ABRACADABRA

Listening for Dark Matter

by Lindley Winslow and Jesse Thaler

Looking out into the night sky, it is humbling to contemplate the vastness of the universe. Yet the twinkling of those stars—both in our Milky Way and in distant galaxies—represent only a small fraction of the universe's mass. Even including plumes of interstellar gas, ordinary matter can only account for around 15% of the matter in the universe. The other 85% is dark matter, completely invisible to our eyes but firmly established scientifically through its gravitational influence.

WHAT IS DARK MATTER? Fundamentally, we simply do not know. We can infer its existence from the dynamics of galaxies, from its fingerprint on cosmic radiation, and from the way it bends light from ancient objects. We know how much dark matter there is now, how much there was in the early universe, and even roughly how fast it moves. We also know that dark

from the Basement of Bldg. 24

FIGURE 1

***The ABRACADABRA-10cm experiment** installed and ready to take data in its dilution refrigerator in MIT's Building 24.*

matter formed a kind of gravitational scaffolding that allowed galaxies like our Milky Way to take shape. In that sense, we owe our very existence to this strange invisible substance.

But we do not yet know what it *is*. This uncertainty surrounding dark matter—along with null results from previous searches—has led to an explosion of new detection proposals in recent years, some more realistic than others. It has also led to an equally large explosion of new theories for dark matter, some more well-motivated than others. To crack this enigma will require scientific ingenuity, collaboration and, above all, perseverance.

While we cannot see dark matter, perhaps we could "hear" it. Dark matter is all around us, even on Earth. If dark matter behaves like a coherent quantum wave, then we might be able to tune in to the right frequency and eavesdrop on the invisible. Since previous searches have not yet turned up any evidence for dark matter, we know that we will have to listen very carefully. And if we succeed, we might find the solution not only to the mystery of dark matter but also to a longstanding puzzle about ordinary matter.

This is the backdrop for the ABRACADABRA experiment (*Figure 1*) and the search for AXION DARK MATTER. It is the story of what happens when a team of MIT theorists and experimentalists becomes convinced that its experiment is just crazy enough to work, and the physics is compelling enough to try.

Theory: making the case for axions

Jesse Thaler's office is on the third floor of Building 6, in the MIT Center for Theoretical Physics (CTP). Like many of his theoretical colleagues around the world, he strongly suspects that dark matter is a type of particle (or maybe a bunch of particles) that we have not yet detected. There is good historical precedent for invoking new particles to solve mysteries in physics, such as the neutrino postulated in the 1930s (and discovered in the 1950s) to explain a puzzling energy imbalance in radioactive decays. While there is still a chance that dark matter could be something more exotic—like primordial black holes or a modification of gravity—all current astrophysical and cosmological probes are consistent with dark matter being made up of particles.

If dark matter is a particle, what is its mass? We simply do not know. For many years, most experimental and theoretical studies were focused on dark matter masses around 10 to 1,000 times heavier than a proton, also known as WIMPs (Weakly Interacting Massive Particles). Not coincidentally, this is comparable to the mass of the Higgs boson (around 130 times the proton mass), since WIMPs often arise in theoretical proposals to explain why the Higgs mass is what it is. WIMPs would behave like microscopic billiard balls, floating around the universe via gravity alone. They would be very dilute; on Earth, a small cardboard box would contain only one WIMP particle. While WIMPs may be the answer to the mystery of dark matter, no WIMPs have been detected to date, either in deep underground detectors, or at accelerators like the Large Hadron Collider, or through astrophysical observations.

What if dark matter were significantly lighter? This is the idea behind axion dark matter, whose mass could be more than a quadrillion times lighter than a proton. Comparing a WIMP to an elephant, an axion would have the mass of a single cell (or even a virus). Because the mass density of dark matter is fixed by gravitational observations, axion dark matter would need to be far less dilute than WIMPs. For example, a small cardboard box could contain the same number of axions as air molecules. Moreover, lighter particles experience larger quantum effects, implying that an axion's quantum wave function would extend well beyond the cardboard box. Instead of behaving like billiard balls, axions would behave like a quantum coherent cosmic ocean, undulating with a frequency proportional to the axion's mass.

The basic idea behind axion dark matter is not new, with a history that goes back four decades. Axions were originally proposed in the late 1970s to solve a puzzle—the strong CP problem [1]—relating to the electromagnetic properties of the neutron in quantum chromodynamics (QCD). In the early 1980s it was realized that axions would be produced in the early universe, behaving exactly like dark matter. Because of the axion's role in solving the strong CP problem, one could search for axion dark matter with a sensitive electromagnetic device, tuned to the precise frequency of the axion wave. This is how the Axion Dark Matter eXperiment (ADMX) works, which for many years was the only major experiment of its type.

The new idea—proposed by Thaler together with former MIT graduate student Yoni Kahn and then Pappalardo Fellow Ben Safdi—was to broaden (literally) the search for axions. Since we do not know the mass of the axion and therefore the right frequency, instead of listening to one candidate axion frequency at a time, one would listen to as many frequencies as one could at once. It would be like listening to all FM radio stations, all AM radio stations, and an orchestra at the same time, trying to find the one axion needle in a cacophonous haystack. A proposed detector design took shape on the blackboards of the CTP, as did a proposed acronym if such an experiment were ever built: ABRACADABRA for "A Broadband or Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus." At least on paper, this new way to search for axion dark matter seemed to work, and it was published in *Physical Review Letters* in September 2016. Now was the time to put theory into practice.

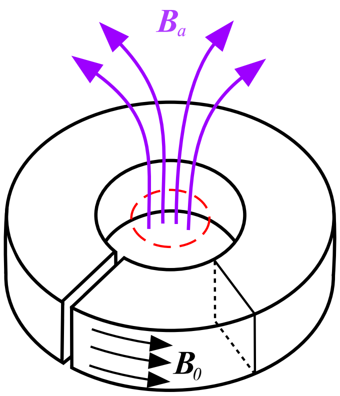


FIGURE 2

***In the conceptual design** of the ABRACADABRA experiment, the axion couples to the magnetic field of a toroidal magnet, inducing a magnetic field through the bore where classically there should be none.*

Construction: from the blackboard to Building 24

Lindley Winslow's office is on fifth floor of Building 26, in the MIT Laboratory for Nuclear Science. A major component of her research involves the study of very rare processes involving neutrinos, so she is used to searching for faint signals using large, exquisitely sensitive detectors.

The ABRACADABRA concept (*Figure 2*) is based on a toroidal, or donut-shaped, magnet. As the dark matter axion wave passes through the magnet, it induces a secondary magnetic field through the bore of the toroid. Continuing the donut analogy, the bore is where the donut hole would be. As any *Physics 8.02: Electricity and Magnetism* student can tell you, a perfect toroidal magnet has no magnetic field in the bore, so finding a magnetic field there would be a candidate signal for axion dark matter. To detect this faint axion-induced signal, one would insert a pickup loop inside the bore, connected to a sensitive current sensor like a superconducting quantum interference device (SQUID).

As any *Physics 8.13: Junior Lab* student can tell you, no experiment is perfect, so we would have to contend with various sources of noise. A key requirement for making ABRACADABRA work was putting it someplace very cold and therefore quiet. Luckily, the Winslow Lab (in the basement of Building 24) already had a dilution refrigerator capable of cooling down to an astonishing 10 millikelvin (mK). This extreme temperature forces various components to go superconducting, slowing the motion of electrons within the apparatus to reduce noisy stray magnetic fields. So we were going to search for axion dark matter with some SQUIDs and a frozen donut hanging from a bullet-proof thread. (More on that later.)

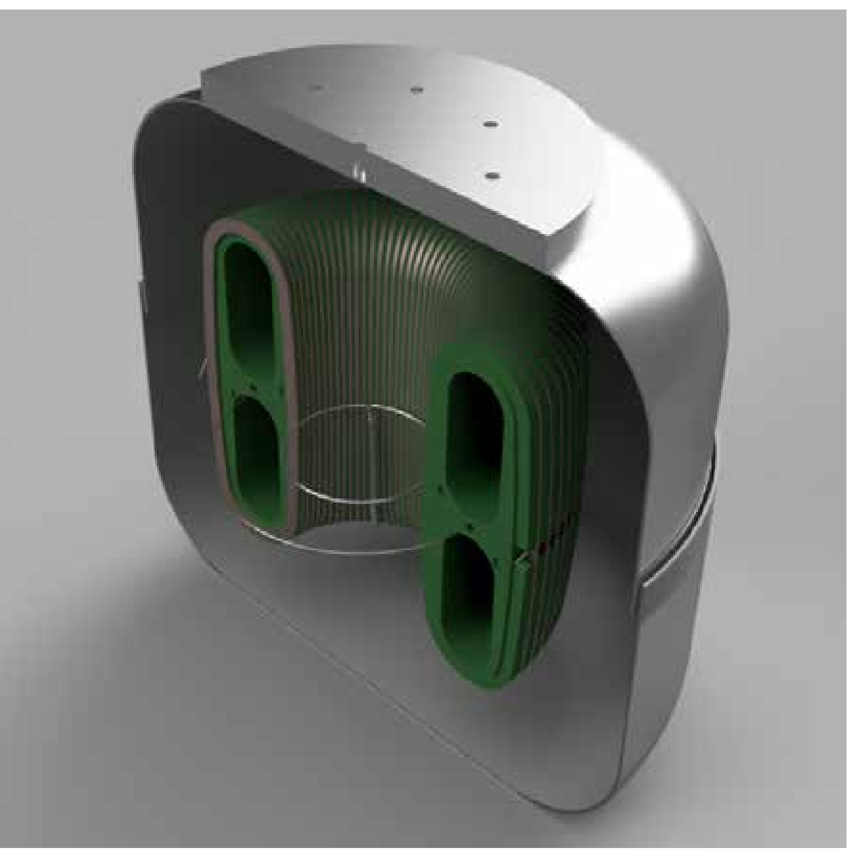
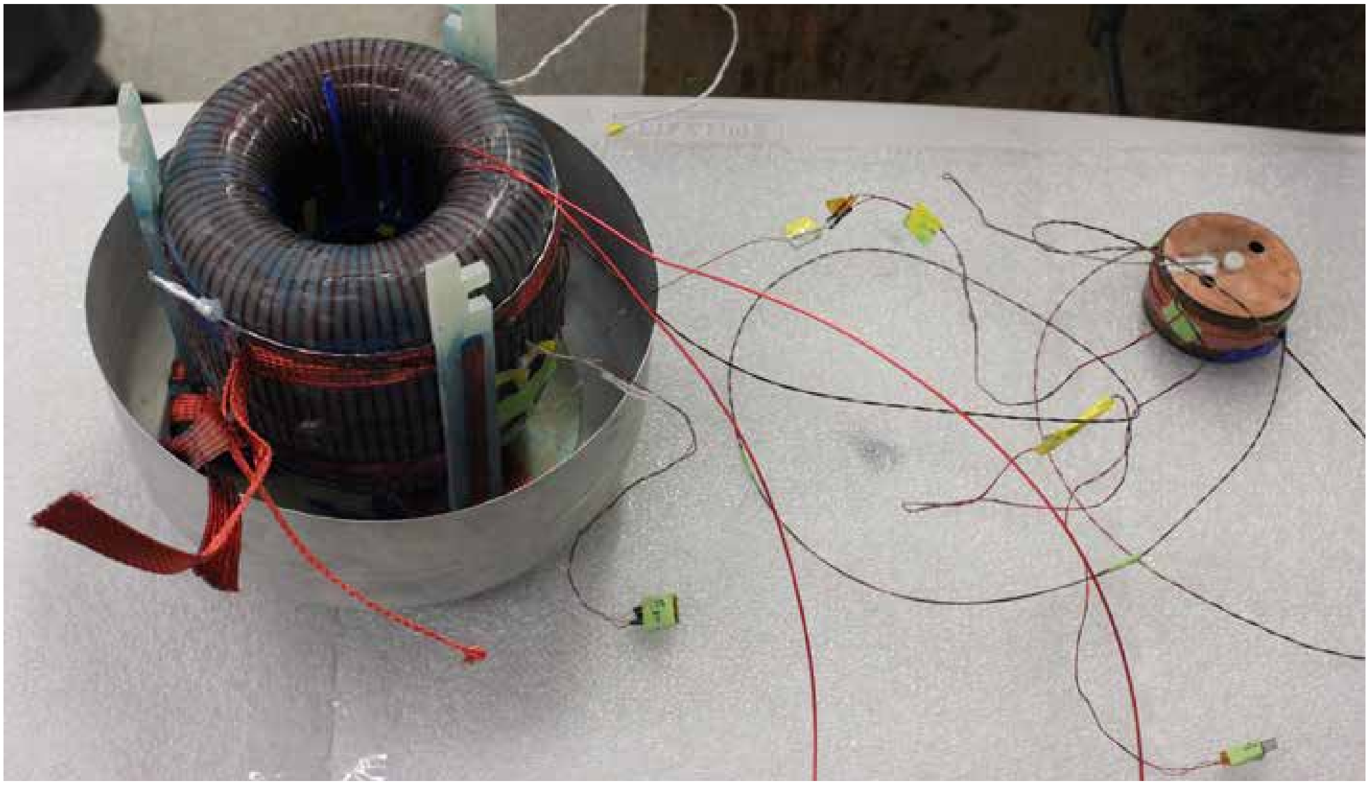


FIGURE 3

***The mechanical design** of ABRACADABRA-10cm with a toroidal magnet, central pickup loop and secondary outer calibration loop. The experiment is housed in superconducting shielding.*

As originally conceived on the blackboard, the magnet would need to be three stories tall and equally wide to hunt the QCD axion, namely, an axion with the right properties to solve the strong CP problem. Although experimental physicists have built magnets of this size and larger, it was prudent to start with a prototype device small enough to fit in Winslow's dilution refrigerator but still large enough to have discovery potential for generic axion dark matter. We also needed to leave room in the refrigerator for a superconducting shield around the device, allowing us to fit a magnet 12 centimeters in height and diameter. Once installed in its superconducting shielding, it is roughly the size of a basketball (*Figure 3*), and we call it ABRACADABRA-10cm.

The magnet was designed and built by Superconducting Systems, Inc., just up the road in Billerica, MA. They specialize in state-of-the-art devices for magnetic resonance imaging (MRI), but they enjoy a new challenge. A key feature of a super-



conducting magnet is that, once cold, one can charge it up with current and then disconnect the power supply; the magnet will stay charged in this persistent mode until it is purposefully discharged. Here, we needed a custom-wound superconducting toroidal magnet, unlike the more standard solenoidal, or cylinder-shaped, magnet used for MRIs. We also needed to eliminate as much non-superconducting metal as possible to reduce noise, so a toroidal support structure was built from a set of interlocking plastic disks. The assembly is shown in *Figure 4*. Once built, the magnet was placed into the superconducting shield, welded shut, and driven over to MIT.

FIGURE 4
ABRACADABRA-10cm being assembled *at Superconducting Systems, Inc.*

Commissioning: hanging by a thread

ABRACADABRA-10cm was installed in the basement of Building 24 on August 14, 2017, with the first cool-down started shortly thereafter. Once we verified that the magnet was working as expected, it was time to see if we could take data. The answer was … no. The very sensitive SQUID sensor was not behaving as expected, with extreme levels of noise much larger than we had anticipated.

Experimental physics is often like solving a whodunnit mystery. Did we somehow damage our SQUIDs? Was the noise associated with the construction of the MIT.nano building next door? With the toroidal magnet off, waving a powerful magnet around the lab could exacerbate the problem. But the problem was even worse with the magnet on, so perhaps stray magnetic fields were being induced by vibrations from the fridge pumps.

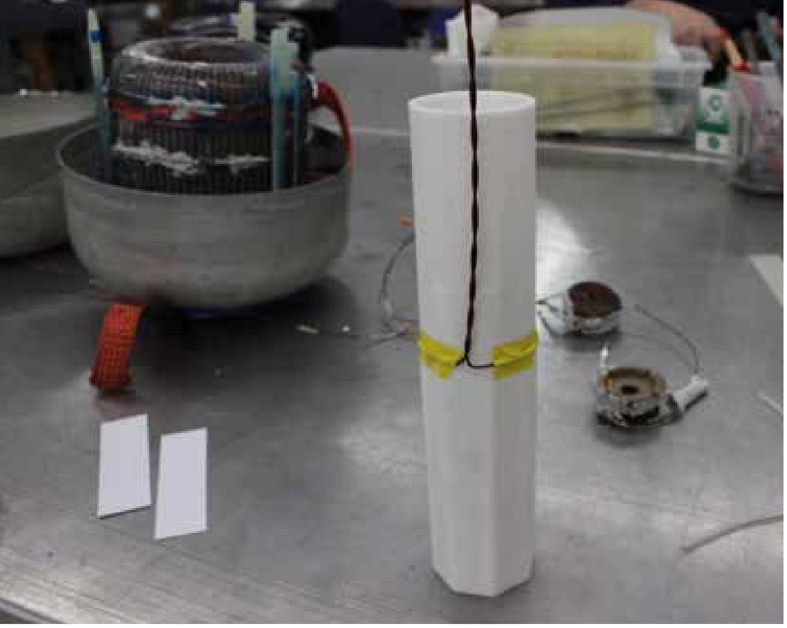


FIGURE 5

***ABRACADABRA-10cm is opened** and the pickup loop remounted to reduce the effect of stray fields from the magnet, which could induce a false signal via vibrations.*

It took a few months, but we finally figured out a solution. Proving that there is always a use for old equipment, some key parts were found for us at the MIT Bates Research and Engineering Center. We used MuMetal from their old accelerator's beam pipes to provide additional warm shielding around the cryostat. We did "surgery" on the experiment, cracking open the superconducting shield to remount the pickup loop on a Teflon cylinder (*Figure 5*). Finally, we repurposed a meter-long flange from Bates and attached it the top of the fridge, to which we mounted a vibration-reducing spring connected to the magnet via a thin strand of Kevlar (*Figure 6*)—hence the "bullet-proof" comment above. Kevlar is chosen because it can withstand one end being at room temperature and the other at 100 mK. This suspension system helped reduce vibrational noise dramatically, but it did mean that the whole experiment was literally hanging by a thread.

FIGURE 6

***ABRACADABRA-10cm hanging** from a Kevlar thread that is run through the plates to a spring that is mounted in a flange on the top of the fridge.*

First results: no axions…yet

After these upgrades and a bit more time to convince ourselves that the detector was behaving as expected, we started up the data acquisition system on July 16, 2018. We turned off the light, closed the door, and put a sign on the door imploring no one to enter. We even rolled an electronics rack in front of the door to really make sure no one wandered in by accident.

The physics run lasted until August 14, 2018. The system constantly wrote the amplitude of the SQUID output to disk, recording 25 trillion data points over a month. Since we could not actually store that much data on hard drives, we had to perform intermediate signal processing and data compression at various intervals. The final data is a frequency spectrum shown in *Figure 7*, corresponding to the full one-month data set.

Since the data is analyzed in terms of frequencies it can be turned into an audio signal—so we are quite literally waiting to "hear" an axion signal. Mostly, we hear mechanical vibrations as clearly as if we were sitting in the lab next to the fridge. The presence of the vibrational noise at low frequencies is comforting, since it confirms the diagnosis of our earlier SQUID noise problems. At high frequencies, we observe broad electromagnetic noise.

The exciting thing is that there is a sweet spot from 75 kilohertz (long-wave radio) to 2 megahertz (short-wave radio). The spectrum is relatively quiet here, with a noise

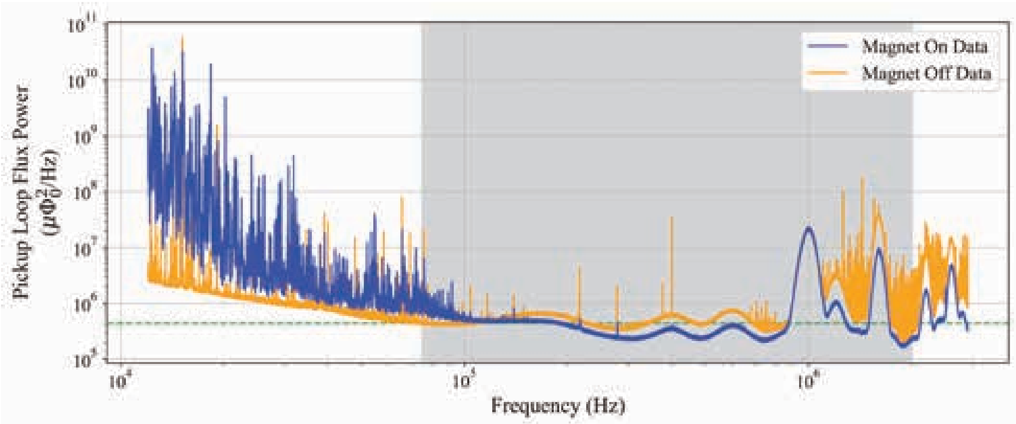


FIGURE 7

***The data from ABRACADABRA-10cm** in frequency space. We observe low frequency noise from vibrations and high frequency noise from other electromagnetic sources, including radio stations. The sweet spot from 75 kHz to 2 MHz is shaded in gray.*

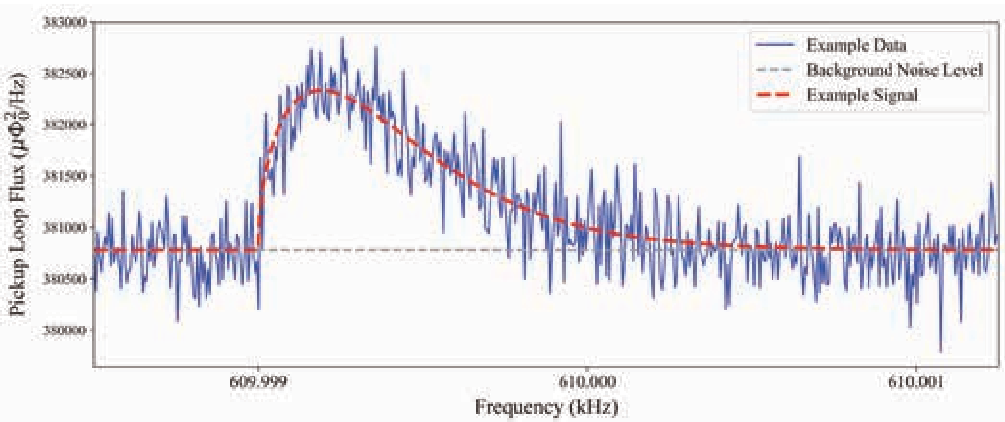


FIGURE 8

***The axion signal** is expected to be a very narrow peak in frequency space corresponding to the mass of the axion, with a characteristic shape due to the velocity distribution of axions in the galaxy.*

level comparable to the intrinsic noise level of the SQUIDs, allowing us to hunt for narrow-band axion signals like the one in *Figure 8*. Mostly we hear local radio stations, and even the frequencies used by the English and Korean Coast Guards. Fortunately, such spurious signals are easily vetoed by taking data with the magnet off. Unfortunately, we haven't heard any axions…yet.

The future: bigger and better

The construction, commissioning and operation of ABRACADABRA-10cm was a major milestone, and the result was published in *Physical Review Letters* in March 2019. It is the first result from a new wave of dark matter detectors coming online around the world, inspired by theoretical ideas and made feasible through experimental advances. It proves that the technique works and can be scaled to larger, more sensitive detectors. It also highlights MIT's strength in translating ideas from the blackboard to instruments in the basement.

We are proud of this first result and the incredible work of our team, but we are just getting started. Because we have that sweet spot where we are already limited by SQUID noise, we know we need a bigger magnet to make further progress. A one-meter experiment is the next physics goal, but the stored energy of such a magnet is too big of a leap, so right now we are working on designs for a

40-centimeter magnet. At the same time, we are using ABRACADABRA-10cm to study better vibration isolation and electromagnetic shielding to increase the frequency range of that sweet spot. Finally, we are still at least an order of magnitude away from the ultimate sensitivity of ABRACADABRA-10cm, so there is still plenty of discovery potential left in our little frozen donut.

NOTE

[1] The strong CP problem is an open question in particle physics: Why does QCD (also known as the strong force) seem to preserve the combined symmetries of charge conjugation (C) and parity (P)? There is nothing in the mathematical formulation of QCD that requires CP to be conserved, yet no violation of CP has ever been observed in any experiment involving only the strong interaction. This either suggests a delicate "fine tuning" to suppress CP violation or a dynamical solution like the axion. The name "axion" was coined by Nobel Laureate Frank Wilczek after the dish soap of the same name, since this proposed particle "cleaned up" the strong CP problem.

ACKNOWLEDGMENTS

MIT-affiliated co-authors include lead author Jonathan Ouellet; Chiara Salemi; Zachary Bogorad; Janet Conrad; Joseph Formaggio; Joseph Minervini; Alexey Radovinsky; and Daniel Winklehner. Other co-authors include Reyco Henning, University of North Carolina at Chapel Hill/Triangle Universities Nuclear Laboratory; Joshua Foster and Benjamin Safdi , University of Michigan, Ann Arbor; Yonatan Kahn, Kavli Institute for Cosmological Physics/University of Illinois at Urbana-Champaign; and Nicholas Rodd, University of California at Berkeley and Lawrence Berkeley National Lab. Technical support was provided by MIT Bates Research and Engineering Center, and the research funded, in part, by the National Science Foundation, the U. S. Department of Energy, and the Simons Foundation.

JESSE THALER *is an Associate Professor of Physics in the MIT Center for Theoretical Physics. He is a theoretical particle physicist whose research focus is the Large Hadron Collider (LHC) experiment at CERN. In his research, Thaler aims to maximize the discovery potential of the LHC by applying theoretical insights from quantum field theory. He is particularly interested in novel methods to test the properties of dark matter at the LHC and beyond, as well as in new small-scale experiments. Thaler also develops new methods to characterize jets, which are collimated sprays of particles that are copiously produced at the LHC. These techniques exploit the substructure of jets to enhance the search for new physics as well as to illuminate the structure of the standard model itself.*

Jesse Thaler joined the MIT Physics Department in 2010, receiving tenure in 2017. He was awarded an Early Career Research Award from the U.S. Department of Energy in 2011; a Presidential Early Career Award for Scientists and Engineers from the White House in 2012; a Sloan Research Fellowship from the Alfred P. Sloan Foundation in 2013; and a Harold E. Edgerton Faculty Achievement Award from MIT in 2016.

LINDLEY WINSLOW *is the Jerrold R. Zacharias Career Development Assistant Professor of Physics at MIT. She is an experimental nuclear and particle physicist whose work focuses upon how the physics of fundamental particles shaped our universe along with the development of specialized experiments—including novel detector technology and algorithms—to address these questions. This research currently prioritizes searches for neutrinoless double-beta decay and axion dark matter.*

Before her appointment in 2015 as an assistant professor of physics in the MIT Department of Physics, Winslow was a postdoctoral fellow in the Department, then a faculty member at the University of California, Los Angeles. She has won several awards, including the L'Oreal for Women in Science Fellowship in 2010 and the 2016 Breakthrough Prize as a member of the KamLAND collaboration.