A Mine for Dark Matter

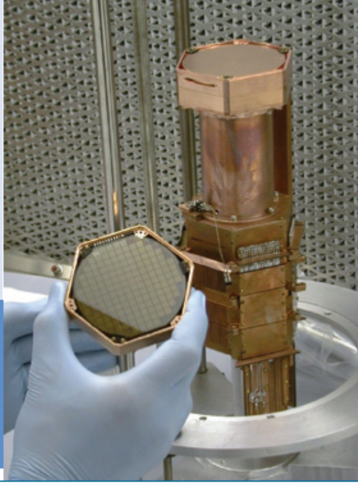
Researchers have built an experiment 230 stories underground in search of an elusive particle that may be dark matter, the mysterious stuff that makes up nearly a quarter of the universe.

For two weeks in mid-December 2009, the physics world was buzzing with anticipation and speculation. A team of researchers was rumored to have made an astounding discovery—they'd detected dark matter, the unknown stuff that makes up nearly a quarter of the universe. The world's leading experiment to find dark matter, the Cryogenic Dark Matter Search (CDMS), had just finished analyzing its final data set. Word had somehow reached the blogosphere that the results would be published in *Nature*; an announcement to be made in such a widely read and prestigious journal must mean big news. This was soon debunked, but it was too late. The rumor had already drawn the attention of physics blogs, including Cosmic Variance (in a post by Caltech senior research associate Sean Carroll), and those of *New Scientist* and *symmetry* magazines.

To further fan the flames, a pair of talks announcing the results were scheduled

Assistant Professor of Physics Sunil Golwala stands in front of a three-dimensional map of dark matter. Measurements of how light bends around massive galaxy clusters, an effect called gravitational lensing, allow astronomers to better estimate not only how much dark matter is out there, but also how it has governed cosmic evolution. This map, which has time as its third dimension, goes halfway back to the Big Bang (over Golwala's shoulder). As your eye moves to the left, the dark matter goes from smooth to clumpy, dragging the visible matter with it to form the galactic structures of today. This map, the first of its kind (see *E&S* 2007, No. 1), was published in a 2007 paper by then-postdoc Richard Massey and others, including JPL scientist Jason Rhodes and Steele Family Professor of Astronomy Richard Ellis. The data came from the Hubble Space Telescope's Cosmic Evolution Survey, led by Moseley Professor of Astronomy Nick Scoville, which spent nearly 1,000 hours looking at a patch of sky about the size of nine full moons.

Each CDMS detector is a 230-gram germanium crystal. Six detectors are stacked to form one of the five towers that make up the whole apparatus.



By Marcus Y. Woo

to be given simultaneously at Fermilab in Illinois and the Stanford Linear Accelerator Center (SLAC) in California. These talks were set weeks before, says Assistant Professor of Physics Sunil Golwala, a member of the CDMS team. But, coupled with the rumors, the scheduled talks only added to the rampant speculation. “Then it got crazy for a couple of weeks,” Golwala recalls. The CDMS team had decided early on not to discuss the results before the presentations, to ensure that data wouldn’t be released before a thorough vetting. The secrecy, however, just got people more suspicious. “People came up to me and tried to read my facial expression,” says Jeff Filippini, a postdoc and CDMS team member.

No one knows for sure what dark matter is made of, but so far the best guess is that it consists of a type of particle called a weakly interacting massive particle (WIMP). If physicists and astronomers are right about this, then WIMPs should be all around us, zooming about at hundreds of kilometers per second. But because they hardly interact with regular matter, you can’t see or feel them. There could be billions of them streaming through your body right now. Once in a while, though, a WIMP could crash into an atomic nucleus like a cue ball hitting an eight ball, and that’s the idea behind most dark-matter searches, including CDMS.

The detector consists of 30 hockey-puck-sized crystals of germanium waiting for a WIMP to come along. To block cosmic rays that might confuse the signal, CDMS sits about 230 stories deep in the Soudan Underground Laboratory, a research facility built by the University of Minnesota, Fermilab, and the Minnesota Department of Natural Resources. Why the DNR? Because the lab sits in the bowels of an old iron mine nestled among the lakes and forests at the northeast tip of Minnesota. The CDMS team numbers nearly 80 people from 16 institutions around the world, including Caltech.

Although CDMS is far from alone in trying to catch WIMPs, it’s been the standard-bearer for the past few years. No experiment has yet detected anything, but each silent result narrows down what WIMPs might look like—any theory that predicts something the experiments don’t see has to be refined or ruled out. CDMS has provided the tightest constraints yet, and these latest results, taken over a period of more than a year, have doubled the collaboration’s data. If physicists were close to finding WIMP collisions, then CDMS would have been the first experiment to do so—which explains why people became so anxious upon hearing the rumors. The hype underscores just how momentous a dark-matter discovery would be. “It’s a really exciting topic,” says Golwala, whose two graduate students, Zeeshan Ahmed (MS ’08) and David Moore, did a lot of the number crunching for the new data. “Suppose you have conclusive evidence that you just discovered the dark matter in the universe,” he says. “I mean, that’s just amazing.”

WHAT’S THE MATTER?

For decades, dark matter remained an abstraction, living within the confines of conjecture and theory. Caltech’s Fritz Zwicky—the eccentric, cantankerous iconoclast who was a professor of physics from 1941 to 1968—coined the term nearly 80 years ago. In 1933, he found that galaxies in a group called the Coma Cluster were zipping around a common center of gravity much faster than they should’ve been—at those speeds they should have been flying apart. The only way the galaxies could stay clustered was if there was more mass to them than met the eye—some new type of matter that only interacted with stars, dust, and gas through mutual gravitation. This stuff couldn’t be seen, and was therefore “dark.” Other astronomers, however, didn’t take his pronouncement seriously. (In fact, much of Zwicky’s research was ahead of its time, and now many consider him to be an overlooked genius.)

Not until the 1970s, when Vera Rubin of the Carnegie Institution of Washington measured how fast spiral galaxies spin, did the notion of dark matter gain greater acceptance. The principle behind her discovery is the same as Zwicky’s—she looked at dozens of spiral galaxies and found that the outer stars were circling so fast that the galaxies should’ve been ripping apart. Since then, even more accurate measurements of galaxies and galaxy clusters have revealed a universe filled with mass we can’t see, holding galaxies together like cosmic glue. Nearly all galaxies appear to be embedded

In addition to CDMS, Golwala's research group works on a variety of other topics in observational cosmology, exploring the origin of the universe and the nature of dark matter. Golwala uses Bolocam—a camera built with Andrew Lange, JPL scientists Jamie Bock and Hien Nguyen, and Jason Glenn of the University of Colorado—at the Caltech Submillimeter Observatory to study tiny fluctuations in the cosmic microwave background (CMB) caused by galaxy clusters. Golwala is also developing a new camera called MUSIC with Professor of Physics Jonas Zmuidzinas (BS '81), Nguyen, Glenn, JPL postdoc Jack Sayers (MS '04, PhD '08), and JPL scientists Peter Day (PhD '93) and Rick LeDuc.

Golwala also plays a role in two more experiments that analyze the CMB. Spider, on which postdoc Jeff Filippini is a team member, is a balloon experiment that will fly from Antarctica and observe at millimeter wavelengths. BICEP2, on which postdoc Walt Ogburn is a team member, is a sister experiment situated at the South Pole.

in huge dark-matter halos several times the size of galaxies themselves. According to the latest estimates, about 85 percent of all the matter in the universe is dark. (And it turns out that most of the cosmos isn't even matter—three-fourths is dark energy, an entirely different beast altogether and an even bigger mystery.)

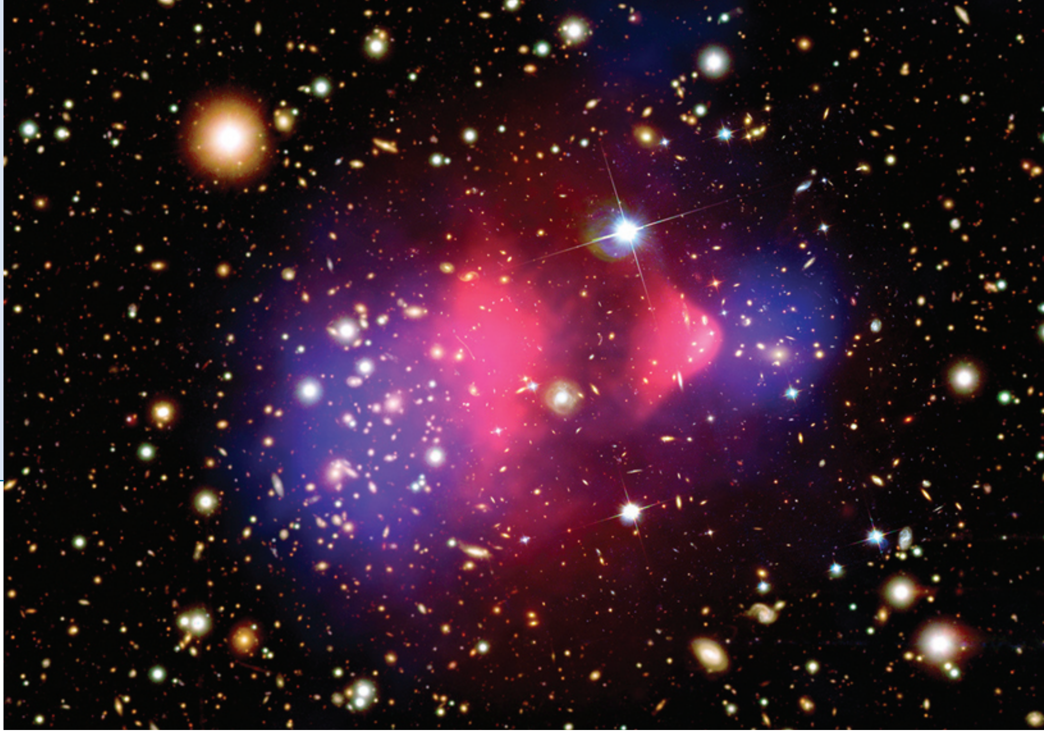
Physicists and astronomers have come up with no end of ideas to account for the universe's invisible mass. Some astronomers have even proposed that our theory of gravity is incomplete, that it behaves differently on cosmic scales. But in 2006, observations of the Bullet Cluster, published by a team of astronomers that included lead author Douglas Clowe (BS '93), Anthony Gonzales (BS '95), and Dennis Zaritsky (BS '86), made a convincing case that dark matter is indeed real. (Clowe, Gonzales, and Stephen Murray [PhD '71] were also among the authors of a lead-up study on the Bullet Cluster's dark matter in 2004.)

Most of the visible matter in galaxy clusters consists of X-ray-emitting hot gas, and the Bullet is actually two galaxy clusters in the midst of a high-speed crash. When two clusters smack into each other, the gas collides, and the clusters slow each other down. Dark matter, on the other hand, hardly interacts with anything, so the two giant blobs of dark matter would pass through each other like ghosts. When astronomers measured how light bends around the Bullet Cluster, an effect called gravitational lensing, they found that most of the mass is not in the hot ball of colliding gas, but in the places where the dark matter would be. For the first time, astronomers had isolated dark matter from visible matter.

Some hypotheses say that dark matter is composed of familiar-but-dim objects, like black holes or brown dwarfs—Jupiter-sized balls of gas too small to form stars. These things have been dubbed massive compact halo objects (MACHOs—since they're obviously not WIMPs), but there doesn't seem to be enough of them out there. Two lines of evidence from the Big Bang have now convinced most astronomers that dark matter isn't normal stuff, made from protons and neutrons, but something completely different.

Right after the Big Bang, the cosmos was a soup of hot plasma. As the universe expanded and cooled from 10^{32} degrees to a balmy 10^{9} degrees, protons and neutrons formed. In this fiery cosmic cauldron, nuclear fusion took place as protons and neutrons slammed into one another, forging the first elements—hydrogen, helium, and lithium—and some of their isotopes, which have varying numbers of neutrons. For example, the nucleus of ordinary hydrogen is a bare proton. Deuterium, the next heaviest hydrogen isotope, has a proton and a neutron, and tritium has a proton and two neutrons. The total density of protons and neutrons dictated the isotopes produced and in what proportions. This primordial process is the only way to make deuterium, so by measuring the abundance of deuterium now, we can gauge the total density of protons and neutrons then. It turns out that there aren't enough protons and neutrons—collectively called baryons—to account for all the mass in the universe.

The cosmic microwave background (CMB), the sky-filling afterglow of the Big Bang, also suggests that dark matter must be different—or nonbaryonic, in physics nomenclature. Observations of the CMB—including those from BOOMERanG, the Antarctic balloon telescope experiment led by the late Goldberger Professor of Physics Andrew Lange—show a stipple that betrays the universe's baryonic density. (See *E&S* 2000, No. 3). "You're looking back in time to a plasma a few hundred thousand years after the Big Bang," Filippini explains. "You can think of it as a snapshot of the way this plasma is frothing and sloshing from place to place." The normal stuff—baryons—is being pushed around by the energy in this cosmic soup, adds Walt Ogburn (BS '99), a postdoc who was also on the CDMS team. "If you have some kind of nonbaryonic dark matter that's not interacting with the protons, then it does its own thing and interacts gravitationally with the soup." So how much the plasma sloshes—its amplitude, which is represented by the prominence of the spots



A composite image of the Bullet Cluster, which is two galaxy clusters that began colliding about 3.5 billion years ago. The red represents each cluster's X-ray-emitting gas, which was slowed down by the collision and remains near the crash site. The blue represents the dark matter. Since dark matter hardly interacts with anything, it sailed right on through the other cluster unimpeded, and it's still going.

in the CMB—tells astronomers what kinds of ingredients are in the soup . . . and a lot seems to be that strange, nonbaryonic dark matter.

Theorists have concocted a smorgasbord of potential dark-matter candidates, exotic particles with names like Q-balls, cryptons, and WIMPzillas. But so far, the particle that is considered to be the most credible candidate is the WIMP. "In my mind, it's the best option," says Golwala. A WIMP is about a hundred times more massive than a proton and interacts with other particles through gravity and the weak force (which are two of the four fundamental forces of nature—the others being the electromagnetic force, which is actually the same as the weak force at sufficiently higher energies, and the strong force, which holds nuclei together). What distinguishes WIMPs as good candidates is that they're really not special at all, but a type of particle predicted by many of the latest theories in particle physics.

The Standard Model, which explains how all the fundamental particles interact with one another, is one of the most successful theories in physics. But it's incomplete—for example, it doesn't explain gravity. It also turns out that if you were to solve the relevant equations, you would find that every particle—except the photon or gluon, another massless particle—should have a mass of 10^{19} gigaelectron volts, the so-called Planck mass. Instead, a proton has a mass of about 100 gigaelectron volts—and the Standard Model can't account for the enormous gap.

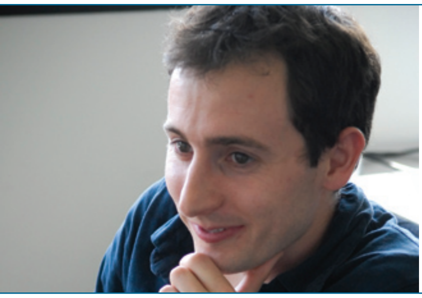
To fix the problem, physicists have cooked up several theories. One of these is supersymmetry, in which every particle has a new partner—for instance, a quark's "superpartner" is a squark. Another group of theories posits that there are more spatial dimensions than the three we normally experience—up, down; left, right; forward, backward. The extra dimensions are curled up into sizes too small for us to see. The theories of supersymmetry and extra dimensions each suggest that there could be particles with the general properties of WIMPs.

If there are WIMPs, they would've been produced in the early universe, back when it was so dense that despite their weak interactions, they would've been dashing around, smashing into each other. When they did, they would have annihilated one another, bursting into other particles and energy. But as the universe expanded and became less dense, it became harder for WIMPs to find and annihilate each other, and they soon were no longer able to, leaving a bunch of them hanging around with nowhere to go. Calculations predict that the quantity of leftover WIMPs is roughly the same as the estimated amount of dark matter. "It's just a complete coincidence—and that is what got people really excited," Golwala says. "There's no reason this coincidence had to happen, and therefore we should take it seriously." Whereas many other potential dark-matter particles are pure invention, WIMPs are born naturally out of particle physics. "It doesn't rely on one specific theory of how things work—that's the most compelling thing about it."

How exactly a WIMP behaves—how frequently it would smash into the nuclei in CDMS's detectors, for instance—depends on the specific variation on supersymmetry or extra-dimension theory, and there are many. "For every theorist who's thought about it, there's going to be a slightly different theory," Filippini says. Still, most of these ideas require, or are consistent with, WIMPs. "A particle physicist and a cosmologist would both think this kind of particle should exist," he remarks. "That's such a cool coincidence that it makes people actually want to look for these things."

SUCH A WIMP

The Soudan iron mine opened in 1884 and would become Minnesota's deepest, as well as oldest, mine, helping the state become the nation's leader in producing iron



Far left: David Moore, Golwala, Jeff Filippini, and Zeeshan Ahmed in front of the Cahill Center for Astronomy and Astrophysics.

ore. It closed in 1962, and is now a state park as well as a physics lab, home also to a neutrino-detection experiment called MINOS. Most flights take the researchers to Minneapolis, where they then drive for four hours to Soudan—a journey made perilous by Minnesota winters. "California drivers don't do well in the snow," says graduate student Moore, who, along with his fellow grad Ahmed, has spent plenty of time in the mine. "Sometimes with the wind chill, it's minus 40 degrees—it's kind of crazy," adds Ahmed, who played a leading role in the latest analysis. Researchers have spun off roads and driven into ditches; they've hit deer and, reportedly, grazed a bald eagle.

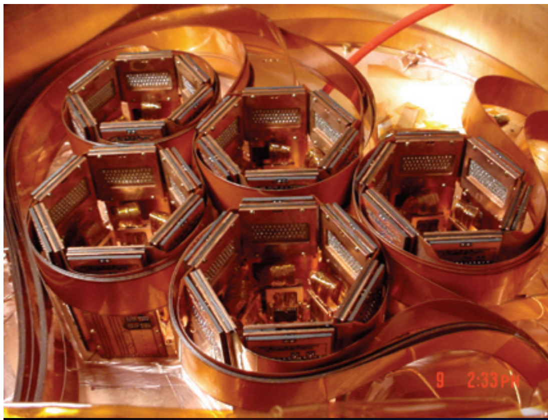
If they make it to Soudan in one piece, they stay for a week or two at a time in a gray, four-bedroom house five minutes from the mine. Every morning at 7:30, they squeeze into the mine shaft's rusty cage, where an operator lowers them into the lab. They don't return to the surface until 5:30 in the evening. The lab is within a four-story high cavern, and with walls, bright lights, a steady temperature of 70 degrees, and even a ping-pong table, it isn't too much different from a lab above ground.

Because they're waiting for a single particle among billions, at a rate of just a few potential hits per year with the current detectors, the team must minimize as much background noise as possible. With almost 700 meters of dirt and rock above, CDMS is protected from cosmic rays, which are not actually rays but primarily particles—protons, helium nuclei, electrons, and muons. A cosmic-ray strike anywhere in the instrument would trigger a cascade of other particles such as neutrons, which could mimic a WIMP's signal if they hit the detector.

Developed by groups at Stanford and UC Berkeley in the 1990s, led by Blas Cabrera and Bernard Sadoulet, respectively, the detectors are composed of 230-gram germanium crystals. The experiment's detection method requires a semiconductor, and of them all, germanium has the heaviest nuclei, maximizing the possibility of a collision. The crystals are arranged into five stacks of six detectors each, and then the stacks are encased in copper, chosen for its low radioactivity. The stacks are kept at a frigid 40 millikelvins—that's 0.04 degrees above absolute zero, almost a hundred times colder than outer space—and surrounded by layers of polyethylene, for more neutron protection, and lead, to shield against gamma rays. Because the lead will inevitably have some radioactive isotopes, spouting the occasional particle, the detectors are surrounded by ancient lead taken from an old sunken ship. Two centuries old, this lead has already decayed away most of its radioactivity. Surrounding the apparatus is something called a plastic scintillator anticoincidence detector, a shield built by UC Santa Barbara that lights up when muons pass through, notifying researchers of events to ignore. Finally, the whole thing sits in a clean room.

When a WIMP smacks into the disk-shaped detector, it rattles a germanium nucleus, sending phonons—quantized packets of vibrational energy—across the crystal. On the detector's surface are thin aluminum films, which act as phonon-collecting antennas. When aluminum is as cold as these detectors are, its electrons—which freely roam in the metal—arrange themselves in so-called Cooper pairs. These pairs form when a free electron tugs at the positively charged lattice of the aluminum nuclei, creating a tiny ripple in the crystal structure. The displacement caused by that ripple then pulls at another free electron, coupling it with the first. The partnership is weak, so the phonons from the crashing WIMP easily split the pairs, transferring their energy as heat to the newly single electrons. The electrons then find their way toward tungsten thermometers.

The tungsten is a transition-edge superconductor, meaning that any bump in temperature would nudge it out of its superconducting state. The electrons—now



Top right: A top view of the five stacks that make up the CDMS experiment. Copper provides a first layer of protection against background particles. Bottom right: This model of the apparatus provides a multisensory demonstration of CDMS in action. It lights up and chimes when it detects particles.

Far left: The Soudan mineshaft in winter.
Middle: The park's mine tour includes a cart ride.
Left: Inside the CDMS lab, where Rupak Mahapatra (left), now on the faculty at Texas A&M University, and Xinjie Qiu (right), now a Stanford postdoc at Fermilab, take a break from dark-matter hunting with a game of ping pong.
Below: Dan Bauer, from Fermilab and project manager for CDMS, removes one of the towers to make room for the first of the next generation of towers, called SuperCDMS. With him are Jim Beaty of the University of Minnesota (center) and Steve Leman of MIT.
Below right: Walt Ogburn is in the "cryopad," the area that houses the liquid-helium and nitrogen dewars and pumps. The computer controls the circulation of the liquids that keep the detectors frigid.

warm from the phonons—push the tungsten toward being a normal conductor. By measuring the sudden changes in electrical current, the researchers can determine the energy of the WIMP-generated phonons—and therefore the energy of the collision.

To be sure, one of the biggest challenges for the CDMS team is to minimize and understand background particles. Despite the mine's depth, the shielding, and the effort to keep materials clean and pure, stray particles still slip through. Electrons from the beta decay of radioactive elements that found their way onto the detector surfaces, and high-energy photons called gamma rays from impurities in the apparatus, both knock electrons loose in the germanium. To distinguish these events from the WIMP-nucleus collisions investigators are looking for, the detector collects and counts the free charge created by the loose electrons. An electric field in the crystal corrals the free charges onto the detector's rear surface (opposite the tungsten and aluminum), where electrodes measure the ionization energy. By calculating the ratio of ionization to total collision energy, the researchers can identify which events were electron collisions and discard them.

The team employs several more tricks to distinguish WIMPs from background particles. They only look at the signals from the most probable energy range for WIMP collisions. They discount anything that happens at the edges of the detector, where signals can get fuzzy. They only consider single-collision events—since a WIMP interacts so weakly, it would only hit one atom in one detector. If the researchers see some particle plowing into multiple nuclei down the whole stack, they know it can't be a WIMP. The team also throws away any collisions that occur at the crystal's surface, as those tend to be caused by stray particles from the apparatus itself—no matter how pure your materials, some radioactive isotopes are bound to sneak in.

To prevent bias on their part—or maybe wishful thinking—the team uses the above requirements to decide on what constitutes a signal before they look at the data. Calibrating with particles generated from radioactive sources, the team determines a set of criteria that allows a reasonable number of WIMPs, but rejects virtually all background particles. Finally, they "unblind" their data by looking at it and seeing whether any fit the criteria, revealing whether any of the elusive particles have been caught.

FINDING DARK MATTER

WIMP fever was running high on December 17, when physicists packed into auditoriums in California and Illinois to hear what, if anything, CDMS had discovered. *The Economist* had written on that day, "If the rumors are true, a solution to one of the great problems of physics may now be within reach." JoAnne Hewett, a particle physicist at SLAC, even liveblogged the event on Cosmic Variance. "The excitement in the air is palpable," she wrote. "Not much work is being done—everyone is pretty much talking in the hallways, trying to pass the time until 2:00."

Finally, the results were announced—two events had been found! The team had actually unblinded the data set a month before, while Golwala was at the Caltech Submillimeter Observatory on Mauna Kea in Hawaii, where he was doing astronomical observations with Bolocam for another project. "I was in my dorm room recovering from altitude sickness that morning," he recalls. "I was floating in and out of the teleconference as the unblinding was happening. I was lying on the bed and heard something about two events. I thought, 'Uh oh. What did we do wrong?'"

After checking the data and instruments, the team concluded that nothing had gone wrong. These two collisions were real. But,

The barn was born during the Manhattan Project, when American physicists needed a shorter way of saying 10^{-24} square centimeters, which is about the size of a uranium nucleus. In the July 1972 issue of *Physics Today*, Marshall Holloway and Charles Baker recount how they coined the term in 1942, after mulling over other candidates like "Oppenheimer" or "Bethe," in honor of the physicists who made the atomic bomb possible. But "Oppenheimer" was too long and "Bethe" was too similar to the Greek letter. In no small part because of where they both were from—Purdue University in Indiana, surrounded by farmland—they decided on the "barn," since a uranium nucleus was as "big as a barn." For security reasons, physicists also wanted to avoid discussing overtly technical terms on the phone. The U.S. government ended up classifying the term anyway, and didn't declassify it until 1948. "Zepto" is the prefix for 10^{-21}, and so a zeptobarn is 10^{-45} square centimeters.

before booking flights to Stockholm, they calculated that there was a 23 percent chance these signals were caused by background—likely electron recoils that had snuck past their set of criteria. As Golwala points out, "No one claims discovery with that high of a chance." The team couldn't say they had discovered dark matter, but they couldn't rule it out, either.

So CDMS hasn't revolutionized our understanding of the universe—yet. As for all the hype? "In a couple of months, no one will remember this," Golwala says. Still, their results—published in the March 26 issue of *Science*—are noteworthy, placing the most stringent constraints yet again on what WIMPs could be. "It's an exciting time in the bigger sense, because we've been producing results from this experiment for about five years," he says. "We've been the premier experiment in this field."

> "It's very possible that in the next five years we might be talking about WIMP astronomy, rather than just trying to detect something."

These data sets are marking the end of the current chapter in dark-matter searches. But new experiments are already under way, including a rival project called XENON100, which uses liquid xenon in lieu of germanium crystals. Situated in Italy's Gran Sasso National Laboratory, the experiment is likely to surpass CDMS's results with new data soon. In the next couple of years, half a dozen more projects will begin—and they'll be many times more sensitive than CDMS. One of those is the next generation of CDMS, called SuperCDMS.

The bigger a detector's crystal, the better the chance a WIMP will hit it. Boasting five "supertowers" with a total of 15 kilograms of germanium, SuperCDMS will improve that chance about fourfold. The team will install these new detectors in Soudan as early as this year. "The experiment could legitimately detect something in the next few years," Filippini remarks.

A couple more years down the line, the team will build even larger detectors—70 units for a total of 105 kilograms. With a twentyfold boost in sensitivity, the team will need to move SuperCDMS to SNOLAB, a mine near Sudbury, Ontario, just north of Lake Huron. At around two kilometers in depth, it's the world's deepest underground laboratory.

If that weren't enough, researchers hope to bury 1.5 tons of germanium in DUSEL, the Deep Underground Science and Engineering Laboratory, which is slated to be built about 2.5 kilometers underground in South Dakota. The experiment won't happen until 2017 at the earliest, but these are the kinds of projects that will increase WIMP sensitivities by a hundred times over the next decade, making physicists optimistic about the future. "It's very possible that in the next five years we might be talking about WIMP astronomy, rather than just trying to detect something," says Filippini.

Now that the latest data run is complete, the CDMS team is turning toward making better detectors. For example, Moore is working on a new sensor design with improved resolution. Based on technology developed by Jonas Zmuidzinas (BS '81), professor of physics, these so-called microwave kinetic inductance detectors would allow researchers to better pinpoint a WIMP's crash site. Ahmed, whose dissertation will include a lot of the latest results, is now designing a device to measure minuscule amounts of radioactivity. As detectors become more sensitive, materials need to be even cleaner, with as little radioactivity as possible. Current instruments, however, can't detect such low levels.

WIMP-search experiments are approaching what physicists call the zeptobarn scale (see box). The zeptobarn, which is 10^{-45} square centimeters, is a unit of cross section, the measure of how frequently a particle interacts. The larger the cross section, the more likely those particles will collide. The latest CDMS results rule out WIMPs with cross sections bigger than about 10^{-44} square centimeters, or 10 zeptobarns. If

WIMPs have cross sections bigger than this limit, then CDMS should've already detected them.

It turns out that the most compelling theories of supersymmetry or extra dimensions predict WIMPs to have cross sections of around a zeptobarn. Because the next generation of WIMP detectors will be sensitive to these kinds of particles, they could be discovered in the coming decade, Golwala says. But below a zeptobarn, things get weird. If you don't see anything by a zeptobarn, "you're excluding the most reasonable models," he says. "But no one said nature had to be reasonable." At cross sections of hundredths or thousandths of a zeptobarn, the likelihood of dark matter being WIMPs drops, and with limited funding, it might not be worthwhile to continue the search.

Regardless of when scientists discover dark-matter particles, it likely won't happen with a single, big announcement in one-inch headlines—despite what rumors might lead you to believe. The search is a slow, systematic sweep of the possible identities of dark matter, and any finding will have to withstand close scrutiny and be confirmed by multiple experiments.

Direct-detection experiments like CDMS are just one of three roads to determining whether dark matter is made of WIMPs. Physicists are trying to detect WIMPs indirectly with satellites like Fermi, which aims to measure the gamma rays that are shot out from WIMP-WIMP annihilations. They also hope to make WIMPs from scratch at the Large Hadron Collider in Geneva, which will be able to recreate the conditions of the universe moments after the Big Bang. These experiments represent a confluence of esoteric theory and tangible hardware that may soon solve one of the great mysteries of nature. "It's amazing that we can even ask the questions, what is the universe made of, and why it's made of that stuff," Golwala says. "And it's even more amazing that we can attempt to answer them."

EUREKA! . . . OR NOT

There have been plenty of tantalizing "discoveries" of dark matter. One experiment in Italy, called DAMA, has claimed to see dark matter not once, but many times. DAMA, like CDMS, tries to measure WIMP collisions. Instead of germanium, DAMA has sodium iodide crystals that glow when struck by particles, and instead of picking out individual WIMPs, it tries to measure the periodic ups and downs of collisions as Earth sails through the dark matter in our solar system. This annual modulation, as it's called, could be a signature for WIMPs. The group said they detected this signature first in 1997 and that they confirmed the signal multiple times, in 2000, 2004, and 2008.

The problem, though, is that no one else has been able to confirm the results. You have to be sure the signal isn't coming from another, non-WIMP source, such as an exploding star or just some artifact of your technique. "Over the last decade, DAMA has managed to slowly knock down all the objections I have had to their result, in terms of possible non-dark-matter explanations," Golwala says. "But that doesn't mean that all non-dark-matter options have been exhausted. And they have never been particularly forthcoming with their data, in spite of the extraordinary claim to have detected dark matter. Again, there is no way to conclusively prove it, but I tend to think it's not dark matter."

Another way to detect WIMPs is to see them annihilate one another in space. In the moments following the Big Bang, pairs of WIMPs—if WIMPs actually exist—would have been smashing into each other, igniting bursts of energy and showers of particles. Even though they wouldn't be crashing as frequently now as they did then, they would still manage to find one another once in a while. In 2008, a satellite called PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) and a balloon over Antarctica, ATIC (Advanced Thin Ionization Calorimeter), found complementary data that could be explained by WIMP annihilations. ATIC detected an excess of high-energy electrons, while PAMELA found extra high-energy positrons, or antielectrons. Last year, Fermi, NASA's gamma-ray space telescope, also detected a subtle boost in electrons.

But these extra particles could also have come from other sources, such as a type of dense rotating star called a pulsar. Golwala remains skeptical. "It's not possible to say this conclusively, but there have been too many of these signals that appear and then can be explained astrophysically to put much stock in any of them." All the different data don't fit together in a coherent picture, adds Moore. "There's no real smoking gun for any of those detections yet."

Sunil Golwala received his BA in physics from the University of Chicago in 1993. He received his MA in 1995 and PhD in 2000 from UC Berkeley, where he worked on the previous generation of the CDMS experiment with Bernard Sadoulet. He came to Caltech in 2000 as a Millikan Postdoctoral Scholar, became an Assistant Professor of Physics in 2003, and Associate Professor of Physics in 2010.

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