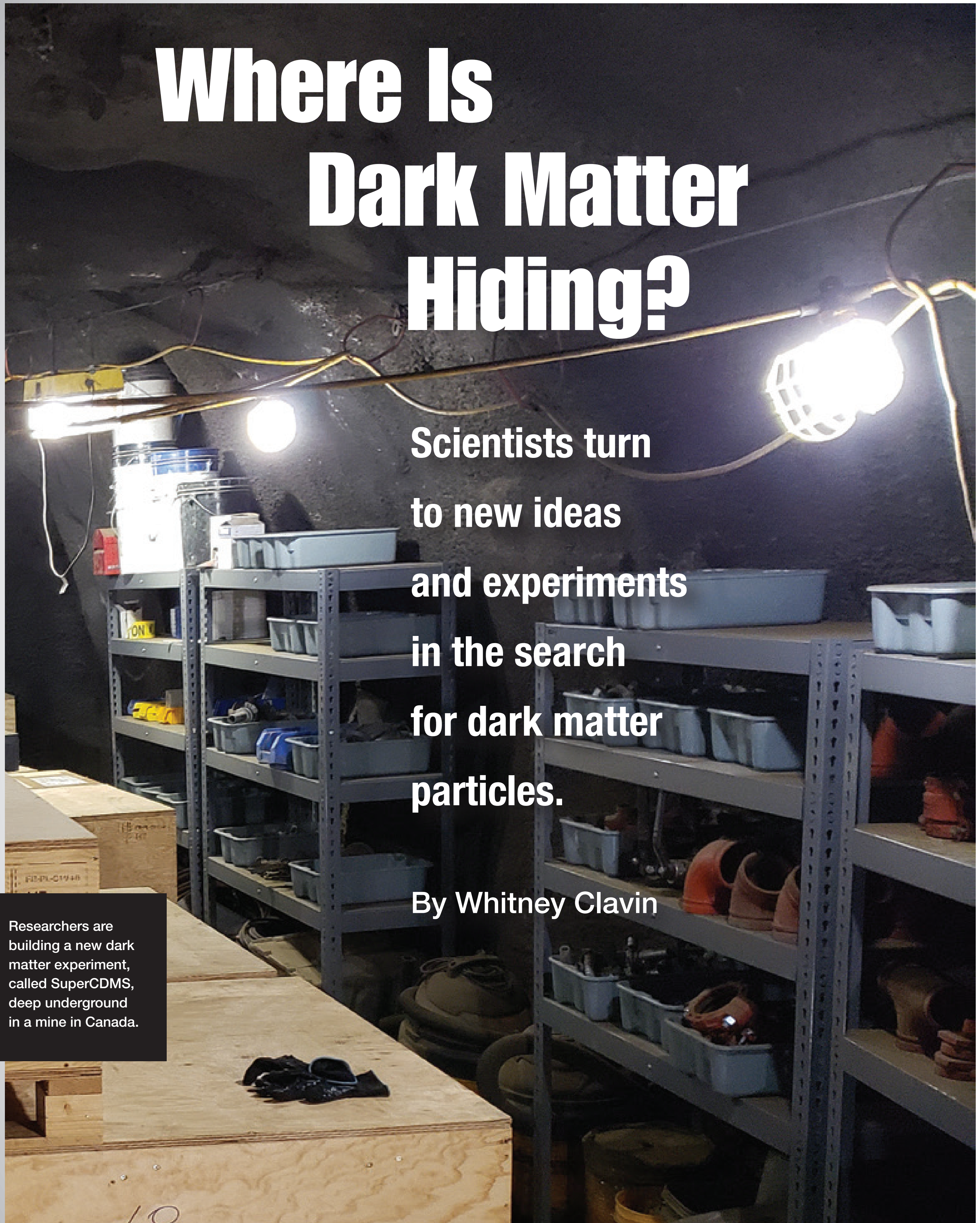
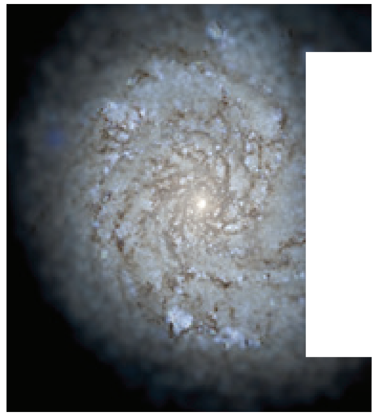


Where Is Dark Matter Hiding?

Scientists turn to new ideas and experiments in the search for dark matter particles.

By Whitney Clavin

Researchers are building a new dark matter experiment, called SuperCDMS, deep underground in a mine in Canada.



Every second, millions to trillions of particles of dark matter flow through your body without even a whisper or trace. This ghostly fact is sometimes cited by scientists when they describe dark matter, an invisible substance that accounts for about 85 percent of all matter in the universe. Unlike so-called normal matter, which includes everything from electrons to people to planets, dark matter does not absorb, reflect, or shine with any light. It is … dark. But if we cannot see dark matter, how do scientists know it is there? The answer is gravity. Astronomers indirectly detect dark matter through its gravitational influences on stars and galaxies. Wherever normal matter resides, dark matter can be found lurking unseen by its side.

The first real evidence for dark matter came in 1933, when Caltech's Fritz Zwicky used the Mount Wilson Observatory (see article on page 7) to measure the visible mass of a cluster of galaxies and found that it was much too small to prevent the galaxies from escaping the gravitational pull of the cluster. Something else, concluded Zwicky, was acting like glue to hold clusters of galaxies together. He named the substance *dunkle Materie*, or dark matter in German. In the 1970s, Vera Rubin and Kent Ford, while based at the Carnegie Institution for Science, measured the rotation speeds of individual galaxies and found evidence that, like Zwicky's galaxy cluster, dark matter was keeping the galaxies from flying apart. Other evidence throughout the years has confirmed the existence of dark matter and shown how abundant it is in the universe. In fact, dark matter is about five times more common than normal matter.

"The universe is hitting us over the head with evidence of dark matter," says Phil Hopkins, professor of theoretical astrophysics at Caltech. "Whether it is the motion of galaxies, or the fact that dark matter bends light, or the expansion of the universe, or the growth of structures in the universe, there are many different types of measurements that have been made and every single one of them fits the same paradigm of dark matter."

Yet, despite its preponderance, scientists have not been able to identify the particles that make up dark matter. They know dark matter exists and where it is but cannot directly see it. Since the 1990s, scientists have been building large experiments designed to catch elusive dark matter particles, but they continue to come up empty-handed. What some still consider the leading candidate for dark matter, called WIMPs (weakly interacting massive particles), have not been found in any of the data collected so far, nor have particles called axions; both WIMPs and axions are hypothetical elementary particles proposed to solve outstanding theoretical mysteries in the widely accepted model of particle physics, called the Standard Model, which classifies all known elementary particles and describes three of the four known fundamental forces (the electromagnetic, weak, and strong interactions, leaving out gravity). Additional dark matter candidates include particles called sterile neutrinos, along with primordial black holes. Some theorists have proposed that modifications to our theories of gravity might explain away dark matter, though this idea is less favored.

In the past decade, another set of dark matter candidates has emerged and is growing in popularity. These candidates collectively belong to a category known as the hidden, or dark, sector. At Caltech, hidden-sector ideas are in full bloom, with several scientists cultivating new theories and experiments.

"When you look beyond WIMPs and axions, a whole range of observational consequences open up," says Kathryn Zurek, a professor of theoretical physics at Caltech and one of the pioneers of hidden-sector theories. "The WIMP and axion paradigms are great because they are very predictive and led to the building of direct-detection experiments. Now we can leverage this beautiful technology to look for hidden-sector dark matter."

Hidden Valleys

In 2006, Zurek and colleagues proposed the idea that dark matter could be part of a hidden sector, with its own dynamics, independent of normal matter like photons, electrons, quarks, and other particles that fall under the Standard Model. Unlike normal matter, the hidden-sector particles would live in a dark universe of their own. Somewhat like a school of fish who swim only with their own kind, these particles would interact strongly with one another but might occasionally bump softly into normal particles via a hypothetical messenger particle. This is in contrast to the proposed WIMPs, for example, which would interact with normal matter through the known weak force by exchanging a heavy particle.

A key feature of hidden-sector particles is that they would be much lower in mass and energy than other

Kathryn Zurek is a theoretical physicist and one of the pioneers of hidden-sector theories of dark matter.

proposed dark matter candidates like WIMPs. Hidden-sector dark matter is proposed to range in mass from about one-trillionth that of a proton to 1 proton. Technically, this translates to masses between milli- and giga-electron-volts (eV); a proton has a mass of about one giga-eV.

"We are moving to a new frontier of lighter dark matter," says Zurek. "At first, we called these particles hidden valleys because the idea was that you would climb a mountain pass and look down to very low-energy particles." But now, she says, the phrase hidden valley has morphed into hidden, or dark, sectors.

Hidden-sector dark matter is thought to range in mass from about one-trillionth that of a proton to 1 proton.

Sean Carroll, research professor of physics at Caltech, and his colleagues also wrote an early paper, in 2008, on the idea that dark matter might interact just with itself. Similar to the hidden-sector ideas, the team proposed that, "just like ordinary matter couples to a long-range force known as 'electromagnetism' mediated by particles called 'photons,' dark matter couples to a new long-range force known (henceforth) as 'dark electromagnetism,'" Carroll wrote in his blog, Preposterous Universe, in 2008.

"Now, years later, scientists are in a phase of ruling out more and more models," says Carroll. "Our dark photon models are still possible but less likely than other models like Kathryn's."

So how does one go about finding a hypothetical particle less massive than a proton? Zurek and others have proposed tabletop-size experiments much smaller than other dark matter experiments, which can weigh on the order of tons. Although hidden-sector particles are thought to only rarely and weakly interact with normal matter, when they do, they cause disturbances that could, in theory, be detected. Zurek and her team have proposed a way to detect a disturbance caused by the hidden sector using a type of quasiparticle called a phonon. A specialized sensor would be used to catch the phonon vibrations, indicating the presence of dark matter. (A quasiparticle is a collective phenomenon that behaves like a single particle.)

Zurek is also developing other methods to help in the hunt for dark matter, including gravitational-based techniques that measure how clumps of dark matter in the cosmos affect the timing of flashing stellar remnants called pulsars. Like many scientists in the field, she feels that it is important to take a multipronged approach to the problem and look for dark matter with different but compatible methods.

Mark B. Wise, the John A. McCone Professor of High Energy Physics, who, in 1982, was among the first to propose that axions could be the missing dark matter particles, says dark matter could be axions, hidden-sector particles, or something else entirely. Wise made his proposal along with John Preskill, Caltech's Richard P. Feynman Professor of Theoretical Physics and director of the Institute for Quantum Information and Matter (IQIM), and Frank Wilczek of MIT. "We look where we can and where nature tells us to look," Wise says. "As a theoretical physicist, I am humbled by the universe. We should be embarrassed at some level about how little we know, but this can also be an opportunity to learn more."

Deep Underground

About 6,000 feet underground, in a working nickel mine in Ontario, Canada, a dark matter experiment is taking shape. Unlike the small experiments proposed by Zurek and others, this one is a massive undertaking. Scheduled to begin operations in 2022, SuperCDMS (Super Cryogenic Dark Matter Search) is designed to find lighter WIMPs than those sought before, with masses of 1 giga-eV, which is close to the mass of a proton. Because SuperCDMS is looking for lower-mass particles, it also has the ability to find lighter hidden-sector particles.

"I am humbled by the universe. We should be embarrassed at some level about how little we know, but this can also be an opportunity to learn more."

-Mark Wise

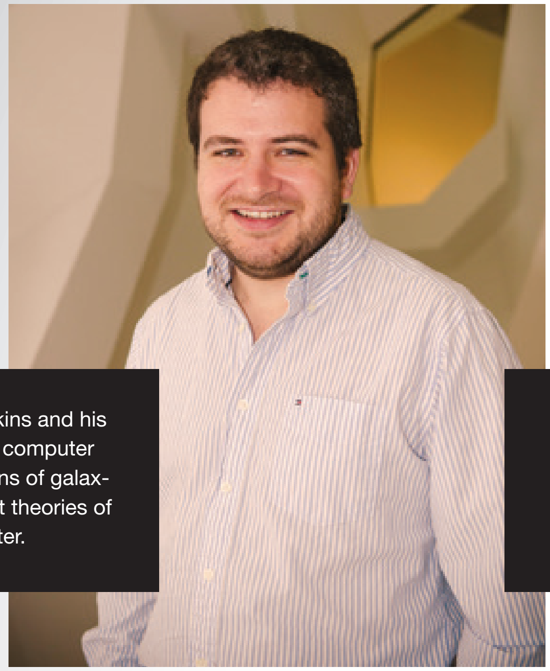
"When you enter the lab, it's an interesting process," says Sunil Golwala, professor of physics at Caltech. "You go down the mine elevator, sometimes with the miners, and then you walk about a kilometer in mine clothes: full-body mine suit, hard hat, boots, and all that. And then when you get to the lab entrance, you take all that off and take a shower. Then you put on a bunny suit and go into a lab, all of which is kept as a clean room. So, the lab is kept extremely clean even though it's sitting in the middle of a dirty mine."

Golwala helps manage the fabrication of the detector assemblies for SuperCDMS; the detectors are being built at the SLAC National Accelerator Laboratory, which leads the SuperCDMS project. Golwala explains that most dark matter experiments searching for WIMPs and hidden-sector dark matter are performed underground, often in mines, in order to shield the instruments from cosmic rays that could mask the dark matter signals.

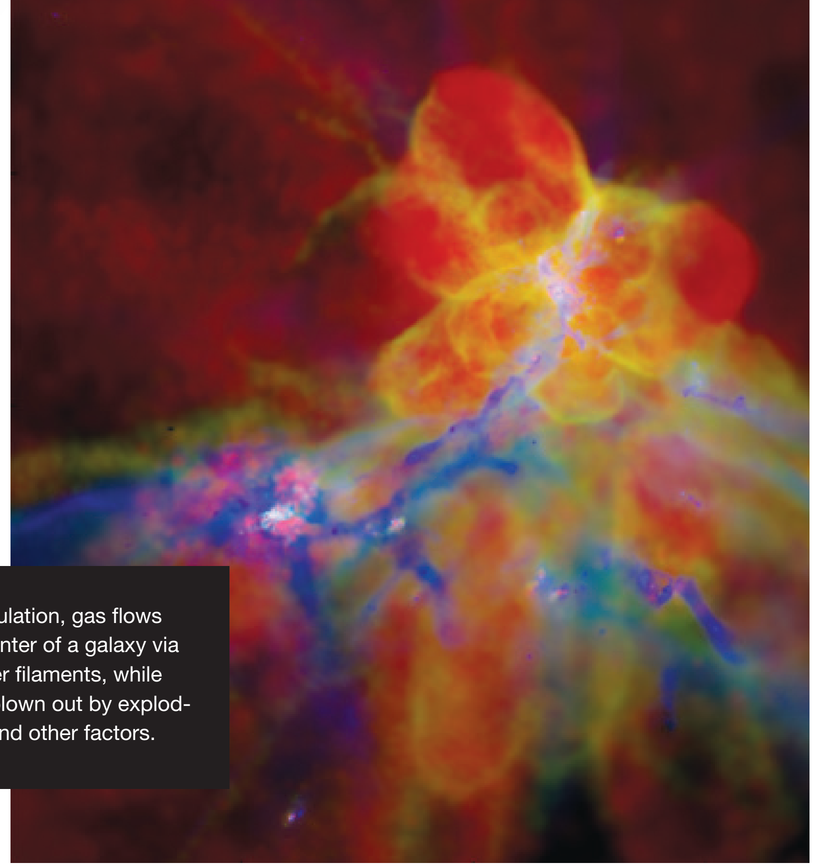
A new underground dark matter experiment looking for WIMPs may also detect hidden sector particles.

WIMPs were proposed in the late 1970s and early 1980s based on the idea that heavier hypothetical particles than those in the Standard Model, with a mass of more than 100 protons, could explain mysterious features of the model and, importantly, would just happen to be produced in the early universe in the amount needed

Sunil Golwala is an experimental physicist working on SuperCDMS, seen here coming together in a cleanroom inside a mine in Canada.



Phil Hopkins and his team run computer simulations of galaxies to test theories of dark matter.



In this simulation, gas flows into the center of a galaxy via dark matter filaments, while matter is blown out by exploding stars and other factors.

to explain the dark matter abundance. In addition, a theory known as supersymmetry (which states that every particle has a partner with a complementary spin) predicts partner particles, one of which could be a WIMP. But, over the years, evidence for supersymmetry has failed to materialize.

"There had been hope for many years that if we saw dark matter it would be a hint that supersymmetry exists, but people are getting less and less convinced. Kathryn is one of the people who has strongly advocated for looking at other models, given that supersymmetry has not turned out to be discovered yet," says Golwala. "That's been one of the big motivations for wanting to look down at the mass range that we're looking at. Twenty years ago, if you told someone you were looking for dark matter at 1 giga-eV, they might say, 'Why are you doing that? There's no supersymmetric particle down at 1 giga-eV.' And now, 20 years later, as far as we know, there's no supersymmetry, so we had better pay attention to these other models. The nice thing about SuperCDMS is that we are looking for WIMPs and the hidden sector."

By adding dark matter physics into computer simulations of galaxies, researchers can make predictions about features that telescopes might observe in the future.

In addition to contributing to SuperCDMS, Golwala is working on tabletop experiments specifically designed to uncover the hidden-sector particles. He says he pays close attention to Zurek's guidance on what types of interactions to look for between dark matter and normal matter. "Kathryn is a theorist, and I am an experimentalist. She says, 'This is the thing you should build in order to look for this model of dark matter.' I take her ideas and say, 'OK, we are going to build an experiment that can do that.'"

Just Add Dark Matter

Outside the lab, there are other ways to probe the hidden sector. Phil Hopkins and his team have embraced the various new dark matter ideas and folded them into their computer simulations of galaxies and the universe. Like baking a batch of cookies, researchers can mix and match cosmic ingredients in a computer simulation and see what arises. If a resulting galaxy looks like the real thing, then scientists know they are closer to understanding its ingredients.

"If you assume that most matter in the universe is dark matter, and that dark matter interacts only with gravity, then it is actually pretty simple to set up your computer simulation," says Hopkins. "You have one force, gravity, and you let everything evolve from there."

Recently, Hopkins and his students have refined this simple simulation to include hidden-sector physics. He says his research serves as a bridge between that of Zurek and Golwala, in that Zurek comes up with the theories, Hopkins tests them in computers to help refine the physics, and Golwala looks for the actual particles. In the galaxy simulations, the hidden sector dark matter is "harder to squish" because of its self-interacting properties, explains Hopkins, and this trait ultimately affects the properties of galaxies. The team's computer creations allow them to make predictions about the structure of galaxies on fine scales, which next-generation telescopes, such as the upcoming Vera C. Rubin Observatory, scheduled to begin operations in Chile in 2022, should be able to resolve.

"You can imagine a whole dark universe or this hidden sector where all sorts of things are happening underneath normal matter or 'under the hood,' as you might say. What we have tried to do is ask, 'What are the astrophysical consequences?'" says Hopkins.

Several other Caltech researchers are also on a quest to uncover the nature of dark matter, including cosmologists who study its effects on vast scales that span the history of the universe, as well as particle physicists who search for dark matter candidates produced in high-energy colliders such as CERN's Large Hadron Collider, or LHC. Cristián Peña (MS '15, PhD '17), a Lederman Postdoctoral Fellow at Fermilab and a research scientist with the High Energy Physics group and INQNET (INtelligent Quantum NEtworks and Technologies) at Caltech, was among the first, in 2016, to attempt to discover dark matter in high-energy proton-proton collisions at the LHC. Those searches for dark matter were made with data collected by the Compact Muon Solenoid instrument.

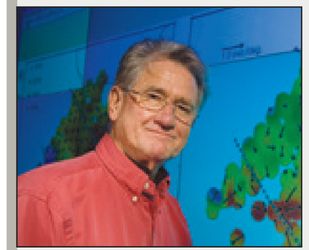
Now, Peña is developing quantum-sensing experiments to detect dark matter. The state-of-the-art sensors he is using are being developed as part of a quantum internet project involving INQNET in collaboration with Fermilab, JPL, and the National Institute of Standards and Technology, among others. INQNET was founded in 2017 with AT&T and is led by Maria Spiropulu, Caltech's Shang-Yi Ch'en Professor of Physics. A research thrust of this program focuses on building quantum-internet prototypes including both fiber-optic quantum links and optical communication through the air, between sites at Caltech and JPL as well as other quantum network test beds at Fermilab. The optimized sensors developed with JPL for this program are also well-suited to detect very-low-mass dark matter and, as Peña says, any "feeble interactions" of hidden-sector states beyond the Standard Model of particle physics.

"Quantum sensing is an emerging research area at the intersection between particle physics and quantum information science and technology," he says.

While most researchers agree that finding dark matter is a long shot, they feel confident that the pursuit, and all the science and technology that has been and will be acquired along the way, is worth the journey. After all, we know that dark matter exists and, as Carroll says, it is "not really all that mysterious." When Carroll explains dark matter to the public, he has them imagine that our moon is made of dark matter and thus invisible. "We would still experience the moon's tides on Earth even though we couldn't see the moon. We know dark matter is there, we just can't see it." [C]

In Memoriam

Read more about their lives at **magazine.caltech.edu/post/in-memoriam**



Donald V. Helmberger 1938-2020

Donald V. Helmberger, who ran the Caltech Seismological Laboratory from 1998 to 2003, passed away on August 13 at the age of 82. Helmberger joined the Caltech faculty as an assistant professor in 1970 and was named Smits Family Professor of Geophysics in 2000. His primary research interests involved seismic-wave propagation and the use of waveforms to recover information about earthquake characteristics as well as the earth's structure.

Masakazu (Mark) Konishi 1933-2020

Masakazu (Mark) Konishi, the Bing Professor of Behavioral Biology, Emeritus, passed away on July 23. He was 87 years old. Konishi was renowned for his work on the neuroscience underlying the behavior of owls and songbirds. His team worked extensively on the auditory systems of barn owls, which use their acute hearing to home in on prey on the ground, even in total darkness. He also theorized and then showed experimentally how the brains of songbirds learn and produce song.

James (Jim) Morgan 1932–2020

James (Jim) Morgan, the Marvin L. Goldberger Professor of Environmental Engineering Science, Emeritus, at Caltech, who previously served as dean of students and later as vice president for student affairs, passed away on September 19 at the age of 88. Morgan, who joined Caltech's faculty in 1965, focused his research on the chemistry of aquatic environments and water treatment, and in particular on the scientific bases for establishing criteria and standards for water-quality protection.

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