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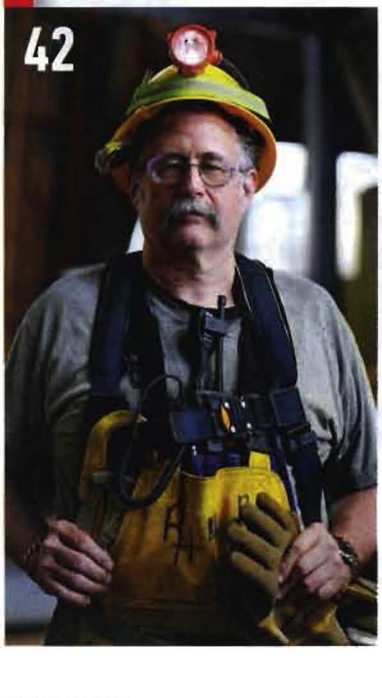
FEATURES



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MINING FOR DARK MATTER

The race to solve one of the biggest mysteries of physics could end with what scientists find 4,850 feet below the Black Hills of South Dakota BY BROOKE BOREL

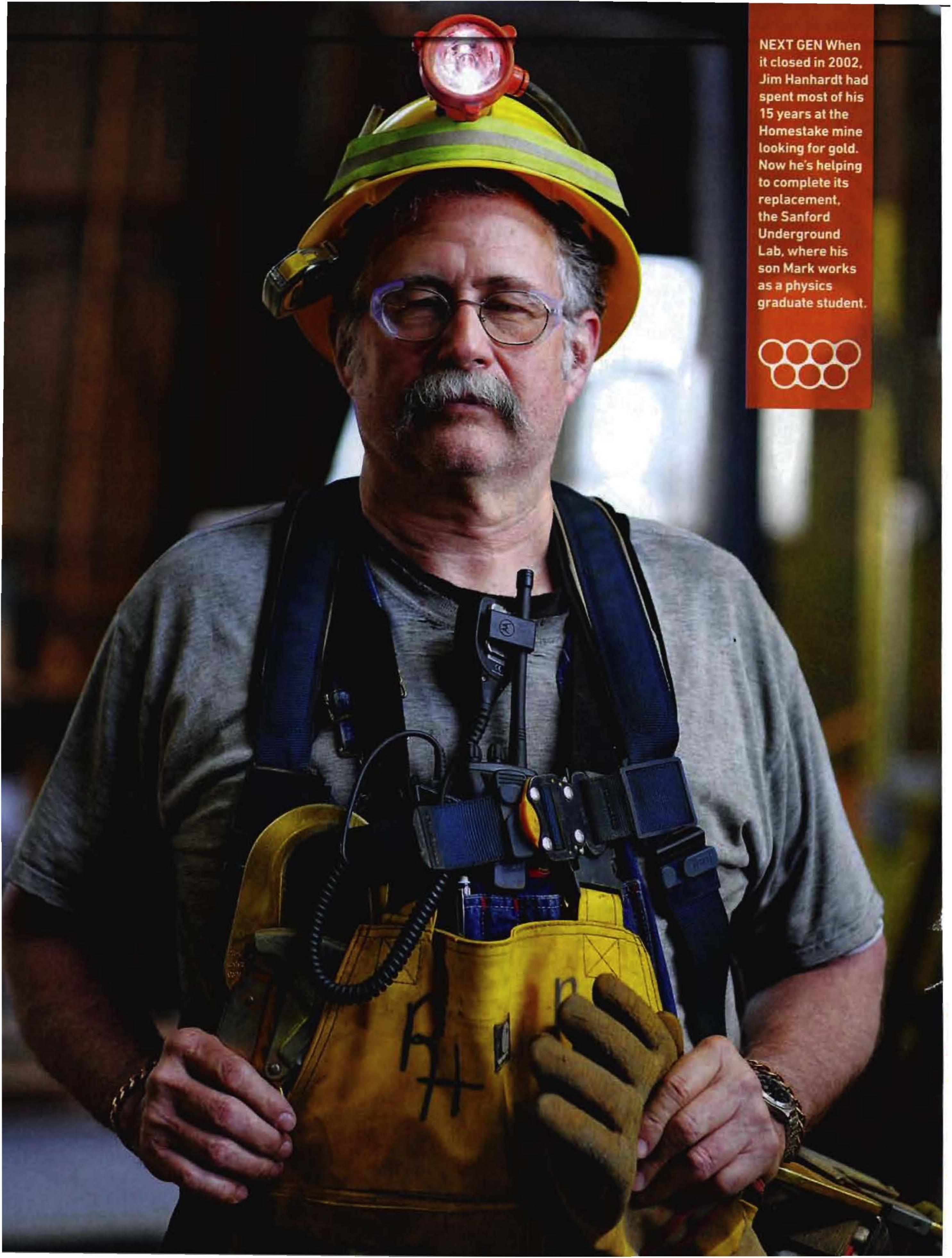
BETWEEN 1876 and 2002, the people of Lead, South Dakota, extracted $3.5 billion worth of gold from the Homestake mine. It was the town's main business, and when falling prices and diminishing returns finally shut it down, no one was sure what to do with the remaining 8,000-foot hole in the ground. Then, in 2007, the National Science Foundation decided that an 8,000-foot hole would be the perfect place to put its proposed Deep Underground Science and Engineering Laboratory, or DUSEL, a massive research complex that will include the world's deepest underground lab.

Now a team of physicists and former miners has converted Homestake's shipping warehouse into a new surface-level laboratory at the Sanford Underground Laboratory. They've painted the walls and baseboards white and added yellow floor lines to steer visitors around giant nitrogen tanks, locker-size computers and plastic-shrouded machine parts. Soon they will gather many of these components into the lab's clean room and combine them into LUX, the Large Underground Xenon dark-matter detector, which they will then lower halfway down the mine, where—if all goes well—it will eventually detect the presence of a few particles of dark matter, the as-yet-undetected invisible substance that may well be what holds the universe together.

The LUX project is just one of at least 10 efforts worldwide to find direct evidence of dark matter, and with a Nobel Prize and longer-term federal investment in play, the 50 researchers of LUX and 2,848 citizens of Lead (pronounced "leed") are pretty open about wanting to be first. But already there are problems.

For several hours now on this June afternoon, I've been watching through a window into the clean room as four physicists dressed in identical white Tyvek suits, latex gloves, blue booties, surgical masks and protective glasses prepare to connect two of the primary components of the detector. The inner cryostat is a hollow cylinder the size of a trash can that everyone refers to simply as "the can," and at the moment it is down below floor-level in a grate-covered pit. Hanging from a frame above the pit is the dome, which is a kind of lid for the can, and hanging from the dome itself is a complex assemblage called the skeleton. The idea is to carefully raise the can up around the skeleton, nesting one inside the other like a matryoshka doll, until it connects with the dome cap, making a perfect seal. The entire assemblage will eventually contain 31 gallons of −154°F liquid xenon—the medium that will

PHOTOGRAPHS BY JOHN B. CARNETT



NEXT GEN When it closed in 2002, Jim Hanhardt had spent most of his 15 years at the Homestake mine looking for gold. Now he's helping to complete its replacement, the Sanford Underground Lab, where his son Mark works as a physics graduate student.

MINE CAPSULE Physicists assemble the LUX (Large Underground Xenon) detector. When in place inside the Homestake mine, the liquid-xenon-filled capsule may detect three or four particles of dark matter a year.

actually detect the dark matter—so precision is essential. But the various parts were machined at different sites, and without that perfect seal, air and impurities could infiltrate the experiment, potentially compromising the results. As Tom Shutt, a physicist at Case Western Reserve University and the co-founder of the LUX project, explains, "We've been on pins and needles to know how tight this can will be."

Before they lift the can, though, the team must complete the skeleton itself. Right now it consists of little more than six thin titanium straps hanging down from the inner rim of the dome. The next task is to insert the three thick disks that make up the bulk of the skeleton. One of the physicists, hand-operating a small forklift, raises one of the copper disks to waist-height, and the others adjust a temporary support that will hold it in place as they make final adjustments to bolt it to the titanium straps. This process continues for each of the three disks: Lift, tighten, adjust, confer, adjust.

The physicists work their way down the skeleton until finally they are on hands and knees, spinning bolts into the last copper slab, just about six inches from the floor. In slow succession, they sit back on their heels or stand up to observe their handiwork. Shutt, who was responsible for coordinating the fabrication of the can, is up next. He excuses himself and heads to the clean room's antechamber to suit up. (Common dust, the type one might drag in from anywhere, can have high levels of radioactivity that could obscure the signal if the detector does find dark matter.) He is soon joined by an additional grad student, and the clean room is getting crowded. The six physicists wheel the skeleton-bearing frame to the side and open the pit's grate. One of them climbs down inside, connects two cables to the can, and scrambles out of the way. The cables are threaded through two pulleys on the frame, which the team slides back into place. They attach stacks of weights to the other ends of the cables, creating a simple elevator, and begin to slowly raise the can up and around the skeleton. Shutt stands to the side, his hands held palms out, fingers wiggling in anticipation like a kid waiting to open a gift.

Other scientists from the LUX project are gathering for the big moment, and I get elbowed over to the side window where the grad students have congregated. As the can nears the top, the murmurs die down. The skeleton is sliding perfectly into place. But, less than an inch from the dome, where the can should finally lock into place, it jams. Shutt and his team try to ease it up, and they try shoving it, but it just won't budge. The physicists suspect that the can's dimensions or the shape of the skeleton are off. Despite this apparent setback, they gamely pose for a few photos. Then they methodically lower the can back into the pit. They'll try again tomorrow.

MOST (BUT NOT ALL) PHYSICISTS AGREE THAT DARK MATTER EXISTS, AND THAT IT IS MADE OF WIMPs.

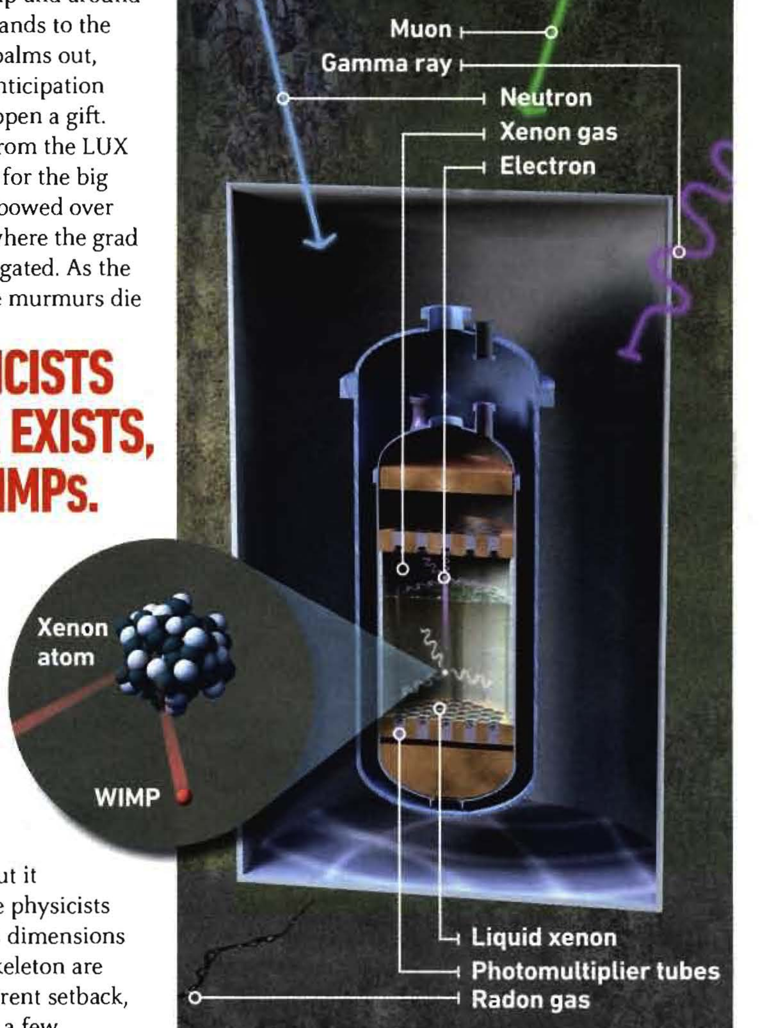
NO ONE KNOWS what dark matter is, or if it even really exists. For now, it is just a placeholder, an *x* that must be plugged into various calculations in order to square

CHRIS SHORT

HOW LUX WORKS

Nearly a mile under the Black Hills, the LUX detector will search for dark matter in the form of weakly interacting massive particles, or WIMPs. "Weakly interacting" is no misnomer: Even though physicists will fill the detector with 750 pounds of **liquid xenon**, they're crossing their fingers for a few WIMPs a year.

They do see the rare events twice. When the **xenon nucleus** is struck by a **WIMP**, it produces light waves and electrons. The light is picked up by **photomultiplier tubes** at the can's roof and floor. Microseconds later, the **electrons** reach **xenon gas**, where they make a second flash that is 600 times as bright as the first.



Suppressing Noise

Many other particles could fool the LUX detector. **Muons** would drown out a WIMP signal, but the earth above the tank pares them down by a factor of five million. The rock creates its own problems: Trace amounts of uranium emit **neutrons** and high-energy **gamma rays**, which can masquerade as WIMPs. The 80,000-gallon pool of water blocks them both, and the half inch of stainless steel surrounding the water keeps out radioactive **radon gas**.

astronomical observations with the rules of Newtonian physics. The name comes from Fritz Zwicky, a Swiss astronomer who in 1933 used two well-established methods to calculate the mass of the Coma cluster, a group of more than 1,000 galaxies. One calculation was extrapolated from the movement of eight galaxies in the cluster using Newton's second law of motion, which says, in essence, that the bigger the galaxy, the faster it spins. The other estimated the cluster's total mass by quantifying the amount of light given off by its stars. The results should have been equal, but instead the movement-based number was an order of magnitude greater. The Coma galaxies were spinning much faster than would be predicted by the amount of overall light emitted. For the Newtonian equation to add up, there had to be more mass. Zwicky dubbed this missing bulk "dark matter."

Zwicky's work was largely ignored until 1970, when another astronomer, Vera Rubin, documented similar discrepancies in the Andromeda galaxy. Since then, researchers have found that the visible mass in hundreds of other galaxies is also too small to explain the rate of motion, at least within the context of our current understanding of physics. Astronomers have also discovered invisible "gravitational lenses" that cause light to bend around themselves—despite these lenses having no identifiable mass with which to distort the fabric of spacetime and bend light in the first place. All of this suggested that more than 80 percent of the matter in the universe was simply invisible to us.

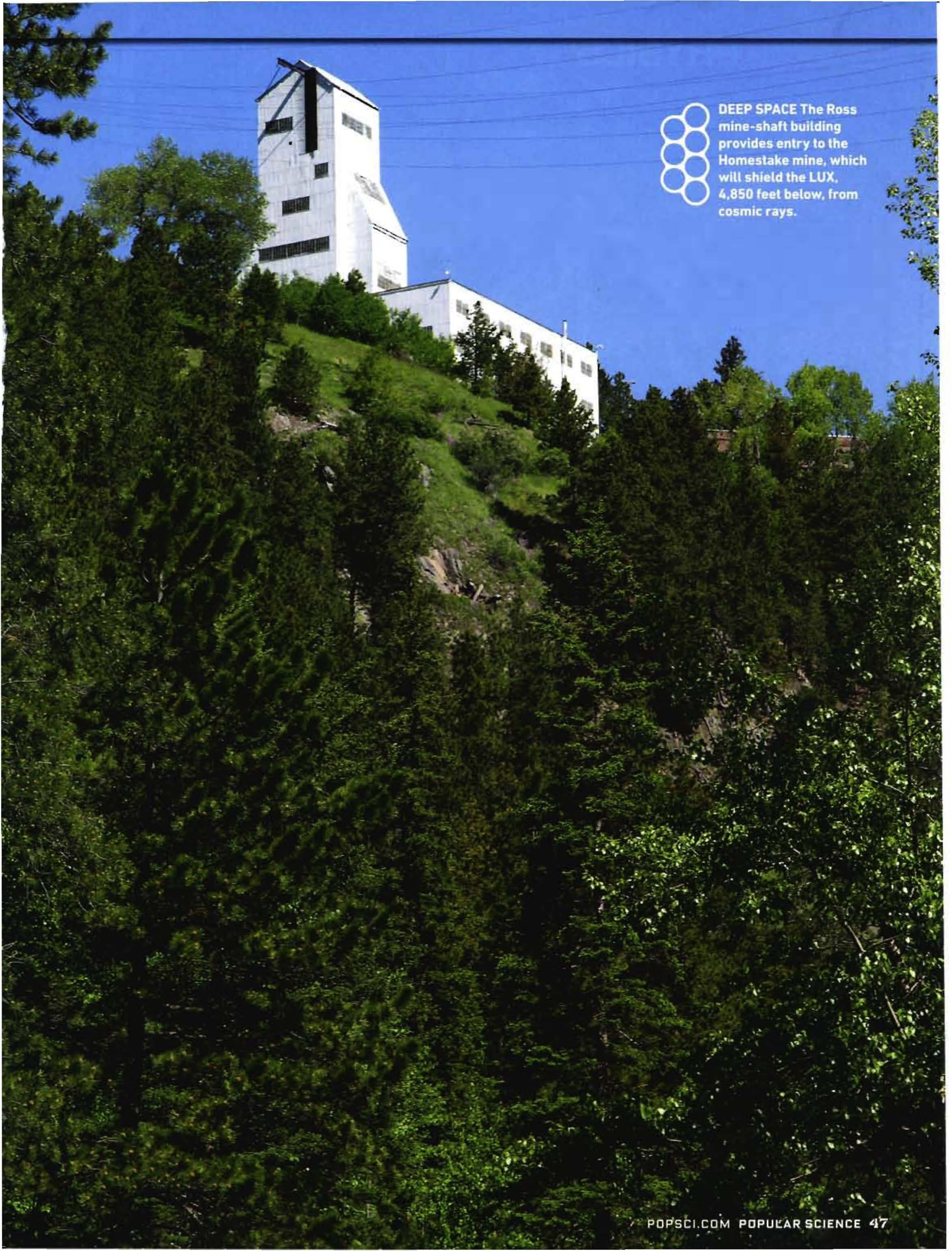
Today, most (but by no means all) physicists agree that dark matter exists, and that it is probably made up of what they call WIMPs, or weakly interacting massive particles. "Massive" doesn't mean that the particles are large, but that they have mass and therefore both respond to and cause gravitational pull. "Weakly interacting" means that the particles, despite having mass, nonetheless only rarely interact with matter. Scientists also assume that WIMPs are electromagnetically neutral, which is why we can't see them. Indeed, as of yet all arguments for the existence of dark matter are made from inference. No one has ever directly observed the stuff. Many scientists, including Rubin, are skeptical about the WIMP theory, and in some cases about the notion of dark matter itself; they think Newtonian physics simply might not describe how motion works on a galactic scale. When I asked Dan Akerib, Shutt's partner at Case Western and a principal investigator on the LUX project, why WIMPs are the most popular candidate, he adopted the standard scientific position—WIMPs are simply the best current theory: "A glib way to say it is that WIMPs are the least crazy thing to look for."

Which is where LUX and other competing programs, all of which are premised on the existence of WIMPs, come in. When astronomers find evidence of dark matter throughout the universe, it appears to be unevenly distributed. Gravitationally, it behaves like regular matter: It clumps together. Dark-matter theorists currently suspect that it concentrates in a spherical cloud encompassing most galaxies. As our own solar system rotates in the Milky Way, both it and the galaxy move within one of these clouds, and the particles in the cloud—the WIMPs—flow through the Earth and everything on it at a rate, physicists guess, of about 100,000 per square centimeter per second. The physicists at LUX and the teams of physicists that run the 10 or so competing programs hope to catch a WIMP in the act. These other detectors (some using germanium as their detector material, others using liquid xenon, as LUX does) are buried underground, in old mines and sewers or under mountains, to shield them from other cosmic particles that could masquerade as a WIMP.

Most WIMPs will evade the detection medium, but Shutt and Akerib theorize that around three or four per year will bump into the nucleus of one of the 1.6 octillion (that's a billion billion billion) xenon atoms in LUX's tank, and that when one does, it will set off two minuscule flashes of light—the first direct evidence that dark matter exists.

HE SEEMS UNFAZED BY THE FACT THAT HIS $3-MILLION DETECTOR TO DETERMINE THE TRUE NATURE OF THE UNIVERSE IS ON HOLD FOR WANT OF AN $80 POWER TOOL.

THE CAN STILL doesn't fit, even after another full day of lifting, tightening and adjusting, so Shutt has recruited me to drive him and one of his students to the hardware store in nearby Deadwood, the town in which famed Wild West lawman Bill Hickok played his last fateful card. The plan now is to file down a near-invisible inner weld seam near the can's bottom, which the scientists think is catching on the skeleton, and to do so Shutt needs a Dremel rotary tool and several diamond-tipped bits. He seems unfazed by the fact that his



DEEP SPACE The Ross mine-shaft building provides entry to the Homestake mine, which will shield the LUX, 4,850 feet below, from cosmic rays.

ARE WE THERE YET? Physicists Tom Shutt, Dan Akerib and Dan McKinsey [left to right] watch as their colleagues piece together the skeleton of the LUX detector inside the Sanford Lab clean room.

$3-million detector to determine the true nature of the universe is on hold for want of an $80 power tool.

Filing a seam would normally be a simple task. But the can is made of titanium, which is extremely hard. The lab is only six months old and doesn't yet have an on-site machine shop or many tools. If Shutt entrusts an unfamiliar shop with the can, he risks exposing LUX to low-level radioactivity from metal filings, which, like dust, could mask WIMP signals down the road. Every last nut and bolt must be as close to radiation-free as possible, so each material it touches or location it visits must be carefully vetted. The team will grind the seam in the clean room first thing in the morning.

The hardware store's well-lit aisles offer up house paint and car parts and, in a nod to the local propensity for motorcycle travel, a calamine-and-cornstarch saddle-sore remedy called Anti Monkey Butt. Shutt asks a woman in a smock where the Dremels are, and we head directly for a central aisle, where we locate a dozen Dremels on a shelf below a pegboard holding hundreds of small plastic boxes of bits. Shutt pulls down handfuls of packages, scanning the labels for diamond, which emits no radioactivity, and instructs his student to do the same. He says that over the past few years he has spent more than $60,000 buying parts on eBay, including precision-cleaned bits, turbo pumps and $10,000 worth of orbital weld fittings. Akerib estimates that the team has also made hundreds of McMaster Carr orders.

As we continue our search, a young, bespectacled clerk with a patchy red beard strolls up, ready to assist. I've been anticipating the moment when I could observe a physicist–local interaction firsthand. The stories the scientists have told me have a common theme: The people who live in the area love the massive physics project taking place around (and beneath) their town. They approach the physicists at bars, grocery stores, gas pumps and the YMCA sauna to voice their support. More than 100 people showed up to a dark-matter talk given by Shutt and project co-founder Rick Gaitskell of Brown University, and afterward audience members followed the pair to a local bar for more. The town's visitor center sells T-shirts emblazoned with the lab's logo and the words "Nerds Searching for WIMPs."

"These Dremel packages have a bunch of different accessories," the clerk notes, pulling a box off the shelf. "We don't need accessories," Shutt says as he rifles through the plastic boxes of individual bits. "We need the most powerful motor you have." They go back and forth a bit more. How about something with a variety of bits? *No, we need diamond.* What about these diamond bits? *Nope, not big enough.* This one, maybe? *Nope.* Finally, the clerk turns to me and asks where we're from. I tell him that Shutt works in the Sanford lab and we're getting tools for the detector. The clerk nods his head and looks at the growing pile of bits. Then he asks, "So how's it going?"

I WASN'T EXPECTING TO BE PUT TO WORK. I TRACE THE ERRANT SEAM WITH A GLOVED FINGER. IT SEEMS IMPOSSIBLE THAT SUCH A SMALL THING COULD CAUSE SO MANY PROBLEMS.

THE LUX TEAM'S competitors, though in some cases further ahead in their projects, are also working through their own problems. One project, the Cryogenic Dark Matter Search II, is located in an old iron mine in Minnesota. The physicists there made headlines in December 2009 when they thought they had detected two WIMP signals. Both turned out to be false alarms, but they intend to try again with a bigger detector called SuperCDMS. Another frontrunner, Xenon100, hidden under the Gran Sasso mountain in central Italy, is already operational. As the name indicates, Xenon100 uses a technology similar to LUX. But Xenon100's detector tank is much smaller than LUX's and also less sensitive. Thus far, it has detected nothing.

Researchers are also using indirect methods of finding WIMPs. In some cases, they aren't searching for dark matter directly, but using Earth and space-based telescopes to search for the odd particles that are expected to result when two WIMPs come into contact and annihilate each other (a phenomenon supported by particle theory). Physicists at the Large Hadron Collider in Switzerland, meanwhile, are attempting to create their own WIMPs from scratch, by smashing protons together. A synthetic WIMP could help physicists recalibrate their detectors to look for natural particles in the correct energy range, but so far scientists have been unable to make one.

All of these efforts are expensive, and so the search for dark matter has created something of a boom in the towns where it takes place. In Lead, for instance, the Sanford lab is causing a rare uptick in the local real-estate market, creating extra business for local stores and restaurants and employing hundreds of local people, from mine-shaft maintenance [CONTINUED ON PAGE 86]

[CONTINUED FROM PAGE 49]

MINING FOR DARK MATTER

workers to geologists to human-resources managers. And the lab is just the first stage in the larger DUSEL project, which is expected to receive more than $875 million from the federal government and has already pulled in another $47.3 million from the state and $70 million from private donors. That will fund the transformation of Homestake's 370 miles of tunnels and 186 surface acres into the DUSEL complex: physics labs that will include LUX's already-planned successors, which will have much larger xenon tanks and thereby increase the chances of capturing WIMPs.

Like the Homestake Mining Company before it, DUSEL is set to make Lead a company town. Homestake was more than just an employer; it influenced nearly every other aspect of life in the community. "If Lead needed it, Homestake built it," says mayor Tom Nelson, whose grandfather, father and brother all worked for the mine. "They did the water system, they brought the power in, the railroad, the hospital, the recreation center, the company store, the bank. Everything was the company." The Sanford lab, and the pending DUSEL project, may not run Lead's local health clinic or bank, but it will bring money and jobs. Philanthropist and lab namesake T. Denny Sanford set aside $20 million of his $70-million donation for a science education center, where DUSEL researchers will lecture and students will get hands-on underground physics experience. The project's annual operating budget is $23 million, more than half of which is spent locally with local suppliers or contractors. And around 70 former mine employees now work for the South Dakota Science and Technology Authority, the entity created to convert the property from mine to lab.

Beyond Lead there is another, larger community—the entire particle physics and astrophysics communities—rooting for the success of the project. Without WIMPs, the Standard Model of physics—the theory that governs the interactions of all known subatomic particles—is weakened, and scientists will have to rethink their assumptions about subatomic physics. And without hard proof that dark matter exists, our basic understanding of the composition of the universe unravels. "If it ends up that dark matter is not made of WIMPs, it will be much more disappointing in a philosophical sense than in a personal sense, in that humankind won't know what dark matter is," Shutt says. "We're fully prepared that we might not find it ourselves. But if we as a community don't find it, that will be awfully disappointing."

YET ANOTHER FULL DAY has passed, and the can still does not fit. This time, though, I'm on the other side of the

FIELDWORK PHYSICS

MINING FOR DARK MATTER

window, dressed in borrowed clean-room regalia. Shutt and I are peering down into the pit, where the can is on its side, two Tyvek-clad legs poking out of one end, as though someone wearing an enormous metal party hat had fallen forward on his stomach. The new Dremel screeches, then the grinding stops. My ears ring. The legs shimmy outward, revealing that they are attached to James White, another LUX researcher from Texas A&M, who looks up at me: "You wanna come help?"

I wasn't expecting to be put to work. I climb down the ladder to the pit, and White hands me the Dremel. He demonstrates on a seam close to the top of the can; the section I need to tackle is farther in, close to the bottom, where there is room for only one. It's a tight fit. I'm folded in on elbows and knees, a position I can't hold for long. A grad student shines a bright light through a flange at the bottom of the can and occasionally snaps my picture. I trace the errant seam with a gloved finger. It feels impossible that such a small thing could cause so many problems. I hold the Dremel bit firmly against it. Sparks fly as I start to grind. The sound is deafening.

I'd like to tell you that my Dremeling saved the day, that we successfully lifted the can shortly thereafter. But we didn't. After hours of grinding and a burned-out $80 Dremel motor, the can still did not fit. It turns out that the LUX team spent another two weeks finishing the can campaign. I later learned, when I spoke to the physicists in September, that the key to success was filing down a few of the copper pieces on the skeleton, copper being much easier to grind than titanium. Between my visit and then, the team had confronted at least five similarly minor yet mission-jeopardizing challenges, including a case of seized bolts (a result of intense cleaning that left the threads of a flange and the rod that screws into it so spotless that they bonded together on a molecular level) that required an emergency search for lubricant and hacksaws.

Now LUX is 95 percent complete. The team is preparing for the first of several test drives in which they will lower the xenon-filled detector into a 66,000-gallon tank two stories below their lab and see how it runs. Next they will begin the work of planting LUX 4,850 feet underground, sometime late this year. And then the wait begins, as physicists and the residents of Lead collectively hope that the giant hole in the ground that over the years yielded so much treasure will provide them with continued economic stability—and possibly the secret to understanding the universe.

Brooke Borel is a writer in Brooklyn. She is the proud owner of a "Nerds Searching for WIMPs" T-shirt.