei-En Wang
Brian Xiao
Daniel Zhou

2022–2023 Buechner Undergraduate Advising Award

Krishna Rajagopal
William A. M. Burden Professor of Physics

Professor Krishna Rajagopal. Credit: Justin Knight Photography

Phi Beta Kappa Inductees. Credit: Justin Knight Photography

Other Undergraduate Awards & Honors

April Cheng (SB '25) was named a 2023 Astronaut Scholar by the Astronaut Scholarship Foundation.

Sahil Pontula (SB '23. Academic advisor: Marin Soljačić) was awarded a 2023 Hertz Foundation Fellowship and a 2023 NSF Graduate Research Fellowship.

Abigail Shull (SB '23. Academic advisor: Nuh Gedik) received the 2023 National Defense Science and Engineering Graduate Fellowship in recognition of an exceptional research proposal in nanophotonics with ultracold atoms, and foreseen success in a doctoral program. She begins graduate studies in Fall 2023 at the University of California, Santa Barbara.

Pamela Stark (SB '23. Academic advisor: Jacqueline Hewitt) received the Laya W. Wiesner Award in recognition of her contributions to enhancing MIT community life; received the Mens et Manus award for her passion and affinity for diversity and inclusion work at MIT; and was named a 2023-2026 Knight-Hennessy Scholar to support her graduate studies at Stanford University.

Clara Xu (SB '24. Academic advisor: Anna Frebel) won the 2023 MIT Symphony Orchestra Concerto Competition.

Student Honors & Awards: Graduate

The Department's graduate awards winners for the 2022-2023 academic year will be publicly announced at an on-campus event in September 2023. Thus, a listing of all prizes and winners for 2022-2023 will appear in the Fall 2024 issue of *physics@mit*.

Other Graduate Honors & Awards

Andrea Sylvia Biscoveanu (Astrophysics. Thesis supervisor: Salvatore Vitale) received a PEO Scholar Award in recognition of her academic achievement as a woman in a doctoral-level program; awarded an NSF Astronomy and Astrophysics Postdoctoral Fellowship and a NASA Einstein Fellowship. She will continue her research at Northwestern University.

Kaley Brauer (Astrophysics. Thesis supervisor: Anna Frebel) was awarded a 2023 NSF Astronomy and Astrophysics Prize Fellowship.

David DePalma (Astrophysics. Thesis supervisor: Robert Simcoe) received the MIT Office of Graduate Education's John A. Lyons Fellowship in 2022-2023 for outstanding academics, research and community involvement.

Calvin Leung (Astrophysics. Thesis supervisor: Kiyoshi Masui) received a 2023 Miller Fellowship at the University of California, Berkeley; and was awarded a NHFP Einstein Fellowship to continue his research in localizing fast radio bursts and using them as cosmological probes.

Scott Moroch (Experimental Nuclear and Particle Physics. Thesis supervisor: Ronald Garcia Ruiz) received a Hertz Fellowship Award.

Nicolas Romeo (Biophysics. Thesis supervisors: Jörn Dunkel, Mehran Kardar) received the 2023-2026 Biological Physics Fellowship from the University of Chicago.

Graduate Degree Recipients 2022–23

September 2022

Sameer Abraham, PhD
Valentin Didier Crepel, PhD
Zhenghao Fu, PhD
Anthony Grebe, PhD
Minyong Han, PhD
Thomas Hartke, PhD
Miao Hu, PhD
Sangbaek Lee, PhD
Junang Li, PhD
Jinghui Liu, PhD
Peter Lu, PhD
Kwan Yeung Ng, PhD
Gregory Ridgway, PhD
Chiara Salemi, PhD
Efrain Segarra, PhD

February 2023

Michael Cantara, PhD
Alejandro Diaz, PhD
Woonghee Han, PhD
Yiwen Huang, PhD
Choongman Lee, PhD
Hyunseok Lee, PhD
Juliana Park, PhD
Aaron Rosenthal, PhD
Graeme Sutcliffe, PhD
Loyd Waites, PhD
Cedric Wilson, PhD
Jinxiang Zhu, PhD

May/June 2023

Eric Anschuetz, PhD
Pierre Barral, PhD
David Berardo, PhD
Andrea Sylvia Biscoveanu, PhD
Kaley Brauer, PhD
Leon Ding, PhD
Zhiyu Dong, PhD
John Frank, PhD
Simon Grosse-Holz, PhD
Nicholas Kamp, PhD
Ethan Lake, PhD
Calvin Leung, PhD
Abraham Levitan, PhD
Zeyang Li, PhD
Nicholas Mehrle, PhD
Enrique Mendez, PhD
Yiqi Ni, PhD
Brandon Roach, PhD
Alyssa Rudelis, PhD
Airlia Shaffer, PhD
Christopher Whittle, PhD
Cagin Yunus, PhD
Cristian Zanoci, PhD
Weishun Zhong, PhD
Junbo Zhu, PhD

Student Profile: Kaley Brauer PhD ’23

by Sandi Miller

PhD ’23 Computational Astrophysics (Frebel Group)

Kaley Brauer is using high-performance computing simulations and theoretical models to uncover new details about how galaxies form (including the origin of the Milky Way), as well as the astrophysical origins of heavy elements—with a focus on the smallest, earliest galaxies that merged into the Milky Way throughout cosmic time.

Kaley originally wanted to be a scientific illustrator, until she took a cosmology class at Brown University. As a graduate student at MIT, she was a Whiteman Fellow in her first year and a US Department of Energy Computational Graduate Fellow for the next four. Kaley recently completed her PhD under advisor Professor Anna Frebel at the MIT Kavli Institute for Astrophysics and Space Research, and will combine her interests in design and cosmology with an NSF Graduate Fellowship to carry out a program of research and education at the Harvard-Smithsonian Center for Astrophysics. Her research focus will be on how stars formed in the earliest galaxies by producing cosmological simulations of dwarf galaxies with individual stars, detailed chemical yields, and highly resolved metal mixing. For her outreach efforts, Kaley will be writing and illustrating a series of astronomy books to be distributed to Boston-area elementary schools and organizing a weekend space summer camp for middle school girls.

Kaley, how were you able to combine your two loves, art and physics, at MIT?

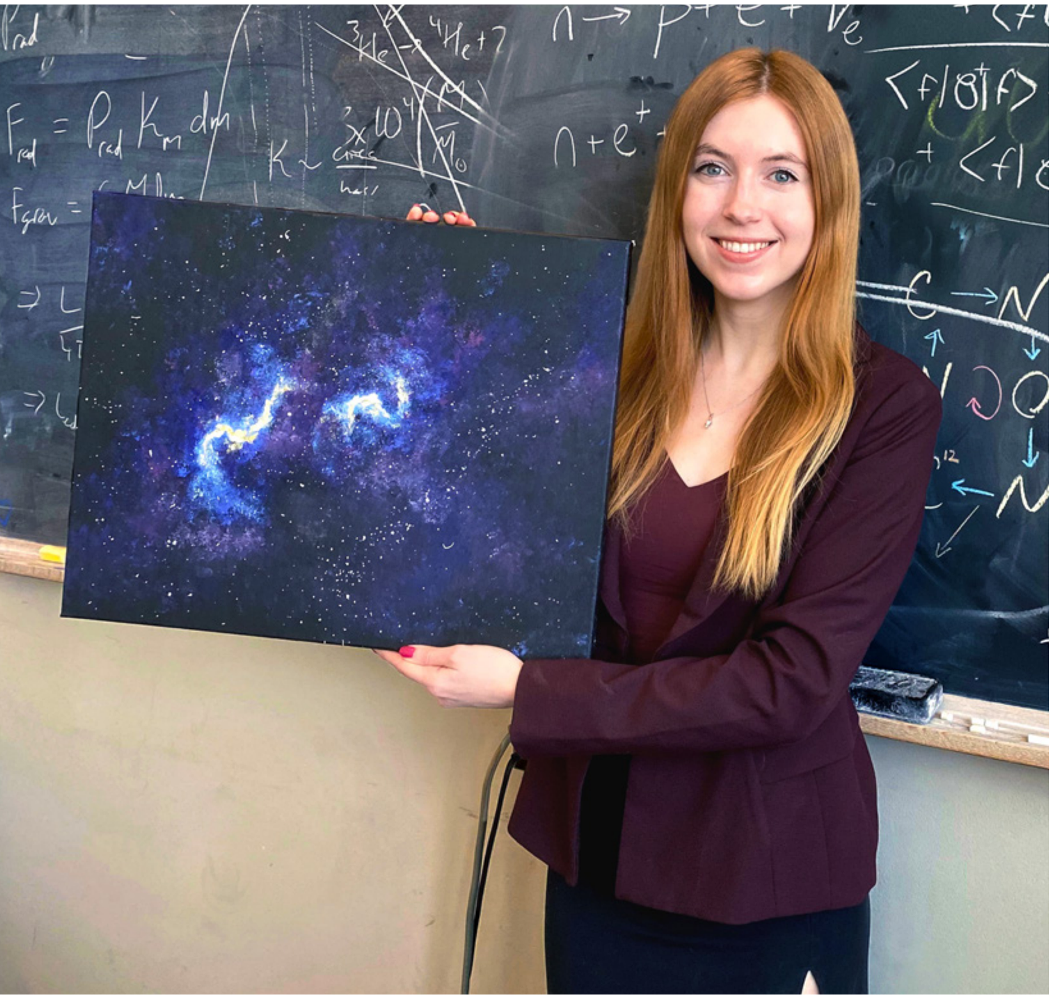
Art is a vital way to both communicate information and engage audiences, two things that are incredibly important in science. This is especially important for concepts in physics and astronomy where we lack natural intuition. Mathematical equations are necessary to create physics models, but nothing makes the average person’s brain turn off faster than a page of math. If you show someone a beautiful visualization, though, you can communicate the same information much more effectively.

Scientists benefit from artistically visualizing models, as well. Years ago, I studied effective ways to visualize complicated atomic and molecular systems. These visualizations were for scientists. As humans, we all enjoy beautiful visualizations and often learn more quickly from viewing pictures and videos than from reading equations. Now, as an astrophysicist, art is an important way for me to understand and communicate my results.

In my office, I hang my paintings inspired by my research. The painting I’ve shown here depicts two galaxies merging: you can see tidal tails of gas and stars caused by the interactions between the two galaxies. Mergers like this take hundreds of millions of years before the galaxies ultimately coalesce into one larger galaxy. This is the primary way galaxies, including the Milky Way, grow. These paintings have repeatedly sparked conversations throughout the years and helped me communicate my work to anyone who passes by.

How does your research benefit from art?

I am lucky that my current astrophysics research lends itself to beautiful visualizations and artistic interpretations. In my research, I produce cutting-edge simulations of early galaxy formation. The most effective



Kaley Brauer PhD '23 with her painting depicting two galaxies merging. "You can see tidal tails of gas and stars caused by the interactions between the two galaxies," she says. Paintings such as this "have repeatedly sparked conversations throughout the years and helped me communicate my work to anyone who passes by."

way to interpret the simulations is to create videos of the stars forming and galaxies merging over time. Without carefully produced visualizations, it would be extremely difficult to understand the implications of our models. For example, by creating visualizations of gas composition and star particles, we can intuitively learn where and how stars are forming. The colors, angles and layout of the visualizations are all important artistic aspects that affect how efficiently we can analyze and understand our results.

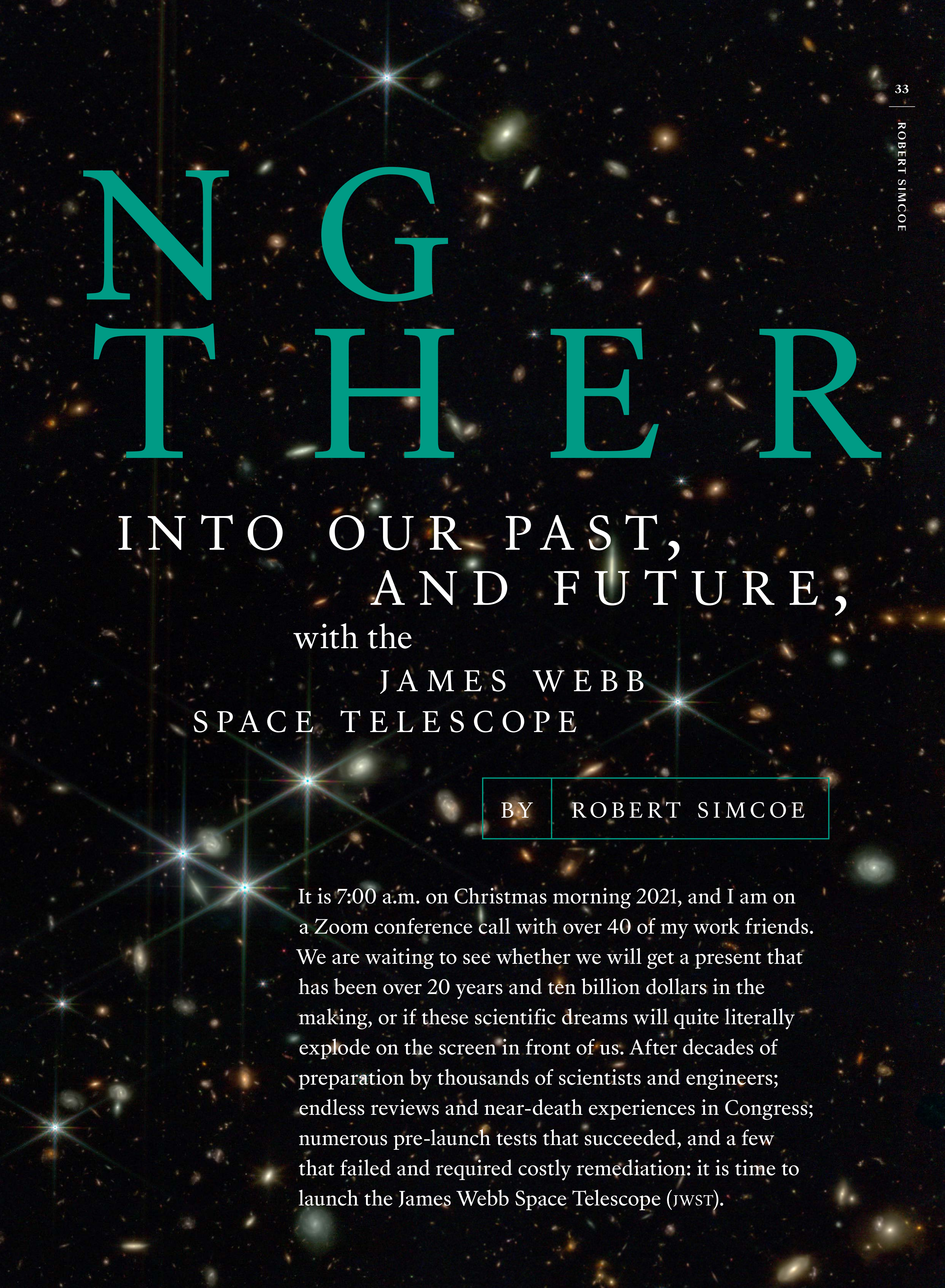
Galaxies are beautiful. The beauty of astronomy is part of what drew me to it. I enjoy using its beauty to draw others to astronomy as well. At scientific conferences, beautiful images and videos help keep the interest of the other scientists who have already watched 15 talks that day. At outreach events with the general public, the visualizations and art help show non-astronomers the beauty of astronomy and inspire them to learn more.

Why write and illustrate an astronomy children's book?

Children are the future of science. Throughout my time at MIT, I deeply enjoyed volunteering time to teach elementary and middle school students through organizations like MIT Spark, Citizen Schools, Adopt-a-Physicist, and others. Compared to the grind of debugging research, teaching children about astronomy is incredibly fulfilling. Kids love space, and I love talking to kids about space.

In high school, I wanted to become an illustrator, and wrote and illustrated children's books for competitions. Art has not been my focus ever since I began studying physics, but I still love it and frequently paint and draw in my free time. Creating an astronomy children's book is a dream of mine, and I am so excited that my NSF Graduate Fellowship is supporting this project. The plan is to write the first book and freely distribute it to Boston-area elementary schools through a series of outreach events. After this book is complete, there are plans for additional books, perhaps with my PhD advisor Professor Anna Frebel.

S E E I
F U R



NG THER

INTO OUR PAST, AND FUTURE, with the JAMES WEBB SPACE TELESCOPE

BY ROBERT SIMCOE

It is 7:00 a.m. on Christmas morning 2021, and I am on a Zoom conference call with over 40 of my work friends. We are waiting to see whether we will get a present that has been over 20 years and ten billion dollars in the making, or if these scientific dreams will quite literally explode on the screen in front of us. After decades of preparation by thousands of scientists and engineers; endless reviews and near-death experiences in Congress; numerous pre-launch tests that succeeded, and a few that failed and required costly remediation: it is time to launch the James Webb Space Telescope (JWST).

My group at MIT has been eagerly preparing for this moment since 2016. Six years before launch, we assembled a small international team that would eventually grow to nine investigators who have planned and executed some of JWST's very first science observations. Our objective is to elucidate details about the internal physics of the first galaxies that emerged after the Big Bang, the growth of their central supermassive black holes, and how primordial stellar nurseries drew in matter from the surrounding reservoir of diffuse gas and converted it into stars.

It is now well-documented that JWST's launch, unfolding, and commissioning were a technological triumph, delivering instrument performance that exceeds nearly every pre-launch projection. The observatory's insertion into a solar parking orbit—at a saddle point in the Earth-Sun equipotential surface, about four times more distant than the Moon—was so accurate that almost no extra fuel burns were needed, doubling the Observatory's expected lifetime. Our team's early science data are consistent with all of these superlatives, delivering all that we had hoped for and more.

As we approach the one-year mark of JWST's science operations, this article offers an opportunity to explain how MIT scientists came to have coveted early access to JWST, and to report on what our group has learned already about early galaxies and intergalactic matter. It is also an occasion to reflect on important problems that JWST will not be able to solve, and opportunities on the horizon to address them in the coming decades.

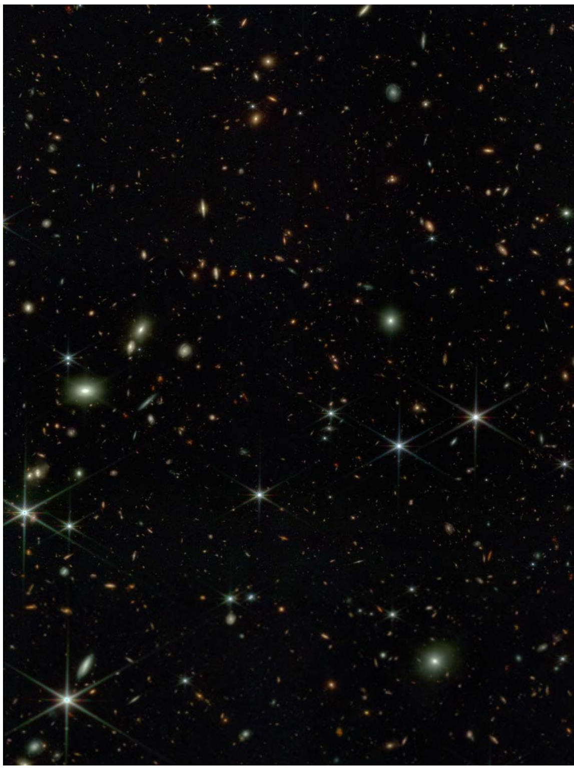
HOW MIT OBTAINED GUARANTEED TIME OBSERVATIONS IN JWST'S FIRST OBSERVING CYCLE

As with any transformational experiment, the demand for open JWST observing time greatly exceeds available supply; for the most recent proposal the success rate was 13%. The review process resembles allocation of other oversubscribed resources such as college admissions—proposal merit is the primary determining factor, but this is mixed with a significant random component that is difficult to eliminate. How did our collaboration earn the privilege of executing 120 hours of guaranteed observations within weeks of JWST's first science operations?

The story at MIT has roots dating back almost 20 years, to when I first arrived as a Pappalardo Postdoctoral Fellow in Physics. I was lured by MIT's recent investment as an institutional partner in the new Magellan Observatory—a pair of 6.5-meter diameter ground-based telescopes located under the dark skies of the Chilean Andes. I had trained during my PhD as an optical spectroscopist, but I was beginning to contemplate shifting my focus towards longer infrared wavelengths, motivated by three convergent coincidences.

First, a new generation of digital sky surveys in the early 2000s had just begun to uncover ultra-distant and ultra-bright quasars whose light was emitted less than one billion years after the Big Bang (the current age of the universe is 13.7 billion years). The redshift effect from cosmological expansion causes ultraviolet and optical light emitted by these quasars to stretch into infrared wavelengths along their journey to Earth. Second, NASA's approval of JWST in 1999 led to massive investment and a concomitant performance revolution in infrared (IR) sensors. These new detectors occupy nearly every instrument port on JWST and were also available for ground-based experimentation. Third, the Pappalardo Fellowship allowed me freedom to explore this new interest, and at MIT we were encouraged not only to observe with our new Magellan Telescopes, but also to improve them by building new and innovative instrumentation.

These factors led me to build an infrared spectrometer for Magellan named FIRE, that formed the main focus of my



pre-tenure research over a decade ago. FIRE's operational lifetime has coincided with a rapid period of discovery for new quasars in the early universe. Thanks to this instrument, my group was able to play a role in uncovering ever rarer and more distant quasars in new sky surveys. We used their spectra to probe the physics of early black hole growth, and the pollution of intergalactic gas with heavy elements fused in stars.

Access to Magellan and FIRE helped to attract prize postdoctoral fellows to MIT, and it was through these connections that our JWST program was conceived. In 2016, Rongmon Bordoloi brought a prestigious NASA Hubble Fellowship to the MIT Kavli Institute. Bordoloi is an expert in using quasars to study intervening gas, and was a student of one of JWST's "builders," who are entitled to guaranteed observing time. Their team was planning to conduct a galaxy survey in blank portions of the sky, but Bordoloi argued that the same survey would be much more valuable if it were undertaken in special fields containing bright quasars that already had exquisite FIRE observations.

The resulting survey, now named "EIGER" (Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization) after the Swiss mountain, has grown to a collaboration across four countries on three continents. Bordoloi has since moved to a faculty position at North Carolina State University, but Pappalardo Fellows Anna-Christina Eilers (now on the MIT Physics faculty) and Rohan Naidu have since joined the MIT team. In this way, MIT's Magellan investment and postdoctoral fellowship programs have both facilitated early access to JWST, and also helped nurture talented young scientists.

FIRST LIGHT, AND WHAT WE ACTUALLY MEASURE

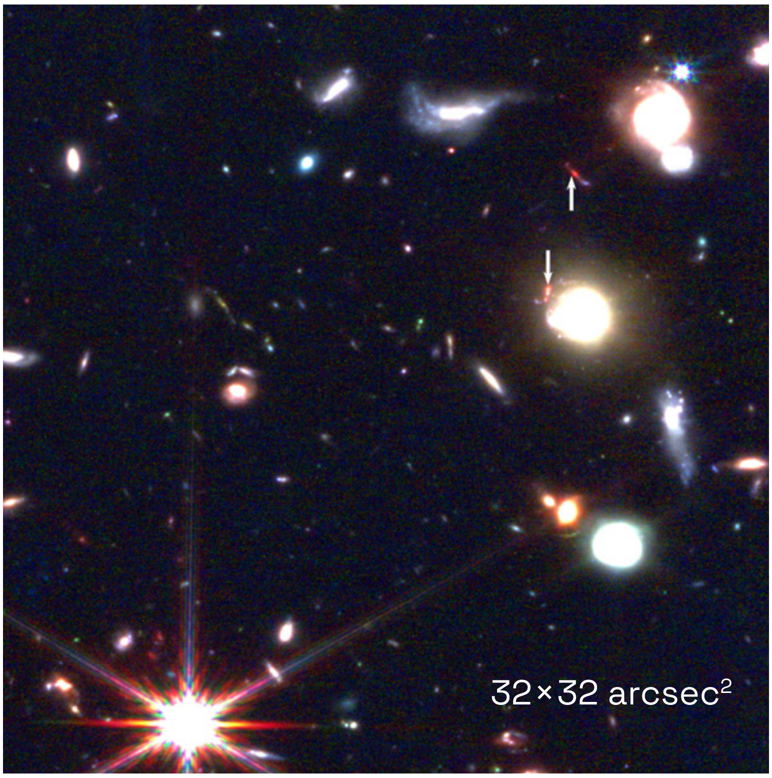
—

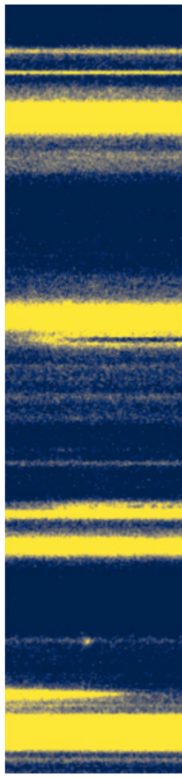
Our first tranche of EIGER data arrived in late August 2022, and comprised 20 hours of imaging and spectroscopic frames on our highest priority field. Our instructions on where to point the telescope and how to configure the instruments had been submitted over five years earlier, and the observations were at long last executed, automatically, by Mission Operations when they reached our slot in the queue. We got the news via Slack, from team members who were obsessively refreshing the webpage with JWST's real-time schedule.

The resultant image from this first visit is shown in Figure 1. It is a color composite of three monochromatic filtered images centered at wavelengths of 1.15 microns, 2.00 microns, and 3.56 microns. These wavelengths are a factor of 2–5× longer than our

FIGURE 1:
Color composite image of the first EIGER field, made from three images taken by JWST's infrared camera at wavelengths of 1.15, 2.00 and 3.56 microns. The prominent red object at the very center of the field looks like a star in this image, but spectra reveal that it is a distant quasar, whose radiation is powered by matter falling into a black hole of more than ten billion solar masses. It is located behind nearly all of the other galaxies and stars in this image, and appears red because it is rapidly receding due to cosmic expansion. This particular object is the brightest object yet discovered in the first billion years after the Big Bang, and was observed by Magellan and FIRE several years before JWST's launch. Credit: EIGER team / Ruari Mackenzie

eyes can see, as JWST is exclusively an infrared telescope and blind at optical wavelengths. Deep IR images are essential for studying the early universe, because cosmological redshifting causes optical light from these primordial objects to arrive at Earth in the infrared band. As soon as our team saw the sharp focus and depth of these images, we knew that the performance of JWST was extraordinary; indeed, we all spent many unplanned hours scanning around the images and taking in their rich detail like a child unboxing a new toy.





Even so, our official objective was to find and study objects from the early universe, and the vast majority of sources in these images are brighter foreground galaxies at lower redshift rather than the most distant objects of interest. We required additional information to screen out these interlopers, and JWST provides this in the form of infrared spectra.

You will almost never see a spectrum in a NASA press release about new discoveries, yet this is where JWST's truly transformative new powers reside. The instrument used by EIGER generates a spectrum for every object in the image shown in Figure 1 by inserting a "grism" (a diffraction grating etched onto one face of a crystalline silicon prism) into the telescope's optical path. The grism splays out each galaxy image into a linear trace on the detectors, encoding the intensity of light as a function of wavelength like a miniature rainbow. A large part of the EIGER team's effort over the past year was spent developing customized Python software to extract these spectral traces from the raw images, solve the mapping between detector pixels and position/wavelength, and calibrate the color-dependent efficiency of JWST's optics to determine fluxes of each astronomical object in physical units.

These spectra are immensely valuable because while stars emit light over a broad range of wavelengths, the emission from gaseous nebulae is driven by electron energy level transitions in atomic spectra, and is therefore discretized around specific wavelengths determined by quantum physics. These nebulae manifest as sharp spikes in a spectrum. The laboratory wavelengths of these transitions have been measured on Earth, so the spikes allow redshift measurements with 0.1% accuracy.

Redshifts are a cosmologists' Rosetta Stone, because they encode the distance to each object, historically the most difficult measurement in astronomy. Knowing the distance lets us convert photon counts per second at the Earth into a galaxy's physical energy output using the inverse square law. The total energy output is in turn proportional to the number of stars in the galaxy—its stellar mass. Likewise, we convert quantitative measurements of nebular emission line flux and image colors into estimates of each galaxy's star formation rate, because nebulae tend to be located in regions of intense star formation featuring blue-hot stars. Taken together, JWST's images and spectra can therefore help us measure physical sizes and shapes of early galaxies, the number of stars they contain, and the rate at which they are forming new stars.

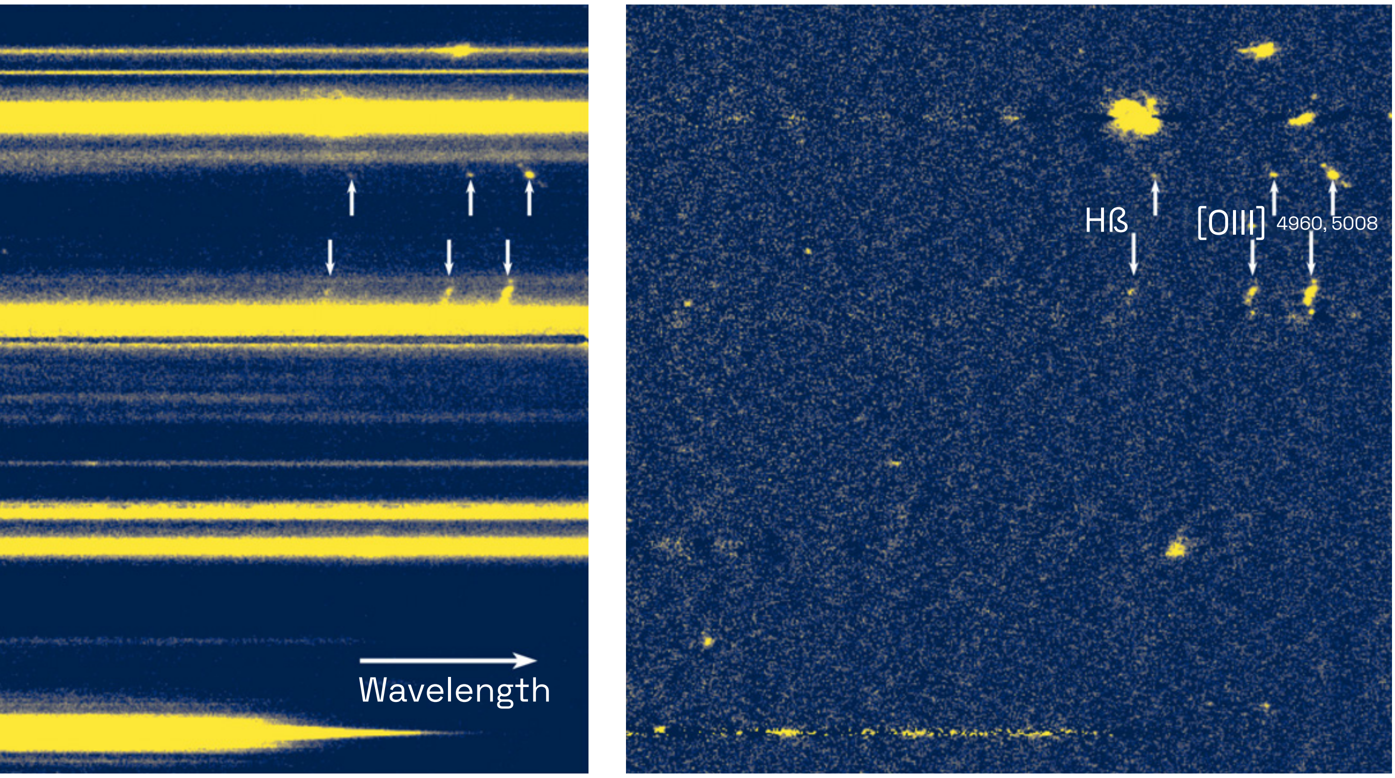


FIGURE 2:
Demonstration of grism spectroscopy with JWST. **LEFT PANEL** shows a sub-region of the image from *Figure 1*, with two galaxies in the distant universe identified with arrows (note their red colors due to redshift). All other galaxies in the cutout are in the foreground, except the quasar, which appears as a bright "star" at lower left in the image. **CENTER PANEL** shows this region of the image after insertion of the grism, which spreads the light from each object into a horizontal spectral trace where bluer light from the object is toward the left, and redder light is toward the right. Individual objects' spectra can be identified by matching their vertical position in the center and left panels. The **RIGHT PANEL** shows the same spectral data after applying a filter to the central panel that highlights sharp spikes in the wavelength direction. Arrows indicate the locations of triplet emission lines associated with the highlighted galaxies in the left panel. These represent atomic emission from nebulae in the host galaxies, in this case from oxygen and hydrogen. The galaxy at the upper right of the image has redshift z=6.764, at which point the universe was 800 million years old. The galaxy itself is 258 million years old; it has roughly 10 billion stars, and is forming over 20 stars per year. Credit: EIGER team / Jorryt Matthee

WHAT JWST IS ALREADY REVEALING ABOUT EARLY GALAXIES

—

July 11, 2023, marked the one-year anniversary of JWST's release to the science community for operations. Our team has already published our first five papers based on EIGER data, and we have concluded an exciting weeklong international conference at MIT, convening 150 of the world's foremost JWST expert users. These groups have barely scratched the surface of what Year 1 data have to offer. Yet a preliminary consensus narrative is emerging about early galaxy formation, summarized below.

EARLY GALAXIES WERE FAR SMALLER IN SIZE AND MASS THAN THE MILKY WAY

—

Modern-day spiral galaxies like the Milky Way and Andromeda have 10^{10}–10^{11} stars, spread over stellar disks that are 80,000–90,000 light years in diameter. The median EIGER galaxy has just 2×10^8 solar masses of stars, and these are concentrated into irregularly-shaped morphologies of just 2,200 light years in diameter. In other words, typical galaxies seen by JWST in the first billion years are about 40× smaller than the Milky Way and have 250× fewer stars. This is consistent with the canonical theory of galaxy formation, whereby large galaxies grow over time from the mergers of smaller proto-galaxies.

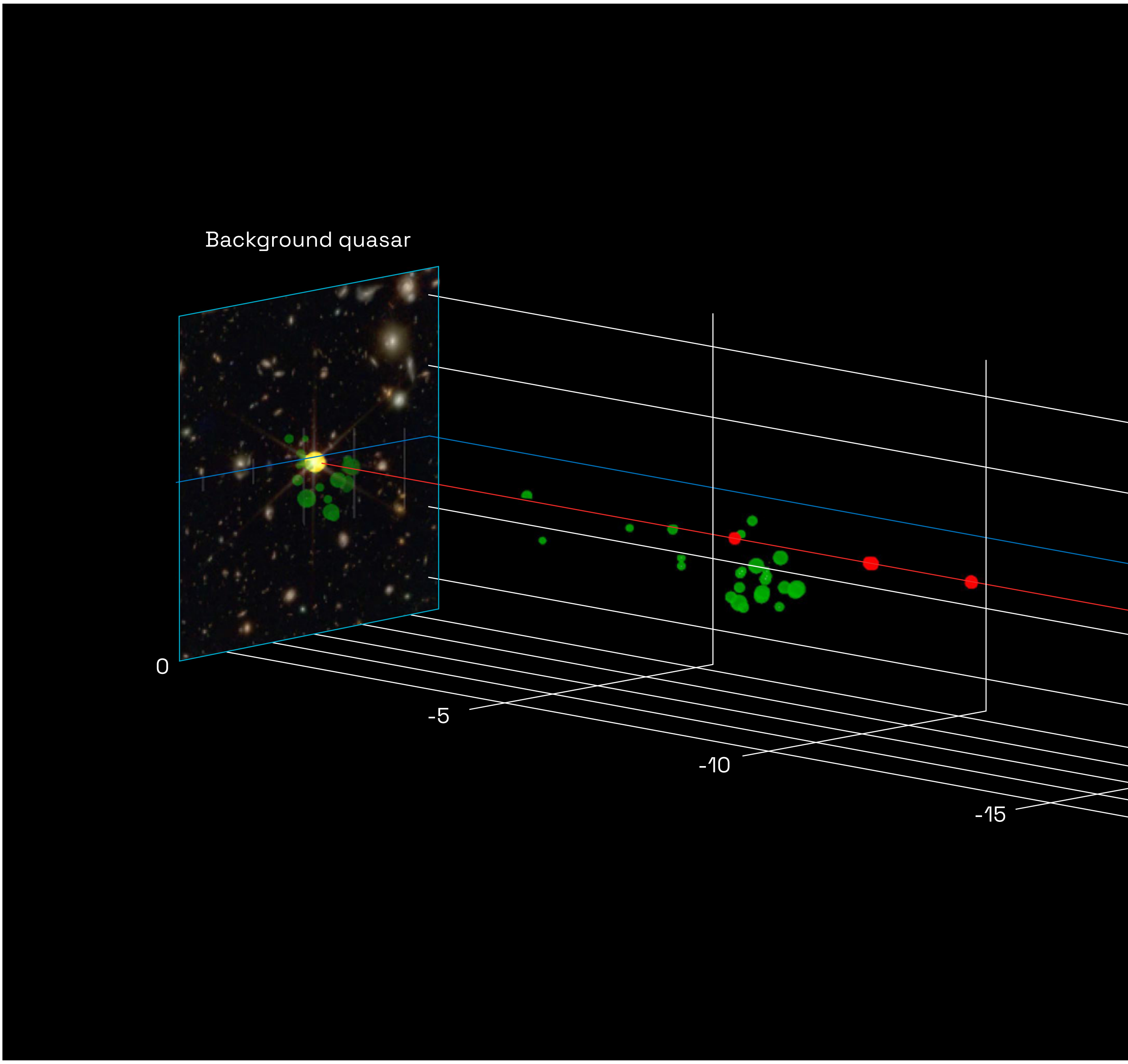
In fact, with your naked eye it is possible to see somewhat similar mini-galaxies in the local universe—these are the Magellanic Clouds, two dwarf galaxies falling into the Milky Way that are visible under a dark sky from the Southern Hemisphere. Our EIGER galaxies resemble the smaller of the two Magellanic Clouds in mass.

However, it is astounding that JWST can easily detect such tiny objects at a luminosity distance of over 200 billion light-years, which is an impressive distance even by astronomical standards!

EARLY GALAXIES EXHIBIT SPECTACULAR NEBULAE AND INTENSE STAR FORMATION

Our team was astonished when analyzing the first EIGER grism spectra at the number of galaxies whose nebular emission lines stood out clearly from the noise, exceeding our most optimistic pre-launch expectations. This is in part thanks to the superb engineering of the telescope. Yet it appears that the universe also conspires to make nebular emission much brighter in early galaxies than we see in the present day.

Emission nebulae like the famous example in Orion's sword are lit up by young, hot stars, and it appears that EIGER galaxies are forming between four and eight such new stars per year, in contrast to the Milky Way, which forms approximately one per year. Their small stellar mass and large star formation rate indicates that these galaxies can double in size every 50 million years—a blink of an eye in cosmic history. If we could somehow transport ourselves in space and time to the inside of one of these rapidly



growing infant galaxies, the sky would be spectacularly illuminated with color.

EXTREMELY MASSIVE BLACK HOLES ALREADY ANCHORED THE NUCLEI OF EARLY GALAXIES

At the center of each EIGER field, there is one very special galaxy from the early universe: the object hosting a supermassive black hole that we see as a quasar. Although the quasar just looks like a bright red star in an image, its spectrum is very distinctive, and does not at all resemble that of a normal star or galaxy. Instead, it has a series of emission lines powered by hot matter accreting onto the black hole. These lines are no longer sharp spikes, but rather are smeared by Doppler shifting of the emitting gas as it spirals in.

The Doppler broadening of these lines encodes information about orbital velocities and hence the mass of the black hole. MIT professor Anna-Christina Eilers analyzed EIGER's first observed black hole using hydrogen lines in the JWST spectrum, and found it weighed in at ten billion solar masses, consistent with other less direct measurements made from the ground. It remains a mystery how anything this enormous can be assembled less than one billion years after the Big Bang; it violates a theoretical speed limit on how fast matter can accrete onto a central body. The existence of these objects requires new theory.

One feature of many black hole growth models is that younger black holes spend some (perhaps most) of their life in a dust-enshrouded cocoon, in which they are growing but we cannot see the light that they emit. Although such veiled accretors have never been seen before, there is tantalizing evidence in data from EIGER and other surveys that JWST may be starting to find small and dusty black holes at early times, filling in a piece of this puzzle.

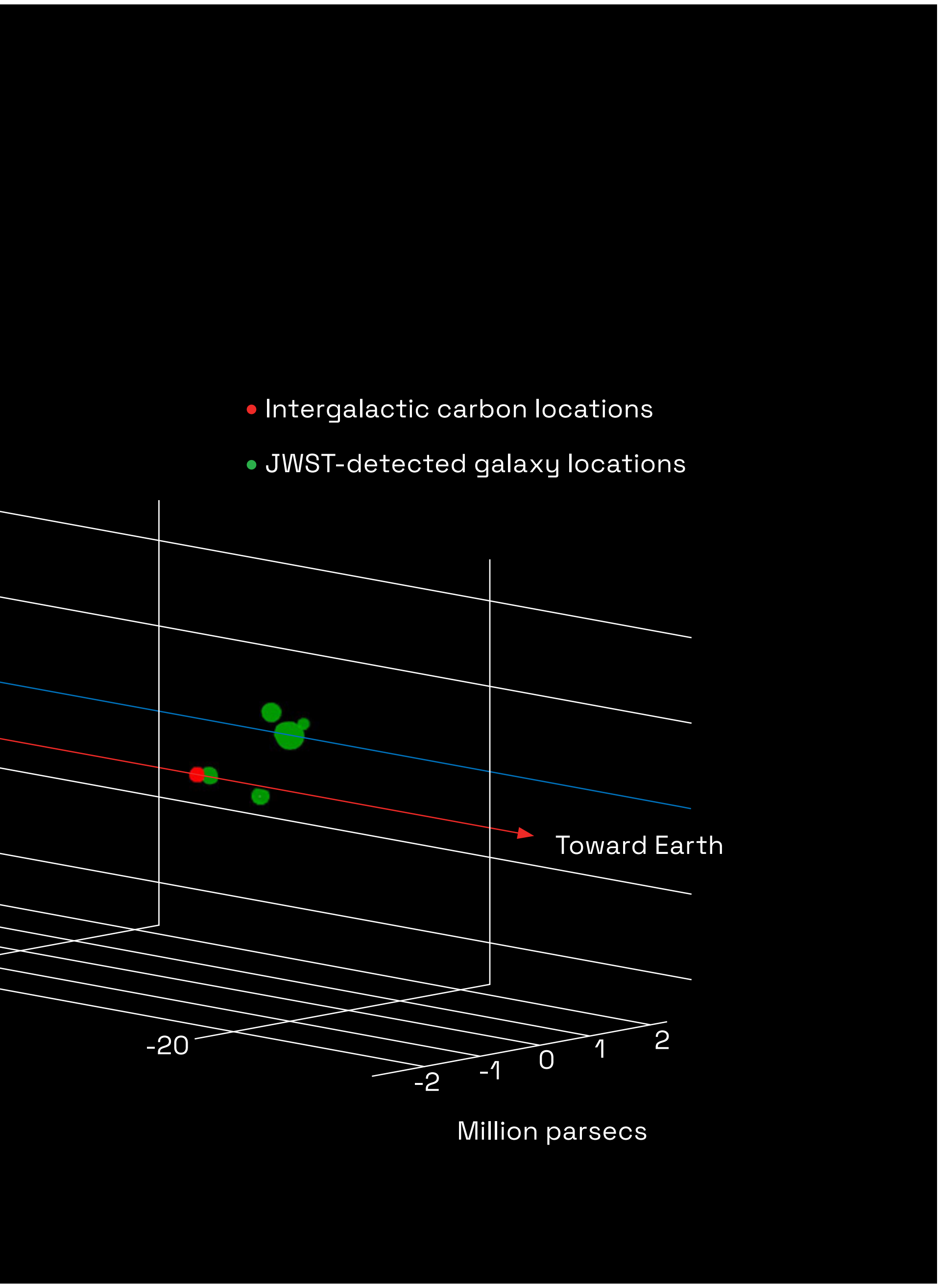


FIGURE 3:
By measuring redshifts, JWST not only provides a "flat" 2D image of the sky, it also measures depth along the line of sight in 3D. This field shows the locations of galaxies (green dots) along the sightline to the quasar in *Figures 1 and 2*; the boresight is indicated by the red vector terminating with a yellow dot at the quasar's location. Red dots indicate concentrations of carbon atoms detected in the quasar's foreground, as measured with Magellan/FIRE. There is clear evidence of clustering among the galaxies interspersed with long voids. Some (but not all) carbon pollution is also occurring near galaxies detected with JWST.

EARLY GALAXIES WERE HEAVY POLLUTERS

Quasars are useful for many things besides the study of black hole physics. As the brightest persistent sources in the universe, their spectra record a 1D density "core sample" of any intervening gas along the line of sight from Earth. This is because gaseous atoms absorb light passing through from the quasar at discrete wavelengths, according to each element's electron energy level configuration. At larger distances the observed absorption occurs at correspondingly higher redshift. All quasar spectra exhibit a menagerie of absorption lines that can be sorted by atomic element, and distance from Earth.

Our team's pre-existing spectra from FIRE and other ground-based telescopes had already revealed the presence of carbon, silicon, oxygen, iron, aluminum and magnesium at precisely determined redshifts toward these quasars. These elements are all heavier than helium and were therefore synthesized in some of the earliest stars and galaxies in the universe. EIGER's JWST observations provided the first-ever 3D map of galaxies at this same epoch, helping us locate stars that are the potential sources of these synthesized elements.

Already we have detected numerous galaxies in the neighborhood of chemically enriched gas, at epochs far earlier than we could previously access. Spatial correlations of galaxies and enriched gas are not surprising *per se*; most galaxies in the local universe have carbon, oxygen and other stellar byproducts gravitationally bound within their halos, which were deposited by supernovae in the galaxy.

The important and surprising difference is that in the early universe, the new elements are somewhat near galaxies yet still too distant to be gravitationally bound, because the galaxies are so tiny that their sphere of influence is small. Apparently, the combination of rapid star formation and small gravitational mass creates conditions where supernova energy can accelerate freshly minted elements beyond escape velocity and into intergalactic space, in an explosion of polluted matter. These free-floating elements may in time fall back into their galaxy of origin to form new stars, or they may travel over to pollute other neighboring proto-galaxies, or they may never return from intergalactic space. Theory suggests that this is an important regulating aspect of the galaxy formation process.

WHAT'S NEXT?

In the next three years, astronomers are preparing for launch and operations of two new wide-field space telescopes: Euclid from the European Space Agency, which launched on July 1, 2023, and the Nancy Grace Roman Space Telescope from NASA, scheduled for 2026. These observatories will survey large swaths of the sky and uncover new, fainter objects suitable for detailed characterization with JWST's narrow but deep capabilities. However, after these two missions, NASA Astrophysics is not planning another flagship until the late 2040s. This is near the end of JWST's operational life, and virtually a career to wait for many young researchers.

During the 2030s, the field is instead focusing resources on a new generation of ground-based observatories to complement NASA's space-based constellation. Three new telescopes with diameters 4–5 times larger than JWST are through the design phase and into early construction, using a public-private hybrid funding model. One of these, the Giant Magellan Telescope (GMT), will be co-located with the existing Magellan Telescopes in Chile, and have 12 times their light-gathering power. Unlike JWST, which only sees infrared light, the GMT will feature a full suite of UV/optical/IR instrumentation, and it will deliver sharper images and deeper spectra in the 1–2 micron band where hydrogen transitions are redshifted in the early universe. In the same way that institutional Magellan access allowed MIT researchers to compete for scarce Hubble Space Telescope and eventually JWST time, partnership in next-generation ground based telescopes will help researchers pursue the best and most ambitious science, and capitalize on discovery opportunities for decades to come.

JWST has already revolutionized our understanding of the early universe, even though we are just one year into its projected two-decade lifetime. If past is prologue with the Hubble Space Telescope, Magellan, and indeed every world-class telescope built since Galileo, the best is yet to come as we gain a full understanding of the instrument and analysis tools, and discover new astrophysical phenomena that have yet to be imagined.

ROBERT SIMCOE is the Francis L. Friedman Professor of Physics in the MIT Department of Physics, and Director of the MIT Kavli Institute for Astrophysics and Space Research. He first acquired an interest in astronomy and telescope making as a hobby through family trips to the Stellafane convention. As an undergraduate at Princeton, he participated in development of the Sloan Digital Sky Survey camera, after which he moved to Caltech where he collaborated on a wide-field camera for the 200″ Hale Telescope at Palomar Observatory and completed a thesis on chemical enrichment of the intergalactic medium using the Keck Telescopes. In 2003 he moved to MIT as a Pappalardo Postdoctoral Fellow, to make use of the newly commissioned 6.5-meter Magellan Telescopes, and joined the MIT faculty in 2006. Three years later he installed the FIRE infrared spectrometer at Magellan, which has played a key role in exploration of cool stars in the nearby universe, and the discovery and characterization of quasars in the first billion years after the Big Bang. In 2023, his research group commissioned one of the first dedicated robotic telescopes to survey the time-variable infrared sky. Later this year, his team will also commission a new hyperspectral imager for Magellan capable of taking 3D images of the astronomical sky.

THE BLACK HOLE INFORMATION PARADOX

A RESOLUTION ON THE HORIZON

BY NETTA ENGELHARDT

The interior of a black hole is one of the most mysterious regions of the universe. By their very definition black holes cannot be directly observed, but a large body of indirect evidence strongly supports the existence of black holes in our own universe. Our job as physicists to describe the nature of our universe is incomplete without a full understanding of the interior of black holes.

General relativity, which governs the behavior of gravitating objects in the absence of quantum effects, predicts a singularity in the black hole interior. Such a singularity generally results in large curvatures on quantum scales; this is in contrast with our standard experiences in the lab, where quantum effects and gravity are happily more or less separate with little to no impact on one another. In the deep black hole interior, however, the strong interactions between gravity and quantum physics require a quantum theory of gravity.

Fortunately, though, we don't immediately lose control of black hole dynamics upon crossing the horizon: gravitational effects do not instantly become strong at the event horizon. Instead, the gravitational field strength increases gradually for an observer who falls into the black hole. The larger the black hole is, the longer it takes for gravitational effects to build up to a strength that requires a full quantum treatment. In particular, the gravitational effects at the putative event horizon of the M87 black hole are *weaker* than those at the surface of the sun! We certainly don't need quantum gravity for a good description of the surface of the sun. So it must be the case that semiclassical gravity—the approximately separate treatment of quantum effects and gravity—governs the physics of the black hole interior as well as it governs the physics of observers near the Sun (say, on Mercury). Which is to say, extraordinarily well! Put differently, if semiclassical gravity were to break down into strong quantum gravity effects at the event horizon of the M87 black hole, the same must also be true of the region between the Sun and Mercury. And we know that our current observational data of the Sun and Mercury can be well-described without any quantum gravity effects.

This means that a good chunk of the black hole interior fits within this approximate semiclassical gravity picture. This innocuous and straightforward conclusion, however, leads to one of the most longstanding problems in modern physics: the black hole information paradox.

THE PARADOX

The black hole information paradox is a conflict between two apparently incontrovertible facts: first, that semiclassical gravity is valid on scales where gravitational and quantum effects are more or less separate; second, that quantum mechanics is "*unitary*" and thus all quantum processes are in principle, though not necessarily in practice, reversible.

What precisely do we mean by "reversible"? How is a black hole different from a fire? Consider the following thought experiment: you write a message—classical information—on a notepad, which you then toss into a fire in some sealed chamber. Once the fire has consumed the notepad, the information appears to be destroyed: how can we possibly reverse the fire and read the message? Well, if we had arbitrarily powerful machinery that could track every molecule and collect all of the fine-grained information about the fire, and we knew the exact equations describing the behavior of every molecule as it interacts with other molecules, we could *in principle* recreate the message written on the notepad from the ash. This is the fundamental difference between a black hole and a fire.

A 1975 calculation by Stephen Hawking showed that if semiclassical gravity is approximately valid at the event horizon of a black hole, then black holes can evaporate. The black hole evaporation process appears to create

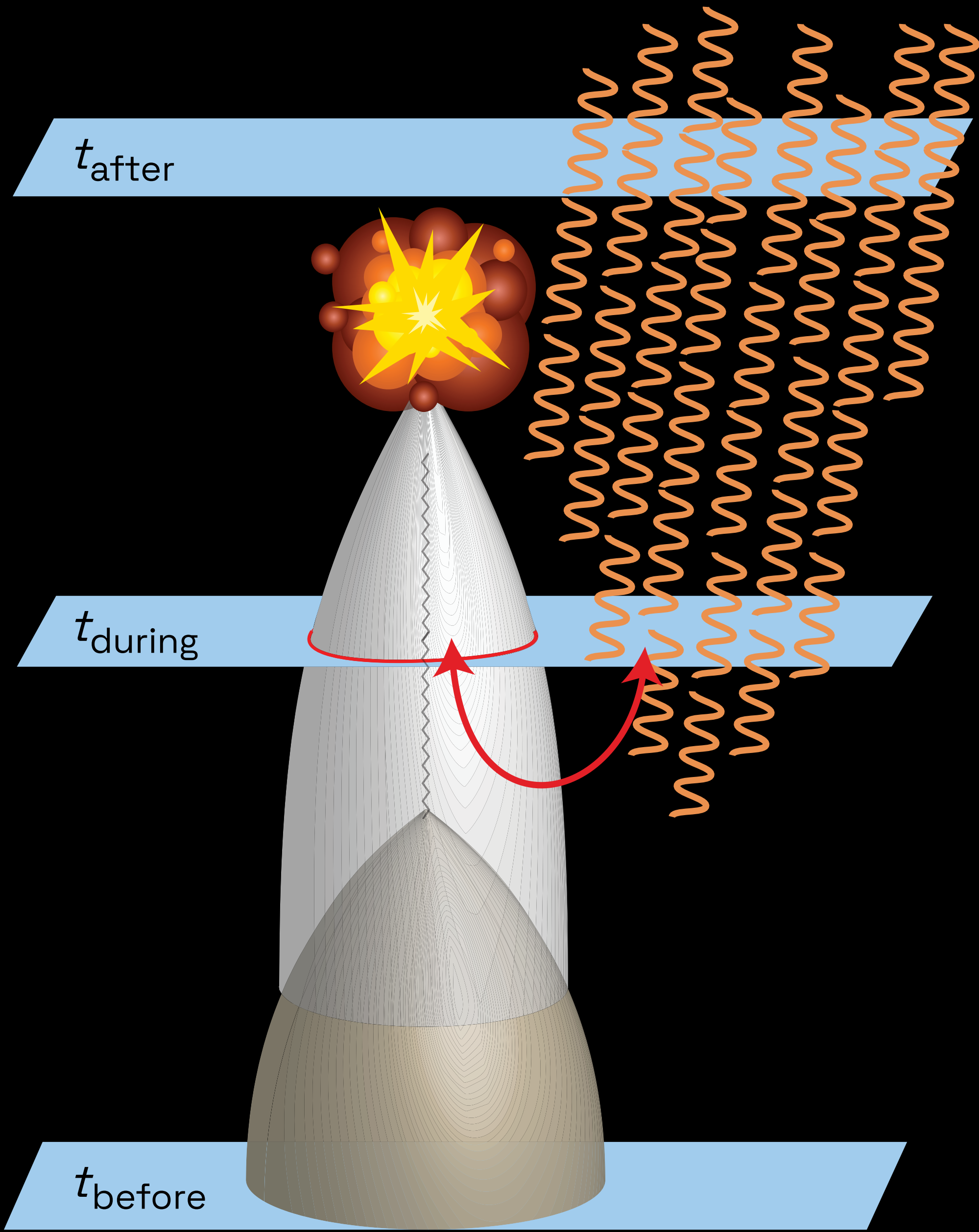


FIGURE 1:
The black hole formation and evaporation process, with time running vertically upwards. At early times, t_{before}, we have a star (brown section) shrinking in radius with time. Eventually an event horizon (gray section) forms. The black hole radiates, shown in the orange waves, during the evaporation process (as illustrated at the instant in time t_{during}). The radiation is entangled with the black hole interior (heuristically indicated by the red arrow). Eventually the black hole evaporates completely, and we are only left with the radiation at t_{after}. Credit: Netta Engelhardt

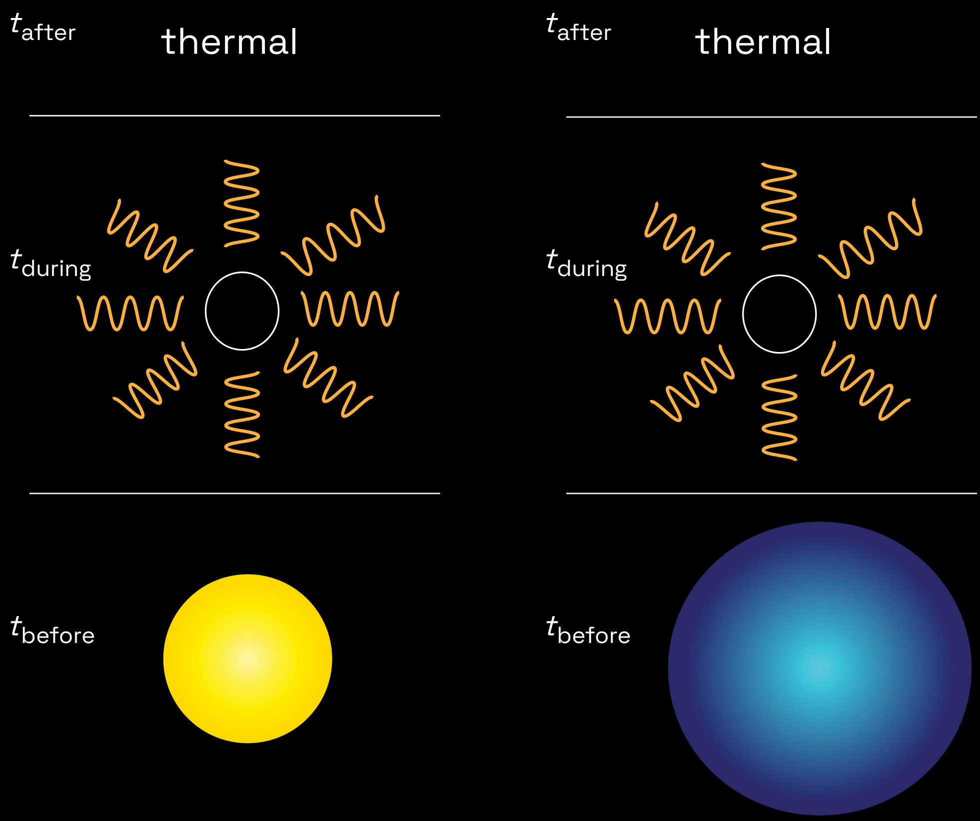


FIGURE 2:
A series of "snapshots" of the black hole evaporation process as analyzed by Hawking. Two very different stars collapse into black holes, which then radiate and evaporate. Once evaporation is complete, the universe is in a thermal state in both cases.
Credit: Netta Engelhardt

an unprecedented problem: it is *in principle* impossible to reverse-engineer the information that went into a black hole that has evaporated. Even if we knew the exact equations of motion of the universe and the exact state of the universe after evaporation, we *still* would not be able to ascertain the information that went into the black hole. The radiation emitted by the black hole as it evaporates must be thermal, and indistinguishable between any two evaporated black holes—even if they were originally formed from two very different stars!

An immediate consequence of this phenomenon is that if we knew the exact and precise state of the entire universe now (down to its fundamental particles), it would be in principle impossible to know what the universe was like a few years ago. Since our business as physicists is to use existing information to predict the evolution of the universe both forwards and backwards in time, this represents a catastrophic and unprecedented loss of determinism in physics. There is no other process which is known to result in *net* information loss.

Thus we appear to require one of two unappealing options: either strong quantum gravity effects are needed to describe the large-scale dynamics of regions of the universe that look just like Mercury and the Sun, or physics is not a deterministic science. This is the black hole information paradox.

This paradox has been a guiding post for progress on quantum gravity since its discovery by Hawking in 1975. Developments in string theory in the 1990s and 2000s provided the first conclusive evidence that information is *not* lost. How information can be conserved, however, remained a mystery. Is semiclassical gravity violated at the event horizon of a black hole? How can this be, given that interactions between quantum effects and gravity must be extremely weak there?

A NEW PERSPECTIVE

In 2019, the tide turned with a set of two simultaneously submitted papers by myself and my collaborators Almheiri, Marolf and Maxfield, and in parallel, Penington. We executed a semiclassical gravity analysis of black hole evaporation that was consistent, by a famous litmus test, with information conservation. This test, known as the Page curve, tracks the behavior of the von Neumann entropy of the radiation. This entropy, which is different from the standard entropy of thermodynamics, measures how "entangled" (or, correlated) a system is with its complement. Given some quantum system, say, n qubits, we can divide it up into two complementary subsystems: R and B. R will stand for the radiation of a black hole and B for the remaining black hole. When R is the trivial empty set, *i.e.*, R contains zero qubits, R is trivially uncorrelated with B: the von Neumann entropy of R vanishes. If we repartition the system so that R has progressively more qubits, we at first expect its von Neumann entropy to increase. Analogously, as the black hole evaporates into radiation, the data in B must end up in R. Eventually, we can repartition the system so that B has zero qubits and R has all of the qubits. That is, the black hole has fully evaporated.

At this point, R is again uncorrelated with B. We thus expect that the von Neumann entropy of R increases and then decreases as a function of the number of qubits in R.

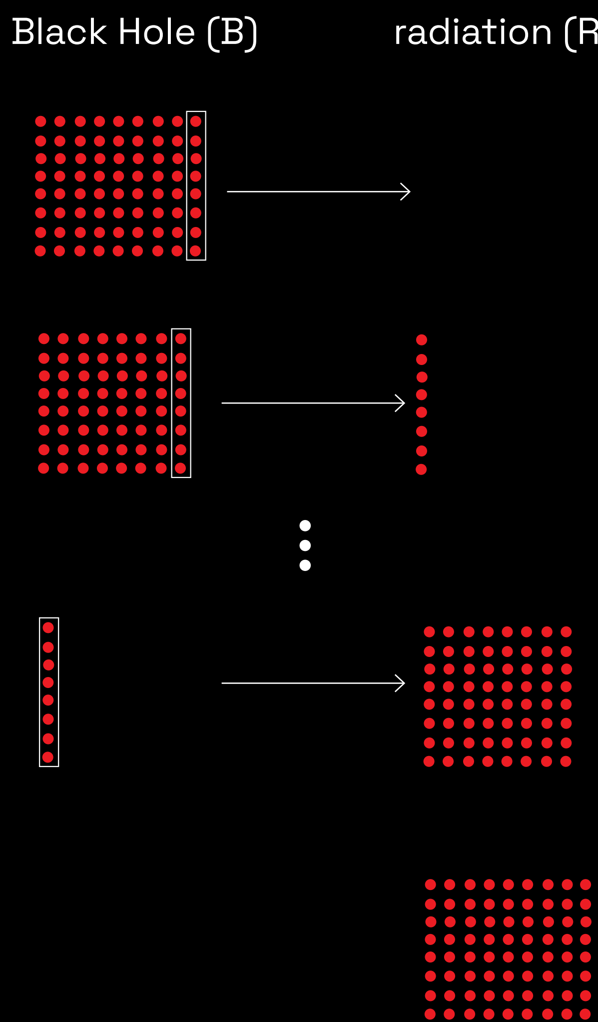


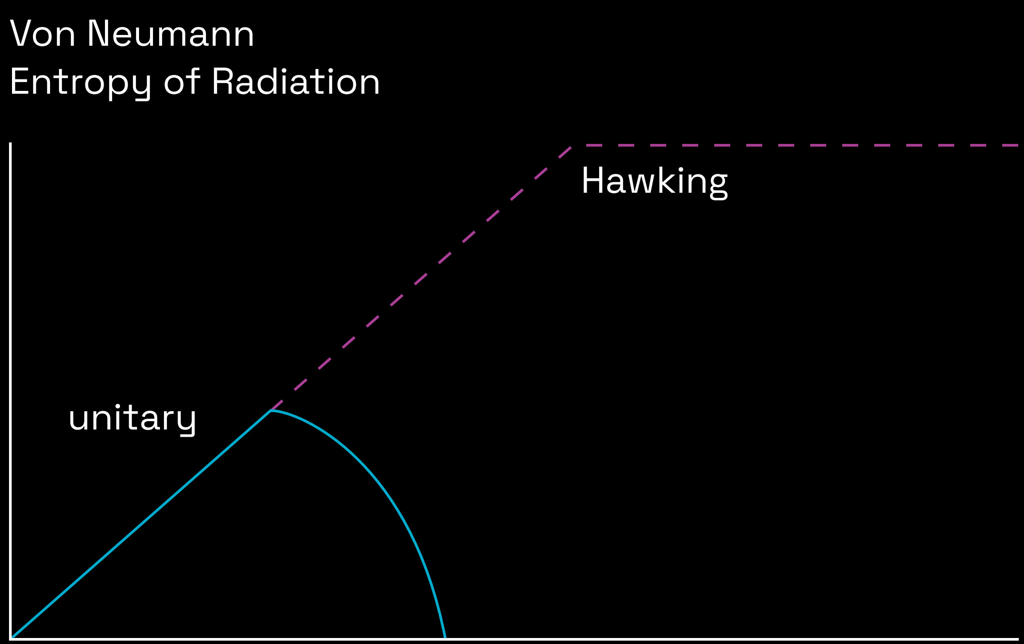
FIGURE 3: A caricature of how a black hole evaporation process should look when information is conserved. Here the black hole B starts out (at the top) as a quantum system with some number of qubits. More and more of the system is transferred into R until eventually R is the entire system. Credit: Netta Engelhardt

If black hole evaporation is to be unitary, then the von Neumann entropy of the radiation should start out at zero, increase for a while, then—once the black hole has fully evaporated—return to zero. The resulting curve is known as the Page curve. However, Hawking's calculation shows that the von Neumann entropy of the radiation increases monotonically until the black hole has finished evaporating! The radiation, according to a semiclassical gravity treatment of the horizon, is now correlated with something that does not exist in the universe.

In 2019 we found that there exists a different semiclassical analysis from Hawking's that yields the Page curve. There was, however, a catch: while our calculation was within the regime of semiclassical gravity, and assumed that the standard picture of semiclassical gravity is an accurate description of the physics, the rules for how to compute certain quantities were vastly different from the standard rules of semiclassical gravity. By analogy, suppose you are asked to compute the pressure of an ideal gas in a cylinder. You may be tempted to compute the average velocity or momentum of the molecules of the gas and then use that to deduce the pressure. However, since the average velocity is zero, you would be led astray! Instead, we know that in the limit where thermodynamics is emergent from statistical mechanics, we must use $PV = nRT$, which is valid thermodynamically, but inherited from statistical mechanics. In complete analogy with the ideal gas law, we used the "quantum extremal surface formula," proposed by myself and A. Wall in 2014, rather than the Hawking formula (analogous to the erroneous zero average velocity calculation). The logic is identical: in both cases, you use an alternative formula which follows from the underlying microscopics of the statistical mechanics of your system.

This unusual approach gave us precisely the loophole we needed: the basic constructs of semiclassical gravity—space and time and its curvatures—can be consistent with information conservation, but only if we use the correct equations inherited from quantum gravity.

FIGURE 4:
The two curves corresponding to the unitary calculation of the von Neumann entropy of the radiation of an evaporating black hole (blue)—the Page curve—and the Hawking calculation of the von Neumann entropy of an evaporating black hole (purple). Credit: Netta Engelhardt



This insight resulted in an explosion of progress across the field of black hole information: finally, there might be a way of having our cake and eating it too! We can have standard spacetime and geometry at the event horizon of a black hole without paying the price of determinism of physics.

TOWARDS A RESOLUTION

A significant question remained, however: why are the equations for various quantities modified by quantum gravity when a black hole is involved, but not modified for the Sun or Mercury? Last summer, my collaborators at MIT (Chris Akers, Daniel Harlow and Shreya Vardhan) and I, together with Penington, proposed a resolution for the distinguishing feature between black holes and other objects. Our resolution was predicated on an older insight by Daniel Harlow and Patrick Hayden that even though the information about the black hole interior must escape in its radiation, actually processing the radiation to distill information about the black hole is incredibly complex. To be precise, this "decoding" process of the black hole radiation would require a quantum computer to implement a circuit whose size is exponential in the size of the black hole. For a black hole with the mass of the Sun, this would be exponential in 10^{77}! Black holes in general are extremely complex objects, which sets them apart from other astrophysical phenomena with similar curvature scales as those at the horizon of an astrophysical black hole. We proposed that semiclassical gravity is valid at low curvatures *and* low complexity; in our quantitative models, we saw that the modifications to the calculations required by the 2019 calculation of the Page curve can be attributed exactly to complexity in toy models of black holes.

We will likely be exploring the consequences of these developments on quantum gravity for years to come. Just as the black hole information problem has served as a point of inspiration for a vast landscape of developments in quantum gravity, I predict — with confidence since the fundamental theory of our universe is, in fact, predictive! — that its resolution will do the same.

NETTA ENGELHARDT is the Biedenharn Career Development Associate Professor of Physics in the Center for Theoretical Physics, and works on quantum gravity, primarily within the framework of the AdS/CFT correspondence. Her research focuses on understanding the dynamics of black holes in quantum gravity, leveraging insights from the interplay between gravity and quantum information via holography. Her current primary interests revolve around the black hole information paradox, the thermodynamic behavior of black holes, and the cosmic censorship hypothesis (which conjectures that singularities are always hidden behind event horizons).

Netta Engelhardt grew up in Jerusalem, Israel, and Boston, MA. She received her BSc in physics and mathematics from Brandeis University and her PhD in physics from the University of California, Santa Barbara. She was a postdoctoral fellow at Princeton University and a member of the Princeton Gravity Initiative prior to joining the physics faculty at MIT in July 2019.

Deep
Learning
+
Deep
Thinking
=
Deeper
Understanding

Infusing physics intelligence into artificial intelligence

by Mike Williams and Jesse Thaler

Artificial intelligence (AI) is transforming many aspects of society, including the ways that scientists are pursuing groundbreaking discoveries. For many years, physicists have been at the forefront of applying AI methods to investigate fundamental questions about the universe. Building on these successes, we founded the Institute for Artificial Intelligence and Fundamental Interactions ("IAIFI," rhymes with "WiFi")[1], a collaboration of MIT, Harvard, Northeastern and Tufts universities. The IAIFI is one of the inaugural National Science Foundation AI research institutes[2], with 11 of our 26 senior members coming from the MIT Physics Department.

The primary goal of the IAIFI is to develop and deploy the next generation of AI technologies, based on the transformative idea that artificial intelligence can directly incorporate physics intelligence. IAIFI researchers are using these new AI technologies to tackle some of the most challenging problems in physics, from precision calculations of the structure of matter to gravitational wave detection of merging black holes. In addition, this interdisciplinary research leverages first principles from physics to drive AI innovations with widespread applications in both fundamental physics research and AI studies.

By fusing the deep learning revolution with the time-tested strategies of deep thinking in physics, we are gaining a deeper understanding of our universe—from the smallest building blocks of nature to the largest structures in the universe—and of the principles underlying intelligence itself.

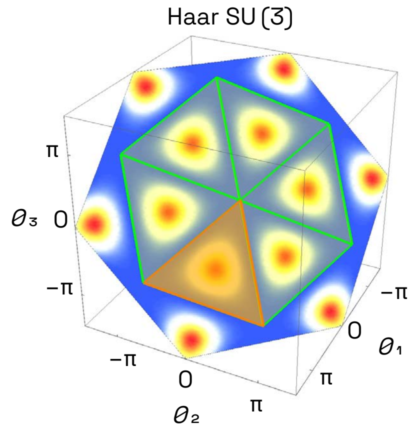


FIGURE 1:
Visualization of the complex symmetry space of variables in first-principles theoretical physics calculations, which have been built into machine learning models. Credit: Shanahan et al: *arxiv.org/abs/2008.05456*

Research in AI and fundamental interactions

Fundamental interactions are described by two pillars of modern physics: at short distances by the Standard Model of particle physics, and at long distances by the Lambda Cold Dark Matter model of Big Bang cosmology. Both models are based on physical first principles such as causality and space-time symmetries. An abundance of experimental evidence supports these theories, but also exposes where they are incomplete—most pressingly, that the Standard Model does not explain the nature of dark matter, which plays an essential role in cosmology. AI has the potential to help us solve this puzzle and many others in physics.

IAIFI researchers, including MIT physics faculty Tracy Slatyer and Lina Necib, are using AI to study dark matter. Prior to joining the MIT faculty, Necib used AI to discover a massive unknown stellar structure that may have helped shape the Milky Way, for which she was awarded the 2023 Valley Prize by the American Physical Society. Now as an IAIFI researcher, Necib is developing new, groundbreaking AI methods for studying the dark matter halo and growth history of our galaxy [3].

For many physics problems, the governing equations that encode the fundamental physical laws are known. However, undertaking key calculations within these frameworks—essential to test our understanding of the universe and guide physics discovery—can be computationally demanding or even intractable. IAIFI researchers, including MIT physics faculty Phiala Shanahan, Will Detmold and Jesse Thaler, are developing AI for such first-principles theory studies, which naturally require AI approaches that rigorously encode physics knowledge.

One such application is focused on developing AI methods for performing calculations involving the strong nuclear force that binds quarks into protons and neutrons, and protons and neutrons into nuclei. Phiala Shanahan and her group in collaboration with colleagues at Google DeepMind have developed machine learning architectures that include the physical symmetries of the theory of quantum chromodynamics, incorporating guarantees of exactness into the novel AI algorithms [4]. If these results can be successfully scaled up to current state-of-the-art applications, they will enable novel first-principles studies of nuclear and particle physics. Beyond the domain of physics, this work can be used in robotics or for artificial limbs, where exact rotational symmetries inherently arise in joints.

Incorporating physics principles into AI is also having a major impact on many experimental applications, such as designing AI methods that are more robust and more easily verifiable. IAIFI researchers are working to enhance the scientific potential of various facilities, including groups led by MIT physics faculty members Phil Harris and Mike Williams at the Large Hadron Collider (LHC), working on the CMS and LHCb experiments, respectively, and by MIT Senior Research Scientist Lisa Barsotti at the Laser Interferometer Gravity Wave Observatory (LIGO).

The IAIFI LHCb group has developed a novel type of neural network that guarantees the interpretability and robustness required for use in real-time data processing at the LHC—applications with some of the largest data rates in the world. Since verification and interpretability of AI solutions are also important in other AI application domains, it is not surprising that these novel neural networks developed for the LHC have also been shown to beat state-of-the-art models in various problems in other domains, including criminal justice, medicine and finance. A related effort led by the IAIFI CMS group is in the area of ultra-low-latency AI inference, where neural networks make decisions in under a microsecond, motivated by the relentless pressure of the LHC's 40 MHz proton-bunch collision rate. IAIFI technology here is also being applied to other domains where real-time decision-making is critical [5].

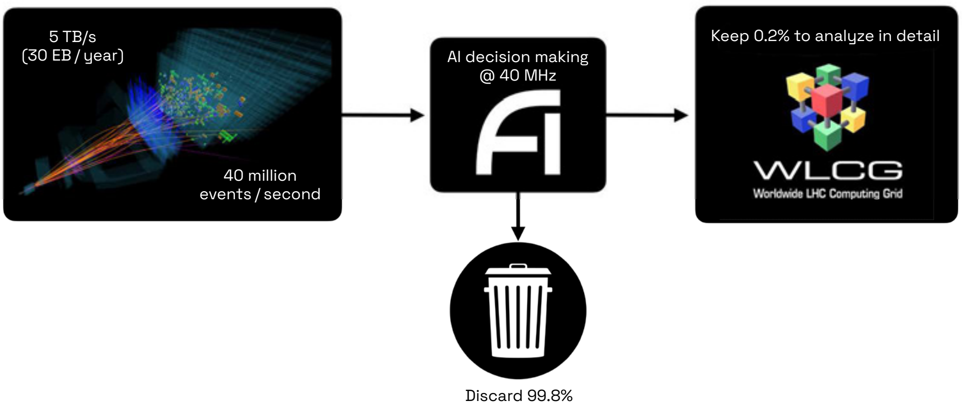


FIGURE 2:
Illustrating the data flow at the LHCb experiment at the Large Hadron Collider. (*From left*) Proton bunches collide at 40 MHz creating 5 TB of data per second. These events are analyzed in real time, with AI making the majority of decisions regarding which data to keep and which to discard. The vast majority of LHCb data must be discarded without ever being examined by human physicists.

The unique features of these physics applications also offer compelling research opportunities in AI more broadly, which is the primary focus of IAIFI and MIT physics faculty members Max Tegmark, Marin Soljačić and Isaac Chuang. A common AI application involves the denoising of images, for which a leading method is the diffusion approach inspired by thermodynamics. Tegmark and colleagues have introduced a new method inspired instead by electrodynamics, and more recently unified this method and diffusion into a new family of physics-inspired AI tools that are superior to all previous methods for many image denoising tasks, and exhibit improved robustness against modeling errors.

Additionally, physics-based tools are being used to better understand AI problems. The IAIFI's Tegmark and LHCb groups collaborated to show how physics tools such as effective theories and thermodynamic phase diagrams can help illuminate many aspects of AI learning dynamics. This project was a highlighted contribution at NeurIPS 2022, AI's leading conference. To truly trust AI models, we need to gain a deeper understanding of how they work, thus we view these efforts as an important contribution from physics to the field of AI.

Cultivating early-career talent, educating at the AI+physics intersection and engaging the public

AI technologies are advancing rapidly, making it both important and challenging to train junior researchers at the intersection of physics and AI. The IAIFI is recruiting and training a talented and diverse group of early-career researchers, especially at the postdoctoral level through our IAIFI Fellows Program [6], modelled after the MIT Physics Department's flagship Pappalardo Fellowships program. By offering our fellows their choice of research problems, and the chance to focus on exciting challenges in physics and AI, we are preparing many talented young scientists to become future leaders in both academia and industry.

The IAIFI Fellows are sparking interdisciplinary and multi-investigator collaborations, generating new ideas and approaches, translating physics challenges beyond their native domains, and helping develop a common language across disciplines. IAIFI Fellows Siddharth

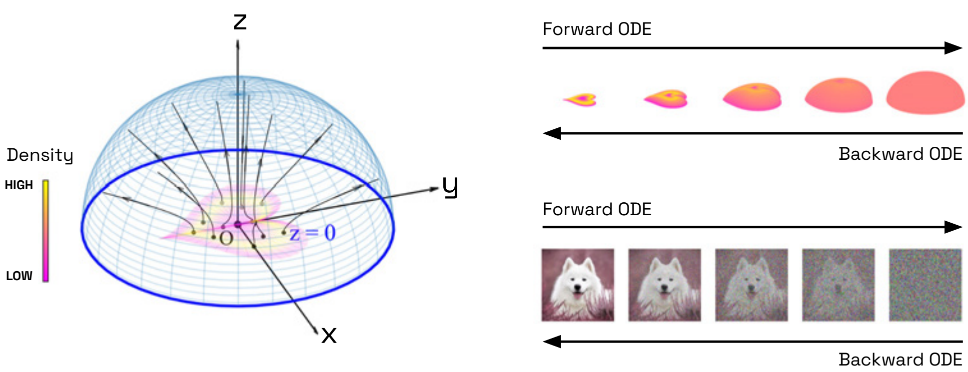


FIGURE 3:
(*From left*) Toy example showing how any 2-D density distribution, a heart-shaped one in this case, can be mapped to random noise on the surface of a 3-D hemisphere by some electric field (which is learned by the machine). The density can be viewed as composed of electrically charged particles. The right panel shows how one can use the learned electric field to generate noise on the hemisphere, which is then mapped to an image. In this way, the learned model can generate realistic images from scratch, or be used to denoise existing images.
Credit: Tegmark et al: *arxiv.org/abs/2209.11178*

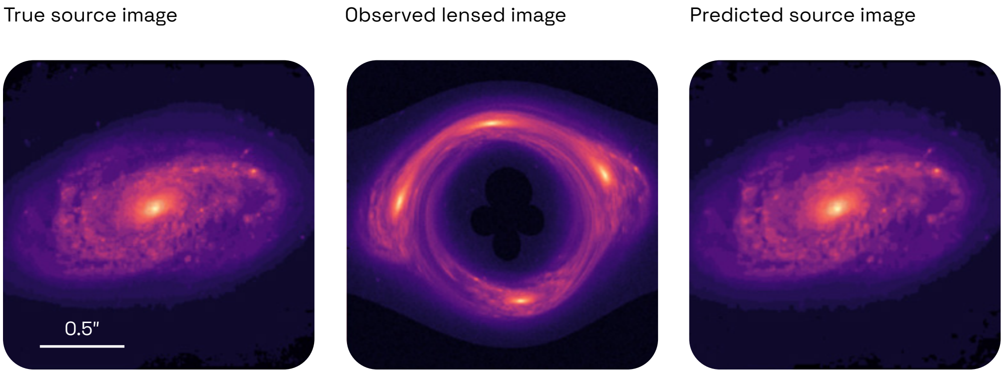


FIGURE 4:
(*Left*) Image of galaxy NGC2906. (*Center*) Simulated effect of gravitational lensing on this galaxy; this is what would be observed if this galaxy did undergo gravitational lensing when viewed from earth. (*Right*) AI prediction for what galaxy NGC2906 looks like given only the center lensed image. The agreement with the true image, which the AI did not have access to, is striking. Credit: Mishra-Sharma and Yang: *arxiv.org/abs/2206.14820*

Mishra-Sharma and Ge Yang, whose primary research focuses are astrophysics and robotics, respectively, collaborated on a project that pushed the boundaries of both AI and physics by making it possible to efficiently model high-resolution strong gravitational lensing observations at their full complexity [7].

Another related effort spearheaded by the authors and Alexander Rakhlin, an MIT professor of brain and cognitive science and IAIFI researcher, is the development of a new interdisciplinary PhD program in Physics, Statistics, and Data Science (PhysSDS). This is a collaborative effort between the Department of Physics and the Statistics and Data Science Center [8]. Statistics and data science are among the foundational pillars of AI. By providing physics PhD students formal training in these areas, we are fostering a new generation of leaders at the intersection of physics, statistics and AI. The first interdisciplinary PhD degree was awarded in Spring 2021, and thus far seven such degrees have been awarded, with more students joining the program every term. Roughly half of the students who have obtained this degree have gone into academia, with the other half now working in industry. To further bolster our industry connections, the IAIFI is hosting monthly lunches for our junior members with representatives from industry, and collating advice on how to get internships and jobs in industry from our alumni who have succeeded going that route.

In parallel with developing the PhysSDS PhD, MIT Physics faculty Phil Harris and Isaac Chuang, along with MITx Digital Learning Fellow Alex Shvonski, have created a new course, 8.16 *Data Science in Physics*, along with a concurrently run graduate version 8.316, which presents modern computational methods in the context of realistic contemporary examples of their applications to physics research. Students, for example, are taught how to confirm the recent Nobel Prize for the discovery of gravitational waves at LIGO,

FIGURE 5:
IAIFI postdoctoral associate Harold Erbin at the IAIFI Galaxy Zoo demonstration held at the Fall 2022 Cambridge Science Festival.

then improve on the published sensitivity using AI and fundamental physics principles. An MITx version of the course is partially online now [9], and planned to be fully available later in 2023. With projects like this, we hope to disseminate knowledge about, and enthusiasm for, physics, AI and their intersection.

To help ensure we are serving our junior members, we created an Early Career and Equity Committee (ECEC) within the IAIFI. The ECEC meets monthly to discuss issues related to the well-being and work environment of IAIFI members, and advises us on ways to create a more equitable, inclusive, welcoming and enjoyable place of work.

To reach beyond the MIT community, we launched a PhD Summer School in 2022 on the intersections of AI and physics. Its inaugural session was a huge success: more than twice as many students than we could accommodate applied, with truly exceptional ratings given by the students in the post-event survey. The weeklong school featured lectures by world-leading experts paired with hands-on tutorials run by our IAIFI Fellows, along with a hackathon, career panel and various networking opportunities. Our 2023 summer school is currently in preparation. At the Cambridge Science Festival in October 2022, Lina Necib hosted a galaxy zoo demonstration using labels created by citizen scientists to automate data analysis leveraging AI to better understand galaxy formation. IAIFI also ran a robotics demonstration, using a robot trained by IAIFI researchers using physics principles. In total, we interacted with about 1,000 people at this event, and another 600 using a similar demonstration at MIT's Winter Family Day.

Building new connections at MIT and beyond

Leveraging MIT's culture of collaboration, the IAIFI is generating new connections and strengthening existing ones across MIT and beyond. Of the 26 current IAIFI senior investigators, 15 are at MIT and members of the Laboratory for Nuclear Science, Research Laboratory for Electronics, Kavli Institute for Astrophysics and Space Research, Computer Science and AI Laboratory, and Institute for Data, Systems, and Society. In addition, IAIFI investigators are members of related NSF-supported efforts at MIT, such as the Center for Brains, Minds, and Machines within the McGovern Institute for Brain Research and the MIT-Harvard Center for Ultracold Atoms.

More broadly, the IAIFI is making Cambridge, MA, and the greater Boston area a hub for collaborative efforts to advance both physics and AI. This past year, the IAIFI hosted Brian Nord, an astrophysicist at the Fermi National Accelerator Laboratory and a senior member of the Kavli Institute for Cosmological Physics at the University of Chicago, as a year-long visitor through MIT's Martin Luther King, Jr. Scholars program. Nord's work involves training machines to explore the cosmos and fighting for equity in research.

As we teach in 8.01 and 8.02 at MIT, part of what makes physics so powerful is that it provides a universal language that can be applied to a wide range of scientific problems. Through the IAIFI, we are creating a common language that transcends the intellectual borders between physics and AI to facilitate ground-breaking discoveries. In doing so, we are tackling two of the greatest mysteries of science: how our universe works and how intelligence works. By linking them, using physics to improve AI and AI to improve physics, we are advancing physics knowledge and galvanizing AI research innovation. More broadly, a revolution is brewing in AI+science, and our efforts are aimed at positioning MIT to be a leader in this electrifying field.

PROFESSOR MIKE WILLIAMS is the founder and leader of the LHCb group at MIT and the inaugural Deputy Director of the IAIFI. He works on advancing our knowledge of fundamental particles by both proposing and performing novel experimental measurements at cutting-edge facilities. Williams is primarily focused on searching for as-yet-unknown particles and forces, possibly components of the dark sector of matter, and on studying largely unexplored emergent properties of the strong nuclear force. The LHCb group at MIT is a leader in the LHCb real-time data-processing system. To enable his scientific pursuits, Mike also works on advancing the usage of machine learning algorithms and other state-of-the-art data science tools within the domain of particle physics research, and on advancing our understanding of AI itself.

PROFESSOR JESSE THALER is a theoretical particle physicist who fuses techniques from quantum field theory and machine learning to address outstanding questions in fundamental physics. His current research is focused on maximizing the discovery potential of the Large Hadron Collider through new theoretical frameworks and novel data analysis techniques. Thaler is an expert in jets, which are collimated sprays of particles that are copiously produced at the LHC, and he studies the substructure of jets to enhance the search for new phenomena and illuminate the dynamics of gauge theories. He joined the MIT Physics Department in 2010, and is based in the Center for Theoretical Physics. In 2020, Thaler became the inaugural Director of the NSF Institute for Artificial Intelligence and Fundamental Interactions.

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Credit: Justin Knight Photography

In Remembrance

X-ray astronomy leader George W. Clark dies at 94

Led investigations in cosmic-ray physics, and gamma-ray and X-ray astronomy.

by Sandi Miller

Professor emeritus of physics George Whipple Clark PhD '52, an astrophysicist who was a pioneer in X-ray and gamma-ray astronomy, died on April 6, 2023, in Boston. He was 94.

Clark employed buckets, balloons, rockets and satellites in his nearly lifelong pursuit to understand the nature and origins of cosmic rays, gamma rays and X-rays.

Clark discovered the polarization of cosmic-ray muons, collaborated with the late Physics professor Bruno Rossi on several large ground-based cosmic-ray air shower experiments, and used balloon-borne and satellite instrumentation to locate X-ray sources.

He was a principal scientist for satellite experiments that resulted in the discovery of high-energy gamma rays from the Milky Way galaxy, and produced evidence for an isotropic component that is now known to arise from other more distant galaxies. His pioneering work in the use of balloon-borne instrumentation for observing celestial X-ray sources led to his discovery of high-energy X-rays from the Crab Nebula. He was also a primary contributor to several NASA satellite X-ray astronomy missions.

On the MIT Physics faculty for 44 years, Clark recruited and mentored several generations of leading astrophysicists. He was a founding member of MIT's Center for Space Research, now the MIT Kavli Institute for Astrophysics and Space Research.

Early interest in science and MIT launch

Born in 1928 and growing up in Harvey, Illinois, Clark's interest in astronomy bloomed when he picked up his father's copy of *Amateur Telescope Making*, which taught George how to ground and polish a six-inch parabolic mirror. He placed this into a four-foot telescope that he mounted in a field near his family's summer home, and would later use it years later while teaching MIT Physics Junior Lab. In high school, he finished in the top ten in the Westinghouse Science Talent Search with an essay about his chemical work with rare-earth elements.

He graduated from Harvard in 1949 with a BA in physics, then pursued his doctorate at MIT, joining Bruno Rossi's Cosmic Ray Group in the Laboratory for Nuclear Science and Engineering. Receiving his PhD in 1952, he joined MIT as an instructor.

"Professor Rossi invited me on a journey of exploration" during a time when "public support of curiosity-driven research was at its peak, based on the recognition that it was the foundation of the spectacular successes of goal-oriented war research," Clark once noted.

When Rossi aimed to discover the origins of cosmic rays, Clark and other group members worked on several large cosmic-ray air shower experiments (EAS) to measure the energy spectrum of the primary cosmic rays, as well as to determine their arrival directions.

"He helped chart the future of X-ray astronomy by prioritizing the *Chandra X-ray Observatory.* He played a major role in the discovery of celestial gamma-ray sources."

Robert Simcoe, *MIT Kavli Institute director*

He partnered with visiting scientist Peter Bassi to set up scintillation detectors–5-gallon cans filled with toluene–on the physics building's roof. Electrical pulses were displayed on an oscilloscope viewed by an automatic film camera, and the resulting measurements proved that using the novel methods of density sampling and fast timing could yield arrival directions within a few degrees and shower sizes within a few percent. This led to a larger such experiment on the grounds of the Agassiz Station of the Harvard College Observatory, and other MIT-led air shower experiments in India, Bolivia and New Mexico.

Clark and his colleague William Kraushaar created balloon-borne experiments to detect a very rare component of the primary cosmic radiation; this was thwarted by the high rate of background events caused by radiation higher up.

Then NASA offered space on its Explorer 11 satellite for their high-energy gamma-ray telescope. The pair designed the 82-pound satellite to tumble in orbit to scan the entire sky; in 1961 it registered 31 events of possible cosmic gamma rays. Gordon Garmire joined in to create an improved gamma-ray telescope in 1967 on Orbiting Solar Observer 3. It demonstrated that gammas of energies above 70 MeV were emanating from the Milky Way and offered the first evidence of gamma rays from distant galaxies.

X-ray vision

The Sun was the only known source of cosmic X-rays, so Rossi asked a former student to find more sources: Martin Annis, president of American Science and Engineering (AS&E), a small research firm co-founded by Clark, Annis' old classmate.

AS&E, Riccardo Giacconi and Rossi with his 1962 rocket experiment discovered a bright celestial X-ray source located in the constellation of Scorpius that they called Sco X-1. This launched the field of extra-solar X-ray astronomy, and Clark's new research focus.

Cosmic X-ray photons with energies greater than 15 keV could penetrate to altitudes accessible by a helium-filled balloon, so he loaded an X-ray telescope with a scintillation detector onto a giant "skyhook" balloon in Texas. This effort located the first known cosmic X-ray source emitting X-ray energies greater than 15 kilovolts, in the Crab Nebula. The balloon program continued, with such notable measurements of a change in the X-ray flux from the source Cygnus X-1 and a flare in the flux from Sco X-1.

"Nobody really predicted that there should be detectable sources of X-rays out there," says Hale Bradt PhD '61, Professor of Physics Emeritus.

Clark pushed for an AS&E/NASA satellite X-ray observatory, launched under Giacconi's leadership in 1970 from Kenya as the *First Small Astronomy Satellite* (SAS-1), named *Uhuru* (Swahili for "freedom").

Clark was a principal investigator on the NASA *Seventh Orbiting Solar Observatory* (OSO-7) Satellite, MIT's first X-ray satellite experiment, which yielded an all-sky survey of X-ray sources, and on the *Third Small Astronomy Satellite* (SAS-3), which carried the first X-ray observatory that could point at a given source continuously for sustained periods.

Clark received the NASA Exceptional Scientific Achievement Award for his work as principal investigator of the Einstein Observatory Focal Plane Crystal Spectrometer, which used the technique of Bragg spectroscopy to perform high-resolution spectroscopic studies of cosmic X-ray sources in the 0.2–3 keV energy range, on the *Einstein X-Ray Observatory* satellite. Clark initiated the use of Bragg reflection for high-resolution X-ray spectroscopy with Claude Canizares, Bruno B. Rossi Distinguished Professor in Experimental Physics.

His push for a NASA mission became the *Rossi X-ray Timing Explorer* (RXTE), which would carry MIT's All-Sky Monitor.

As a member of the National Academy of Sciences decadal study (the "Field Report"), Clark helped chart the future of X-ray astronomy by prioritizing *Einstein's* successor, the *Advanced X-Ray Astrophysics Facility* (AXAF), also known as the *Chandra X-ray Observatory*. Clark used Chandra data to study the grain-scattered X-ray halos of accretion-powered binaries, and from the shape and size of a halo he tried to figure out the location and characteristics of the dust and the distance of the star.

"He helped chart the future of X-ray astronomy by prioritizing the *Chandra X-ray Observatory*," says MIT Kavli Institute director Robert Simcoe. "He played a major role in the discovery of celestial gamma-ray sources."

Earth-bound professor and coach

One day, Clark said to Canizares, "Did you ever think what we would be doing if we weren't being paid to have fun?"

When Clark hired Canizares in 1971, it was a period where most astrophysicists in the department were physicists learning astronomy as they went. Clark "took Bruno Rossi's original ideas and really was able to move them forward," says Canizares. "He really helped me throughout my career and did a lot to further the careers of his students and colleagues."

A member of the MIT Physics faculty for 44 years, Clark was appointed Instructor in 1952, Assistant Professor in 1954, Professor in 1965, and in 1985 the first Breene Kerr Professor of Physics, and was Astrophysics division chair from 1983–1988. In 1991, Clark received the MIT School of Science Teaching Prize for running the Junior Physics Laboratory, "Junior Lab."

After becoming a professor post-tenure in 1996, he continued to teach 8.13/8.14 (Junior Lab) until 1998, and mentored students until retiring in 2001. He published a major single-author paper based on *Chandra* data in 2018.

"My greatest satisfaction from sixty years of work in science is having participated in the start of several new areas of research in cosmic physics," Clark once said. "I'm astonished and delighted to see how those areas have developed and awed at the scale and complexity of the projects developed to support them."


Credit: Darren Stahlman Photography

Professor Emeritus Roman Jackiw, “giant of theoretical physics,” dies at 83

Over more than 50 years at MIT, he made fundamental contributions to quantum field theory and discovered topological and geometric phenomena.

by Sandi Miller

Eminent theoretical physicist and Dirac Medalist Roman Jackiw, MIT professor emeritus and holder of the Department of Physics’ Jerrold Zacharias chair, died June 14, 2023, at age 83. He was a member of the MIT physics community for 54 years.

A leader in the sophisticated use of quantum field theory to illuminate physical problems, his influential work on topology and anomalies in quantum field theory (QFT) underlies many aspects of theoretical physics today.

Iain Stewart, the MIT Center for Theoretical Physics (CTP) director and Otto (1939) and Jane Morningstar Professor of Science, says that Jackiw “served as an inspiration for what one can achieve as a theoretical physicist. He made profound contributions to physical problems in a wide range of areas, including particle physics, condensed matter physics and gravitational physics.”

“Professor Jackiw was a pioneer in the field of mathematical physics,” says Nergis Mavalvala, the Curtis and Kathleen Marble Professor of Astrophysics and dean of the MIT School of Science. “His imaginative use of quantum field theory shed light on physical problems, including his work on topological solitons, field theory at high temperatures, the existence of anomalies and the role of these anomalies in particle physics.”

Says Frank Wilczek, a CTP colleague who is the Herman Feshbach Professor of Physics and a 2004 Nobel Laureate, “Roman Jackiw had an uncanny knack for identifying ‘curiosities’ that have grown into fertile, vibrant areas of physics research. His seminal contributions to the theory of anomalies, the interplay of topology with quantum theory, and fractional quantum numbers are a rich legacy which has become central to both fundamental physics and modern quantum engineering.”

“He was a major, major figure in theoretical physics,” Wilczek said to his audience at a conference he attended a day after Jackiw’s death. “Roman was a pioneer in all these subjects, and advanced them greatly, before they became so popular.”

He is renowned for his many fundamental contributions and discoveries in quantum and classical field theories. Among his major achievements is the establishment of the presence of the famous Adler-Bell-Jackiw anomalies in quantum field theory, a discovery with far-reaching implications for the structure of the Standard Model of particle physics and all attempts to go beyond it.

Jackiw shared the Dirac Medal with Stephen Adler of Princeton University for their “celebrated triangle anomaly, one of the most profound examples of the relevance of quantum field theory to the real world,” says the citation from the International Centre for Theoretical Physics. "Jackiw made a major contribution to field theories relevant to condensed matter physics in his discovery (with Boston University's Claudio Rebbi) of fractional charge and spin in these theories." They received the medal in 1998 from the International Center for Theoretical Physics in Italy.

"Roman's style was rigorous and mathematically sophisticated, but not pedantic," says Robert L. Jaffe, the Otto (1939) and Jane Morningstar Professor of Science, Post-Tenure. "After his early groundbreaking work on the 'triangle anomaly,' Roman for many years focused on the application of topological methods in quantum field theory. Although Jackiw was not directly involved in the creation of the Standard Model, which revolutionized physics in the last third of the 20th century, the methods of analysis that Roman invented were often essential to its development."

Bolek Wyslouch, professor of physics and director of MIT's Laboratory for Nuclear Science, calls Jackiw "a towering figure in theoretical physics—one of the leaders that made MIT and the Center for Theoretical Physics world's first... His foundational work was instrumental in establishing the Standard Model of particle physics, one of the most successful theories in physics."

East European roots

Born Roman Volodymyr Yatskiv to a Ukrainian family in Poland, in 1939, his name was Romanized to Jackiw. The family eventually moved to Germany before settling in New York City when Jackiw was about 10. In New York, he was educated privately in Catholic schools, by the Xaverian Brothers (junior high) and the Christian Brothers (high school). "I became convinced I wanted to be a physicist after reading [George] Gamow's 'One Two Three... Infinity,'" recalled Jackiw. "He describes people doing things that sounded fascinating to me and I wanted to do them. It was actually an act of faith because I didn't get to do them until graduate school."

After graduating from Swarthmore College in 1961, where he majored in physics with minors in history of science and mathematics, he went to Cornell University, where he worked with professors Hans Bethe and Kenneth Wilson and received his PhD in 1966.

He had wanted to work with Bethe, but Bethe was doing nuclear physics while Jackiw was more interested in particle physics. However, Bethe asked him to co-author a textbook on quantum mechanics: "Intermediate Quantum Mechanics." The popular book, most recently revised in 2018, was for many years the basic introduction to the application of quantum mechanics to atomic physics.

From 1966 to 1969, he was a junior fellow at Harvard University. In his second year he went to CERN, working with John Bell. "I discussed current algebra a lot with him," Jackiw recalled, "and then we fell into the problem of the decay of the neutral pion into two photons, which was a puzzle at that time, and we studied the properties of the axial vector current and discovered the axial vector current anomaly, and wrote a paper, which is my most cited paper and also John Bell's most-cited *Particle Physics* paper, in fact."

At the time, theory seemed to predict that the neutral pion could not decay into two photons, but the decay had been observed in experiments. With the Bell-Jackiw-Adler anomaly, clarified later by Stephen Adler, they "were able to explain the observed decays theoretically by adding an 'anomalous' term resulting from the divergences of quantum field theory," according to an article in *Physics World*.

In his final year at Harvard, Jackiw had been working with other theorists at MIT. Physics professors Steven Weinberg and Sergio Fubini, together with physics department head Victor Weisskopf, helped to initiate Jackiw's long career as a professor at the Institute, which began in 1969. (He became an emeritus professor in 2013.)

In his first years at MIT, Jackiw and David Gross showed that cancellation of gauge anomalies implied an interesting connection between fermions in the Standard Model—in particular, that fermions in two classes, those which are strongly interacting and those which are not, have to appear the same number of times. Over the years this cancellation continued to suggest the existence of new fermions before they were observed.

An unusual kind of greatness

Jackiw had said he had two bodies of work. The first were "mathematical investigations which fit Dirac's criterion of beauty and have physical application because they are beautiful, like fractional charge phenomenon that I mentioned earlier, and like the anomaly phenomenon, like the Chern-Simons terms which I introduced with the help of [Stanley] Deser and students and later explored with So-Young Pi." Pi, currently a Boston University physics professor emerita, is a physicist who was a co-author on many of Jackiw's papers, and is Jackiw's widow.

"But on the other hand, I've also done kind of methodological investigations, which weren't necessarily original but applied existing schemes to new context. Like for example, figuring out how to do quantum field theory at finite temperature and relativistic quantum field theory at finite temperature, taking over what they do in condensed matter physics and non-relativistic quantum field theory approach to condensed matter physics at finite temperature."

Jackiw was known for working on mathematically intricate physics without an application in mind. "What I've always liked is to do work which seems obscure but interesting, and then decades later it catches on," he said.

"Roman Jackiw was a giant of theoretical physics, but of a somewhat unusual kind," recalls Daniel Harlow, the Jerrold R. Zacharias Career Development Associate Professor of Physics at the Center for Theoretical Physics. "He was rarely working on the same thing as others, and indeed if something he was doing started catching on then he would often turn to something else. And yet his ideas had a way of growing up—he would leave them lying around, and then a decade or two later everyone else would realize that he had really been on to something."

"His work on low-dimensional gravity from the 1980s has really taken off in the last five years," says Harlow. "His influence will be felt both here at MIT and around the world for generations."

David Kaiser, a physics professor and the Germeshausen Professor of the History of Science, says that, while working with a CTP doctoral candidate, "It seems like every other day we discover that Roman had first published on this-or-that piece of what we are trying to figure out, many years ago, in greater generality and with far more elegance than we had ever aspired to. He and his work remain a major inspiration for us."

Indeed, besides Jackiw's celebrated work on anomalies, other important examples of his contributions include providing the first example of charge and spin fractionalization with solitons; elucidating the periodic vacuum structure of the non-abelian gauge theories that form the core of the Standard Model of particle physics; launching the use of quantum field theory for the rigorous study of systems at finite temperature; and determining the nature of Chern-Simons terms for both gauge and gravitational theories.

This broad range of research influenced countless others. "To get an appreciation of Roman's impact on theoretical and mathematical physics, one need only look at how often people refer to him by name in their papers, for example, 'Adler-Bell-Jackiw anomalies,' 'Jackiw-Teitelboim gravity,' 'Fadeev-Jackiw quantization,' the 'Jackiw-Nohl-Ressen ansatz,' and the 'Jackiw-Rossi' model," says Stewart.

Roman had over 30 PhD students, including Estia Eichten (Cornell), Joseph Lykken (Fermilab), and Andrew Strominger (Harvard); he was "a very successful mentor to generations of PhD students who formed a 'school' of theoretical physics focused on the use of sophisticated mathematical methods to explore the physical content of quantum field theories," recalls Jaffe.

Other awards and honors

Jackiw's numerous awards and honors included an Alfred P. Sloan Research Fellowship and John Simon Guggenheim Memorial Fellowship; the Dannie Heineman Prize for Mathematical Physics from the American Physical Society; and the Bonnor Essay Prize from Queen Mary University of London. He was a member of the American Academy of Arts and Sciences, the American Physical Society, the National Academy of Sciences, and a foreign member of the Ukrainian National Academy of Sciences. Honorary doctorates were awarded by Turin University; Uppsala University; the Kyiv Bogolyubov Institute; and Montréal University.

"I have immense respect for his legacy and achievement, and greatly appreciate the doors he has opened for the rest of us," says Stewart.

Alumni Notes

'51

Josef Eisinger (PhD) did his graduate research in Jerrold Zacharias' atomic beam lab in the now-vanished Building 20. He lives with his wife, cellist and Brahms scholar Styra Avins, in Greenwich Village, NY. A collection of Eisinger's essays and art work was published in 2023, *Glimpses. A Sundry Life.*

'57

Paul H. Carr (SB; SM '61; PhD '66, Brandeis University. Thesis advisors: David Frisch, Woody Strandberg) recently gave a talk, "Can Green Technology Save Us from Climate Change in Time?" at the Academy of Senior Professionals at Eckerd College, Florida.

Edward A. Friedman (SB; PhD '63, Columbia University) is an Emeritus Professor of Technology Management, Stevens Institute of Technology. In February 2023 he was a featured speaker, via Zoom, for the Energy Dissected Conference in Bulgaria, highlighting energy issues of significance for the country. Ed spoke on the potential for the use of small modular nuclear reactors. In April 2023, the *New York Times* published Ed's letter, "Grappling with Artificial Intelligence," wherein he suggested the National Science Foundation establish a new division devoted to "Safe AI."

'58

Joel Rogers (SB) completed his paper, "Ontology of Space-Time Following Quantum Theory and Relativity Constraints," dedicated to the memory of Herman Feshbach. The paper modifies the Copenhagen formulation of quantum mechanics and the version of the classical R^4 that emerges from quantum fluctuations in the emission/absorption of gravitons between pockets of positive mass/energy in the universe, and discusses their ubiquity. A detailed abstract and a copy of the paper are available from Joel at *jcwrogers@optonline.net*.

'59

William A. "Bill" Cramer (SB. Thesis advisor: W. Kraushaar) retired last year as Distinguished Professor of Biological Sciences, Purdue University (1978-2022). In 2021 he authored publications on structure/function of photosynthetic cytochrome electron transport proteins and bacterial cytotoxin, "colicin." His recent lectures included the American Chemical Society Symposium, *History of Cytochrome c*; Structure-Function of the Cytochrome b_6f Complex; as well as the conference on Photosynthetic Electron Transport (Kyoto, Japan).

'61

Lloyd C. Kannenberg (SB) is translating articles by Marian Smoluchowski, most recently, "The concept of chance and the origin of the limits of probability in physics," *Naturwissenschaften* 6, H. 17, 253-263 (1918). Next up is, "Irregularities of the distribution of molecules in gases and their influence on entropy and the equation of state," *Boltzmann-Festschrift*, 626-641 (1904). It is Smoluchowski's anti-Zermelo contribution to the Boltzmann-Zermelo debate.

Stephen Salomon (SB. Thesis advisor: Wayne B. Nottingham) says his contribution to physics is indirect, via counseling his daughter Rachel, who continues promoting better relations between Azerbaijan and Israel. Stephen used Landau's theory of quantum liquids at Purdue University before leaving for Siberia in 1969 under the auspices of the Academy of Sciences. Stephen passed on to his daughter stories about Landau, learned from John Bardeen, who was Landau's good friend.

Robert A. Saunders (SB. Thesis advisor: Jack Dennis) amused himself during the pandemic by writing a book, *Knowledge: What can we know, and how can we know that we know it?* The book describes the scientific method based on Karl Popper's thesis about the necessity of refutability for any proposition to be considered to be valid. (Bob proved that Popper was correct).

In 2018, the MIT Lemelson Center hosted a conference to create an oral history of "Spacewar," the first video game, for which Bob designed and built the controllers. All of the living perpetrators of the game and other interesting software for the PDP-1 computer attended. More information is available on Wikipedia.

Homer Schaaf (SB. Thesis advisor: Melville Clark) continues to work as counsel to Norton Rose Fulbright, while living in NYC's Central Park West and going out to jazz clubs. He and his daughter Katie received lifetime achievement awards in 2022: hers from her equestrian group, and Homer's from the Municipal Forum of NY.

Malvin Carl Teich (SB. Thesis advisor: Theos J. Thompson) is a Professor Emeritus at Columbia University and Boston University, and completed the manuscript for his most recent textbook, *LED Lighting: Devices and Colorimetry*. Prior textbooks include *Fundamentals of Photonics* (3rd edition) and *Fractal-Based Point Processes*. Malvin's recent research interests in physics are in quantum photonics, particularly the properties and applications of entangled-photon pairs. In computational neuroscience, his efforts have centered on the fractal behavior of neurotransmitter exocytosis and optic-nerve-fiber action potentials, as well as on heart-rate variability. Malvin is currently working on a new book in detection theory in hearing and vision.

'63

Jeffrey Linsky (SB) evaluated the properties of interstellar gas in the local region of our Galaxy. His studies of the chemical composition, ionization and kinematics of interstellar gas are based on ultraviolet spectra obtained with the Hubble Space Telescope and *in situ* measurements with the Voyager spacecraft. He finds the local interstellar medium consists of overlapping clouds identified by their kinematic structure. Recent results consist of the highly inhomogeneous nature of these clouds and the total pressure balance between the heliosphere, the local interstellar medium and the gravitational force of the Galaxy.

'63

Wallace Manheimer (SB; PhD '67. Thesis advisor/supervisor: Uno Ingard, Thomas Dupree) This past year, Wallace continued his efforts as a "snake at the garden party." He is authoring a short book, *Mass delusions, how they harm sustainable energy, climate policy, fusion and fusion breeding*. It doubts there is a climate crisis and doubts that solar and wind are viable power sources. Lastly, it makes the case that fusion breeding could be a valuable outcome for the controlled fusion project. The book is due to be published by Generis by summer 2023.

'64

Chuck Tyler (SB. Thesis advisor: Henry Kendall) recently returned from travels to the Amazon River, Machu Picchu and Galapagos, as well as the Nile River. He is busy fly fishing locally, running ranch game cameras and angel venture capital. Chuck lives in Sunnyvale, CA.

Robert J. Weggel (SB. Thesis advisor: Bruce Montgomery) joined the ranks of octogenarians in March 2023, outliving both his parents by more than twenty years. Miraculously spared major mental senility and physical decrepitude, he continues his lifelong career in magnet design, summits Colorado fourteeners, and at his Casco Bay summer home builds (single-handedly or with his mirror twin Carl) soil-retention walls with boulders as huge as half-a-ton.

'67

Charles MacFarland (SB) lives in Australia, and enjoyed a wonderful trip to visit Pedro in Mallorca, Danny in the Czech Republic, Mathias in Berlin, as well as two weeks on Naxos with Dominika. These are all friends he made through *couchsurfing.com*, a great site for international friendship.

'68

Michael Riordan (SB; PhD '73. Thesis supervisor: Jerome Friedman) has been working with publisher W.W. Norton to bring out an electronic edition of his book, *Crystal Fire*, co-authored with Lillian Hoddeson, in Spring of 2023. Widely identified as the definitive history of the transistor's invention and development, this book has remained in print for over 25 years since its initial 1997 publication.

'69

Robert Markey (SB) is an artist (*robertmarkey.com*). This past year he created a "Peace Song Art" installation, with each painting and sculpture based on a peace song, mostly from the '60s, but which he feels are relevant now. Robert also creates mosaic mural projects in different countries with at-risk children: orphans, street kids, and others. This year's mural took place in Boca, Mexico; this winter 2023–24, he will be in Sri Lanka. Robert has illustrated a number of children's books, as well, with another planned for later this year.

'71

Andrew J. Hanson (PhD. Thesis supervisor: Kerson Huang) In 2017, Andrew contributed both a memoir and a chapter on the isometric embedding of the 1978 Eguchi-Hanson gravitational instanton to *World Scientific*'s "Memorial Volume for Kerson Huang." In 2020, he published a review, "The Quaternion-Based Spatial-Coordinate and Orientation-Frame Alignment Problems," in *Acta Crystallographica*, following up on topics from his 2006 book, *Visualizing Quaternions*. In 2022, Andrew's first grandchild was born, and in April 2023, he unveiled his four-foot, 1,000 lb. steel Calabi-Yau space quintic sculpture at his alma mater, Indiana University. His next book, *Visualizing More Quaternions*, will be published in December 2023. Altogether, Andrew is keeping himself busy during his 80th year, his 11th year of being not-exactly retired!

Jim Mannoia (SB) is pushing the 74-year-old mark and retired now for 15 years. Life is full of non-profit boards, exercise either at the gym or walking 30 miles a week, and as much travel as time and money permit. His board duties include universities (Burundi and India), an environmental group, helping out interviewing MIT applicants, and running his HOA board. (That last one makes his former work as a university provost and president seem tame by comparison!) Recent travels took him and his wife to Central Europe, Zimbabwe, South Africa, Peru and the Amazon. This year included trips to the Mexican Baja and Paris, with plans for an extended time in France and Italy. Jim and his wife are doing their best to take the advice that in old age they must just keep on moving!

Sekazi Mtingwa (SB. Thesis advisor: Victor Weisskopf) received the 2023 Philip Hauge Abelson Prize of the American Association for the Advancement of Science for his many contributions to the US scientific community, including co-developing the theory of intrabeam scattering that is foundational to particle accelerator research; co-founding the National Societies of Black and Hispanic Physicists; and helping to rejuvenate university nuclear science and engineering programs by chairing a 2008 American Physical Society study on the readiness of the US nuclear workforce. The latter played a key role in the US Department of Energy allocating 20% of its nuclear fuel cycle R&D budget to university programs.

'72

Maury Goodman (SB) is a neutrino physicist at Argonne Lab and continues the 32nd year of his monthly, free electronic "Long-Baseline Neutrino Oscillation Newsletter." The Deep Underground Neutrino Experiment (DUNE) will soon be the flagship program of particle physics in the United States. Those interested are welcome to subscribe at *hep.anl.gov/ndk/longbnews/* or by emailing Maury at *maury.goodman@anl.gov*.

Charlie Smith (SB. Thesis advisor: Gene Stanley) and his wife are looking forward to spending five months at Osaka University's School of Engineering Science on a Fulbright research/teaching award, starting in September 2023.

'74

William Ladd (SB; SM '76; MD, Tufts University. Thesis supervisor: Lee Grodzins) retired in July 2023 from teaching and practicing diagnostic radiology at UC-San Diego Medical Centers, and plans to work intermittently thereafter. Bill remains a co-founder and part owner of a veterinary radiology business with global clientele. His wife of 47 years recently retired after a career involving biotech startups and a French wine import business. The Ladds currently plan to travel more often. Bill has kept in touch with a few Kappa Sigma fraternity brothers, and attended the April 2023 Patrons of Physics dinner, along with his almost 93-year-old thesis advisor and mentor, Lee Grodzins.

Saeqa Dil Vrtilek (SB. Thesis advisor: Philip Morrison) recently published his book, *New Windows on the Universe: Advances in Multimessenger Astronomy* (Institute of Physics Publishing, November 2022). The book was written for anyone interested in an overview of multimessenger astronomy and provides a good overview of the multiple paths through which we gain physical information about the universe and relates some of the most important contemporary results.

'75

G. P. Yeh (SB; PhD '85. Thesis advisors/supervisors: Jerome Friedman, Robert Jaffe, E. M. Riordan, Frank Taylor) started working on particle therapies in 2003, thanks to particle physics and the important pioneering work at Fermilab for proton therapy and neutron therapy. G. P. leads an international team that has developed and is building accelerator boron neutron therapy (BNCT) for clinical use. BNCT, targeting cancer cells, has been effective in treating patients with glioblastoma and other difficult and/or late-stage cancers. Ninety percent of patients have needed only one BNCT treatment session.

'76

David G. Stork (SB; PhD, University of Maryland) was invited to present his computer image analyses of paintings by Johannes Vermeer at the International Vermeer Symposium at the Rijksmuseum in March 2023, the world's largest exhibition of this master's works. He continues to teach this material in several departments at Stanford University.

'77

Alberto C. Sadun (SB; PhD '84. Thesis supervisor: Philip Morrison) is providing optical support to high energy TeV observations of blazars, which are active galactic nuclei with jets pointed in our direction. Optical photons are Compton boosted to high energy due to their interaction with ambient highly relativistic electrons. The optical observations are made by way of an automated system of data acquisition and reduction. The TeV observations are made with satellites and ground-based Cherenkov telescopes. By connecting both energy regimes, a complete spectrum of the blazar outburst can be analyzed and understood.

'80

Namir Kassim (SB) is an astronomer at the Naval Research Laboratory. This past June 2023, his group participated in the annual Astronomy Festival on the National Mall in Washington, DC, hosted by Hofstra University.

John A. Serri (PhD. Thesis advisor: David Pritchard) is CEO of EyeQue, a Silicon Valley-based company he founded in 2015. The company provides a variety of smartphone-based vision tests to measure various conditions of the eye, including refractive error. It recently expanded to offer a "one-stop shop" solution: vision testing at home, a prescription via telemedicine and home testing, and offering a variety of high-quality eyeglasses available online. In his spare time, John grows tomatoes, exercises and watches a lot of YouTube videos!

'82

Zvi Bern (SB, *Physics*; *Mathematics*) is director of the Mani L. Bhaumik Institute for Theoretical Physics at UCLA. He was one of three co-winners of the 2023 Galileo Galilei Medal Award of the INFN for the development of powerful methods for high-order perturbative calculations in quantum field theory.

'83

Steven Janowsky (SB, *Physics*; *Mathematics*. Thesis advisor: Michael Sipser) After 25+ years in financial software and the last ten at Bloomberg LP, Steven has put aside his keyboard and retired. He's looking forward to visiting Cambridge for his 40th reunion.

'84

David Thayer (PhD. Thesis supervisor: Kim Molvig) retired in 2022, after an initial 20 years in physics research at UT-Austin, LBNL and SAIC, thereafter joining the faculty of the University of Wyoming in 2000. There, he focused on high quality physics instruction and continuing a variety of research endeavors. In 2019, David published a best-selling quantum mechanics textbook, *Modern Introductory Quantum Mechanics with Interpretation*. Post-retirement he published a physics book, *Universe in a Nutshell: Fundamentally Oscillatory at All Scales*.

'85

Nuri Dagdeviren (PhD. Thesis supervisor: Arthur Kerman) continues at Microchip Technology in San Jose, CA, as Corporate Vice President responsible for secure computing products.

'90

Priyamvada Natarajan (SB. Thesis advisor: Alan Guth) is an astrophysicist on the faculty at Yale University, continuing her work on mapping dark matter to trace the formation and growth of black holes in the universe. She was appointed the inaugural Joseph S. and Sophia S. Fruton Professor of Astronomy and Physics and currently serves as Chair of the Department of Astronomy.

'92

Cameron Miner (SB. Thesis advisor: Bruno Coppi) has had a busy year. After leaving Meta Reality Labs, he rejoined his video startup, Fleye, which has secured a licensing deal with Surfline to install cameras and RF tracking at premier surfparks around the world. This project required Cameron to invent a new, long-range UHF RFID wristband, but now the company is exploring other applications for the technology, such as water parks, running events and healthcare.

'94

David S. Hales (SB. Thesis advisor: Richard Yamamoto) was honored last year to accept the role of CEO of Global Innovations Bank. He is leading a team in expanding strategic partnerships that are part of the Fintech revolution, transforming the scope and nature of financial and banking services offered to consumers in the US, Asia, Europe and Africa.

'02

Yang-Hui He (PhD. Thesis supervisor: Amihay Hanany) is a mathematical physicist and professor jointly amongst the London Institute for Mathematical Sciences, Oxford University and the University of London. He remembers his time at MIT fondly, especially the great mentorship from Amihay Hanany. Yang's highlight of 2022 was being the invited lecturer for the Friday Evening Discourse at the Royal Institution of Great Britain. A public lecture series initiated by Michael Faraday in 1825, it has been a UK tradition ever since. Yang was humbled and excited, as past speakers included scientists such as Rutherford and the Curies. It was also the first time Yang had to deliver a lecture in a tux! He had a lot of fun telling the story of how geometry laid the foundations of physics.

'03

Alex Wissner-Gross (SB, *Physics*; *Electrical Science & Engineering*; *Mathematics*. Thesis advisor: Bolek Wyslouch) has now incubated and participated in more than 33 startup ventures in a variety of sectors, with an aggregate public and private market valuation of over $950 million. To learn more, visit *alexwg.org*.

’05

Marc Fernandes (SB) After nine years with Koch Industries, Marc started a new position as energy trader at Antimo LLC, where he has replaced business casual attire with athletic shorts and hoodies. His daughter, now 2.5 years old, identifies as Luke Skywalker to his Vader.

’08

J. Colin Hill (SB, *Physics*; *Mathematics*. Thesis advisors: Claude Canizares, Kenneth Rines) Together with colleagues from Columbia, NYU and IAS, Colin received first prize in the Buchalter Cosmology Prize competition in January 2023 for their paper, “Squeezing f_NL out of the matter bispectrum with consistency relations.” Colin is an assistant professor of physics at Columbia, leading a research group in physical cosmology primarily focused on data analysis for the Atacama Cosmology Telescope and the Simons Observatory, two major experiments mapping the cosmic microwave background from northern Chile.

’12

Leo C. Stein (PhD. Thesis advisor: Scott Hughes) was awarded a 2023 Sloan Research Fellowship. He is currently an assistant professor of physics and astronomy at the University of Mississippi, and the first faculty member at UMiss to receive a Sloan Fellowship. Leo’s research focus is simulating and modeling binary black hole mergers in general relativity (GR), as well as theories beyond GR, to be tested with gravitational waves detected by LIGO/Virgo/KAGRA.

’14

Natalia Guerrero (SB. Thesis advisor: Peter Dourmashkin) earned her MS in astronomy at the University of Florida in Spring 2023. She continues on the astronomy PhD track, studying exoplanet demographics and dynamics with advisor Sarah Ballard.

’15

Will Yashar (SB) is a fifth-year MD/PhD student at the Oregon Health & Science University. His thesis research, “Disruption of the MYC Super-Enhancer Complex by Dual Targeting of FLT3 and LSD1 in Acute Myeloid Leukemia,” was published this year in *Molecular Cancer Research*. Will and his group also finished the development of a computational algorithm, “Priori,” and he won an award for a poster presentation at a local conference describing it. Priori is publicly available for researchers to use. Abstracts for Priori were also accepted for oral and poster presentations at the international computational biology conference, RECOMB, in April 2023.

’20

Ji Seok Kim (SB. Research advisor: Nikta Fakhri) spent the last two years teaching high school AP physics at his alma mater, Phillips Academy, Andover. This fall 2023 he begins medical school. Ji fondly remembers learning about waves in Wolfgang Ketterle’s classroom; working in Nikta Fakhri’s biophysics lab with graduate mentors Tzer Han Tan and Sebastian Coupe; and playing on the MIT Squash Team.

’21

Yunjie Yang (PhD. Thesis supervisor: Michael Williams) After earning his PhD, Yunjie accepted a Postdoctoral Research Fellowship at the New York Proton Center, where he studied and published on various topics related to the novel ultra-high dose rate (FLASH) proton radiotherapy. In early 2023, he joined the Medical Physics Residency Program at the Memorial Sloan Kettering Cancer Center, where he will train to become a clinical medical physicist.

’22

Kylie Yui Dan (SB) is currently in Japan on a Fulbright Fellowship, working with Hanae Inami at Hiroshima University. His research is focused upon NGC1275, a Seyfert galaxy. Kyle has IFU data from the Keck Telescope, which he has been analyzing for the past few months.

Patrons of Physics Fellows Society

Graduate fellowship recipients share their stories at the Society's 18th anniversary dinner.

by Danielle Forde

Gefen Baranes *is a first-year graduate student and recipient of the Peskoff Fellowship. Gefen received her BSc in Physics and Electrical Engineering from the Technion–Israel Institute of Technology, and is now working with Vladan Vuletić, Lester Wolfe Professor of Physics.*

"My name is Gefen Baranes and I grew up in Israel. My parents are first-generation Israelis. Their parents immigrated from Iraq and had to begin their life from scratch. Education could not have been a priority. Instead, with hard work and persistence, they built a successful woodwork factory. Growing up, I remember them leaving the house before dawn and returning after I fell asleep. They taught me the importance of devotion and perseverance, and encouraged my drive to excel. I am the first generation in my family to go to university.

Doing army service in Israel gave me the opportunity to meet, lead and be a part of big projects. At 19 years old, I was privileged to be an officer in the Israel Defense Forces' intelligence corps. Commanding requires an understanding of each person's needs and abilities. I strived to be a good model, motivating others and helping them fulfill their ambitions.

The love of teaching has been threaded throughout my life. I started tutoring my classmates and younger students when I was nine. I taught numerous students during elementary and high school. In addition, during my army service, I initiated a program where soldiers taught math and physics in underprivileged schools. At the same time, I advanced a set of lectures introducing physics to soldiers, friends, family and Holocaust survivors. I am still giving these lectures and very excited every time. Last month I taught more than 100 elementary school kids about quantum physics, and it was very exciting to give my first lectures as an MIT student. I envisage teaching as an essential part of my career in the future, alongside research.

I was the only female in the room in all my advanced math classes, high school physics and 'gifted children' programs. Out of the electrical engineering students at the Technion, less than 10% are female. Due to these statistics, I work to advance equitable access to higher education for women. I reached out to the nonprofit organization, Shavot, which equips girls with tools that will aid them to reach their full potential, and over time minimize gender inequality. In Shavot, I deliver physics lectures voluntarily and share my personal story as a woman in science. I believe that STEM fields must be accessible regardless of social barriers, gender or background. Therefore, along with my goals as a quantum physicist, I also plan to foster women in science.

All photos in this section: Justin Knight Photography


(FROM LEFT) Frank Fellow Wenjie Gong, Alex Hastings and Tom Frank '77 (VIII), PhD '85 (VIII).

I want to thank the Peskoffs sincerely for their generosity in sponsoring my fellowship. The fellowship has given me the security I needed while moving to a new country with my husband and starting my new way at MIT. I was very confused at the beginning, didn't know whether I should work on experiment or theory, and didn't know if I wanted to focus more on atomic, molecular and optical physics (AMO) or quantum information (QI). This fellowship allows me to collaborate with many researchers without worrying about my funding. I feel grateful and lucky to use the fellowship to find my unique place at the Physics Department and understand what I truly aspire to be.

As a physicist at MIT, I want to combine two different fields– AMO and QI. Also, I want to build a strong bridge between theory and experiment. With these capabilities, I envision new theoretical applicable ideas for exciting experiments that will advance our knowledge and even create new quantum technologies. I am proud to be a part of the MIT Physics Department and believe that my fellowship provides me the flexibility to fulfill my dream. For this I want to thank you again, because this fellowship inspires me to be a better version of myself and allow me to chase my dreams without worrying about my funding."

Dasol Kim *is a first-year graduate student and recipient of a Whiteman Fellowship.*

"I would like to express my deepest gratitude for the generous support from the Whiteman Fellowship in funding my graduate studies in MIT's Physics Department. Your support has given me the opportunity to pursue my passion for research on cutting-edge topics in the field of two-dimensional materials, without financial concerns. I am truly grateful for your contribution, which has made a significant impact on my academic journey.

My parents were both blue-collar workers living in a remote rural area where education was not emphasized. Neither of them had a college degree. Growing up in this environment made it difficult for me to think about higher education opportunities. However, with the help of a teacher in middle school, I was able to enter a science high school and receive an education that allowed me to develop my abilities and become the first person in my family to attend university. Multiple sources of financial support were critical in enabling me to continue my studies, and this experience taught me the importance of social environment and financial support in facilitating individual development.

During my undergraduate years, I worked as a research assistant at the Ultrafast Quantum Photonics Laboratory at Seoul National University, where I became fascinated by the physics of 2D materials. As a result, I started my physics PhD program at MIT in Fall 2022, and joined the group of Assistant Professor of Physics Long Ju to investigate the light-matter interaction in 2D materials.

I am now a first-year grad student at MIT Physics, supported by a Whiteman

Fellowship. Over the past few months, I have learned FTIR photocurrent spectroscopy and the attitude required for conducting research. During my PhD program, I aspire to probe the exotic properties of 2D materials and develop novel optical spectroscopy techniques to explore more exotic quantum phenomena. I believe these studies can help the understanding of strongly correlated phenomena, which could have a significant impact on the future of condensed matter physics. The potential applications of the above studies are attractive as well. For instance, I am eager to contribute to the field of applied sciences, including computing, quantum sensing and imaging. Ultimately, I would like to advance the field of condensed matter physics by discovering novel phenomena in quantum materials.

Your generosity has not only provided me with the financial means to pursue my passion for research but also the opportunity to explore the world of physics and make meaningful contributions to the field. Without your support, it would be difficult to pursue my interests in experimental condensed matter physics. I am grateful for the doors you have opened for me, and I will always remember your kindness and support.

Once again, thank you for making a difference in my life and helping me achieve my academic goals. Your contribution is deeply appreciated and I look forward to the day when I can pay it forward and help aspiring students like myself realize their dreams."

Wenjie Gong *is a first-year graduate student and recipient of the Frank Fellowship.*

"I'm Wenjie, a first-year graduate student in MIT's Physics Department supported by the Frank Fellowship. I grew up in Orlando, Florida, and I completed my undergraduate degree in physics and mathematics at Harvard. Ever since my first AP Physics class in high school, I've been enraptured by the subject, and that interest has led me to the physics graduate program here at MIT.

I work in the field of quantum information, with emphasis on quantum simulation of physical phenomena on near-term technology. Specifically, I am currently working on methods for the robust implementation of single-qubit unitaries and Hamiltonian engineering in experimental platforms such as Rydberg atom arrays. During my PhD, I hope to contribute to building scalable, robust quantum hardware for widespread usage. I am incredibly grateful for your generous contribution, which has allowed me greater freedom in exploring my interests early on in my program. Thank you so much for your support!"

Gianni La Vecchia *is a second-year graduate student and this year a recipient of the Whiteman Fellowship. Last year, he held a Frank Fellowship.*

"I want to personally thank you for making my education possible. Your generosity, and others like you, are what let disadvantaged students like me pursue our dreams and develop our potential for the betterment of society. To show you the kind of students you are supporting, let me tell you a little bit about myself and my work.

I was born in Miami to an immigrant Hispanic family, who focused on having a strong work ethic and a passion for service. My parents both passed away when I was 18, leaving me in charge of my younger brother and with an uncertain future. Through kindhearted donors like you, however, I was able to attend the University of Chicago to pursue my deep interest in physics, while also making enough to support my brother back home until he, too, obtained a full academic scholarship to UPenn. It has always been my dream to study physics, specifically the mysteries of the universe and cosmology.

Thanks to your compassion and generosity, I am now able to fulfill my dream here at MIT.

The work you are supporting is one of the most unique and groundbreaking experiments in physics: the AMS (Alpha Magnetic Spectrometer). Located on the International Space Station, it is a one-of-a-kind mass spectrometer that is capable of collecting data on cosmic rays, which are particles coming in from all over the universe. The AMS is the only mass spectrometer in space, and will be the only one with that distinction for some time with the upcoming retirement of the International Space Station. Through the AMS, we are making theory-defining measurements and collecting data that could solve mysteries in dark matter, anti-matter and the origins of the universe. My work specifically is to study the data for fractionally charged particles, which are previously unobserved particles that, if found, would revolutionize our understanding of particle physics.

I want to stress how truly grateful I am for you to be supporting me. I, and many others like me, owe everything they have to donors like you."

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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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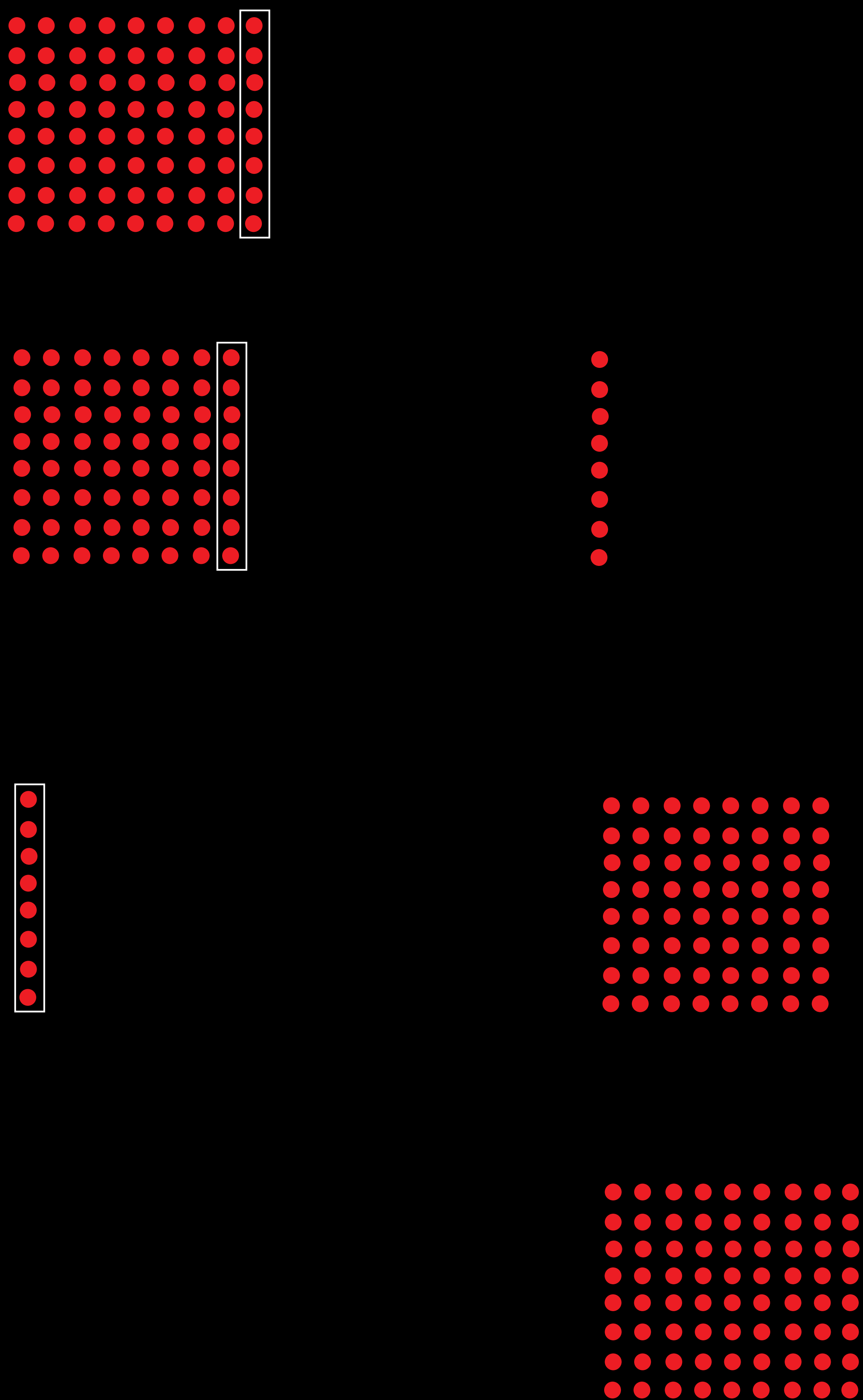

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