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dimensions of particle physics
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Illustrations: Sandbox Studio, Chicago

Almost a mile underground, in a new science facility in South Dakota, scientists of the LUX collaboration are building the world's largest dark-matter search experiment.

By Bill Harlan

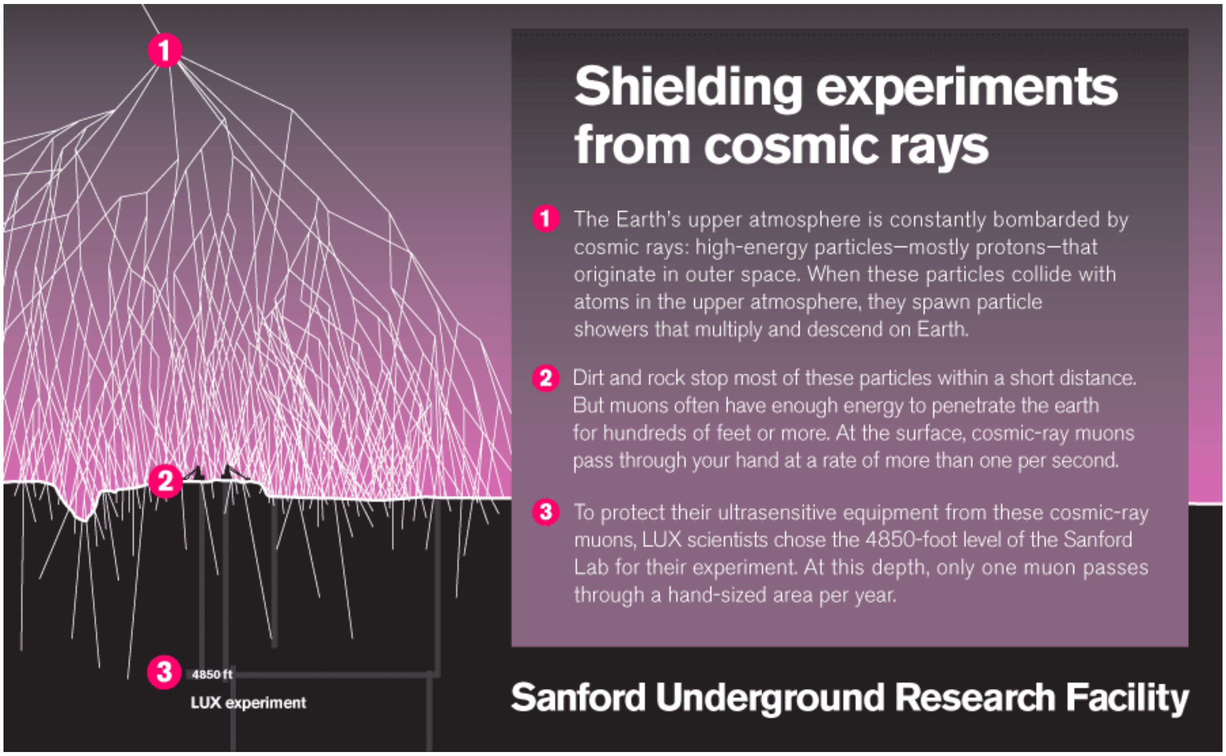
This summer, researchers working in a former gold mine in South Dakota will slowly lower a titanium thermos the size of a phone booth into a large tank of purified water. The cylindrical thermos—nicknamed "the can" by its inventors—will hold ultra-pure liquid xenon and an array of photosensors, each capable of sensing a single photon of light.

The can will be the core component of the Large Underground Xenon detector, or LUX, the most sensitive experiment yet to search for the elusive substance called dark matter.

Physicists will install the LUX detector deep underground to protect it from the noise of cosmic radiation. The Earth's upper atmosphere is constantly bombarded by high-energy subatomic particles—mostly protons—that originate in outer space. When these cosmic particles collide with nuclei of oxygen and nitrogen atoms in the atmosphere, they spawn showers of smaller particles. The resulting cosmic din would drown out the faint signals in ultra-sensitive detectors like LUX, if they were on the surface of the Earth. Deep underground, however, the noise abates, and the LUX detector will reside very deep—4850 feet beneath the surface—where cosmic radiation is more than a million times quieter. The water in the tank surrounding the LUX detector will further protect it from extraneous noise, such as naturally occurring radiation from the nearby rock.

Once LUX has been lowered into the water, the detector will be cooled to minus 162 degrees Fahrenheit (about minus 108 degrees Celsius) and filled with liquid xenon. By October, the experiment could be collecting data.

"We'll turn it on, take data for one week, and see what we get," says Brown University physicist Simon Fiorucci. "It could be a very interesting result."



First signs of invisible matter

Interesting indeed. Physicists have suspected the existence of a mysterious, undetected form of matter since 1933, when Swiss astronomer Fritz Zwicky noticed an apparent discrepancy between two methods of estimating the mass of distant galaxies. The mass of galaxies as measured by the light emitted from them was less—far less—than the galaxies' mass measured by applying Newton's theory of gravity to their relative motions. To move as fast as observed, the galaxies had to contain more matter.

Observations over the past 80 years have confirmed Zwicky's discovery, leading physicists to a startling conclusion. The universe, it seems, contains a large amount of invisible matter, and so far we've never been able to catch it on Earth. This substance, whatever it is, does not emit light and only rarely reacts with other matter, except through gravity. Yet this missing matter is five times more abundant than the ordinary matter that makes up everything we can see or detect—planets, solar systems, galaxies, interstellar dust, and gas—everything.

"It's simply remarkable that we're still so ignorant about the dominant form of matter in the universe," says Brown University physicist Rick Gaitskell, who with physicist Tom Shutt of Case Western Reserve University is leading the LUX collaboration. Gaitskell and Shutt each have more than 20 years of experience searching for dark matter. "I've worked with five different technologies," Gaitskell says, but so far none of them have yielded a direct detection of dark matter.

The prime suspect

Physicists, of course, do have theories about what dark matter might be. The leading candidate is the "weakly interacting massive particle," or WIMP. More than a dozen research teams on three continents are hunting WIMPs, among them the Xenon 100 experiment at the Gran Sasso National Laboratory in Italy, which already is operating a detector using 100 kilograms of liquid xenon. LUX, with 350 kilograms of xenon, will take that search to a new level.

"There were good physics principles for why building a detector at the scale of LUX was a much better investment of time and money than building another small instrument," Gaitskell says. "It's proportional to the mass." In other words, the more xenon in the detector, the greater the likelihood of a xenon-WIMP collision. Gaitskell and Shutt chose the South Dakota location not only for its great depth, but also for its capacity to host larger experiments.

A new lab a mile underground

The Homestake gold mine in Lead, South Dakota, is 8000 feet deep, with more than 370 miles of tunnels. The mine closed in 2003, but the state of South Dakota began reopening it for science in 2007. Today the Sanford Underground Research Facility, or SURF, is operated by the South Dakota Science and Technology Authority, or SDSTA, in partnership with the Department of Energy's Lawrence Berkeley National Laboratory. The Department of Energy also is considering SURF for a number of long-term experiments. They include a SURF partnership with DOE's Fermilab to build a neutrino experiment that would explore whether neutrinos are the reason that matter dominates over antimatter in our universe.

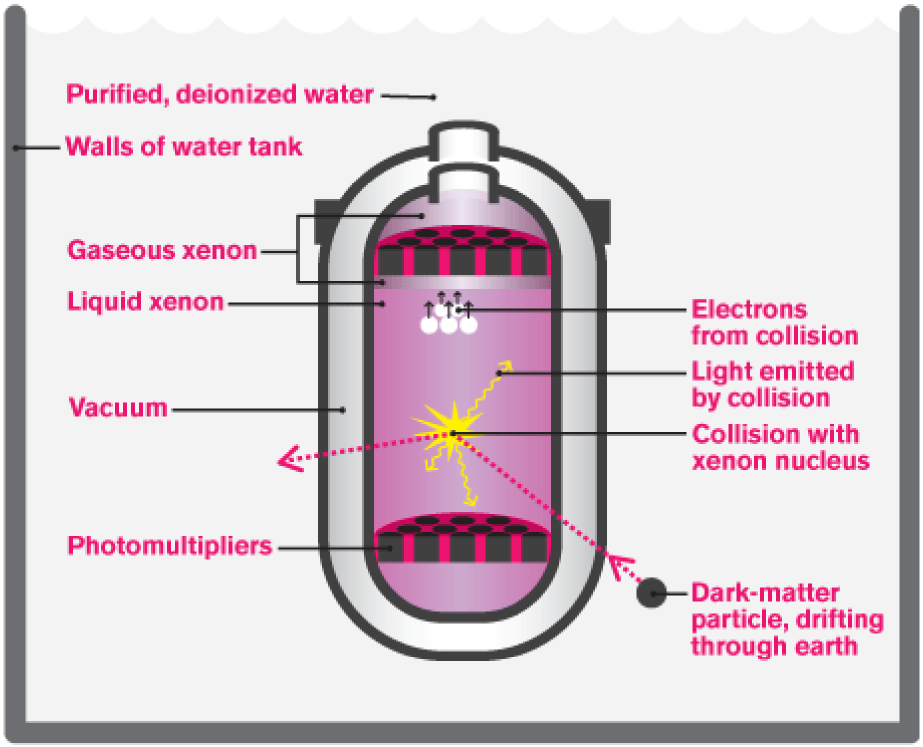
For the first experiments at Homestake, the SDSTA has nearly completed construction of a 12,000-square-foot research campus at the 4850-foot level of the mine. In the 1960s, nuclear chemist Ray Davis installed a neutrino detector at that level. He and his colleagues operated the Homestake experiment for three decades, working alongside gold miners who affectionately referred to his 100,000-gallon chlorine-based detector as "the neutrino tank." Davis, who worked for DOE's Brookhaven National Laboratory, went on to earn a share of the 2002 Nobel Prize in Physics for that research. Now his cavern has been enlarged and outfitted for LUX.

The SDSTA also has excavated an adjacent cavern to house a second experiment, the Majorana Demonstrator, and its installation is in full swing. Majorana will look for a rare phenomenon called neutrinoless double-beta decay to find out whether neutrinos are their own antiparticles.

Catching WIMPs with a can

The LUX collaboration includes 14 universities and research institutions and dozens of scientists from around the world. LUX physicist Fiorucci, for example, grew up in Paris. Like Gaitskell and Shutt, he's a veteran of the dark-matter hunt. He's worked on the EDELWEISS dark-matter detector in France and the XENON dark-matter experiment at Gran Sasso in Italy. Fiorucci has been working on LUX since 2007—dividing his time between Brown University and SURF in South Dakota, helping to design, build, test and, now, deploy the experiment.

WIMPS drift all around us, and through us, Fiorucci explains, mostly without hitting anything. (Remember, they're called "weakly interacting.") WIMPs will drift through LUX, too. Scientists expect that occasionally, maybe a handful of times a year, a WIMP will hit the nucleus of a xenon atom. When it does, something wonderful happens. "Xenon is a great scintillator," Fiorucci says, explaining that the WIMP-xenon collision will generate a tiny amount of light—a photon or two—enough to be picked up by the 122 photomultipliers at the top and bottom of the titanium can. On the surface, where a hundred cosmic-ray particles per second hit every square meter, these rare, WIMP-produced photons would get lost among the noise generated by other particles. Deep underground, LUX has the chance to record this telltale signal.



LUX detector

Looking for mayhem

The initial flash will reveal the time of the collision and its energy. To make sure a photon doesn't originate from a non-WIMP process, scientists are recording a second signal stemming from the WIMP-xenon collision.

"What really happens is, the WIMP bumps into a xenon nucleus and causes all kinds of mayhem," Fiorucci says.

The mayhem temporarily frees electrons, which tend to re-attach themselves to atoms once they calm down. That re-attachment process causes the first flash of light. However, the LUX detector also has been rigged with an electrical field that will pull some of the free electrons into the gas phase of the xenon surrounding the photosensors at the top of the LUX detector, where they too will emit light. That second signal carries with it more information about the energy of the collision, as well as the collision's location within the detector.

LUX sensors will note the time difference between the two sets of flashes—hence the detector's full scientific name, a two-phase, time-projection chamber. The ratio between the two signals will be unique, depending on what kind of particle produced it. "That tells you if you have a WIMP," Fiorucci says.

Unless, in a twist, the signal comes from a neutron. Neutrons produced in naturally occurring subatomic reactions in the rock and material surrounding the LUX detector could wander into the liquid xenon, producing a signal nearly identical to that of a WIMP. That's why LUX will have more than three times the amount of xenon than the largest existing dark-matter detector. Unlike WIMPs, neutrons are likely to bump into multiple xenon atoms on their way through the detector, creating multiple flashes. Near the edge of the detector, a neutron might escape after producing just a single collision, mimicking a WIMP signal, but in the very center of LUX—the sweet spot—the neutrons' multiple interactions will be a dead giveaway. Because of its large volume, LUX will have the largest sweet spot of any xenon-based detector in the world. "The backgrounds are suppressed exponentially as the experiment gets larger," Gaitskell says.

More stringent constraints or a discovery?

That advantage, plus the shielding provided by SURF's great depth, gives the LUX collaborators a certain amount of confidence—tempered with caution. "In the perfect world, we'll take a week of data, and already we'll have results better than anyone in the world," Fiorucci says. "In practice, however, you look at the data and you spend a few weeks calibrating the detector."

Shutt also is reluctant to compare LUX's sensitivity to other experiments. "If you haven't turned it on yet, you don't really know," he says. "We should be more sensitive by a factor of 10, but it really depends on how well we do." Still, after a year of operation, which is the duration researchers are planning for this version of the experiment, LUX will likely have advanced the search for dark matter far beyond its current boundaries—even if it detects nothing. In fact, especially if it detects nothing. That result will allow scientists to set stringent constraints on the properties of dark-matter particles. "The more you see nothing, the better your detector is," Fiorucci says.

The ultimate prize, of course, would be the actual discovery of dark-matter particles. Planning already is under way for a bigger version of LUX, with 3 to 5 tons of xenon. The water tank at the 4850-foot level at SURF was specifically designed to accommodate the larger, next-generation experiment.

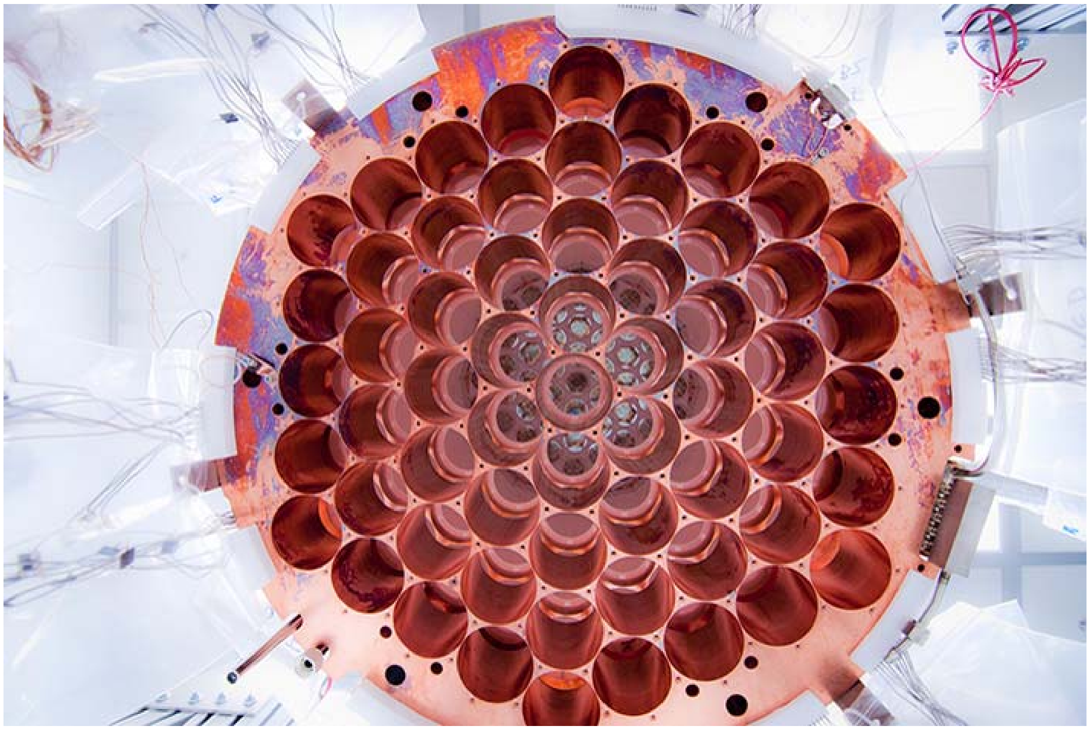
Why should we care about detecting dark-matter particles? Shutt answers by citing the relationship between mathematical models and practical applications. "Our ability to harness things is based on our mathematical understanding of the world," he says. "That's led to all the engineering we have. It's how we build airplanes, it's how we build anything." Newton, Einstein and others have built a mathematical model of gravity, and for 80 years it has been telling us there's more to the universe than meets the eye. One explanation could be that we don't understand gravity, but for Shutt, the mathematics suggests a more compelling explanation. "Somehow, there's a whole chunk of the universe we're not seeing."

LUX will begin looking for that chunk later this year.

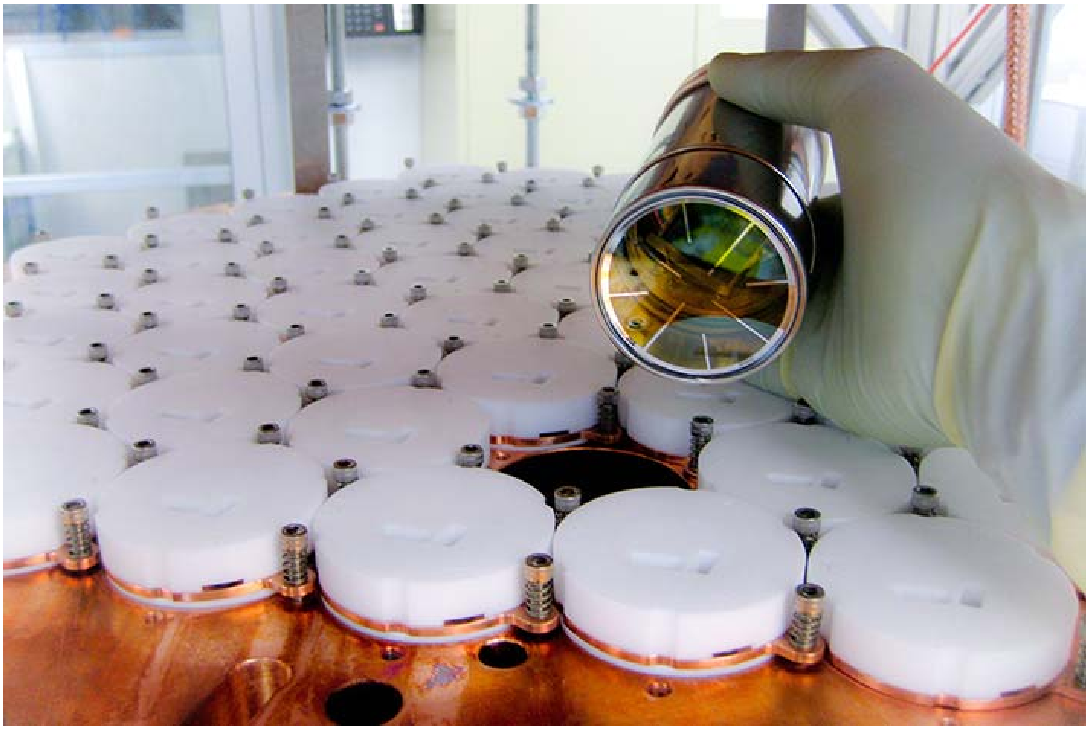
The Homestake mine in South Dakota, known for its iconic headframes and a depth of more than 8000 feet, closed in 2003. The state of South Dakota began reopening the mine for science in 2007. *Photo: Reidar Hahn*

The former gold mine is located in Lead, South Dakota, which has a population of about 3000 people. South Dakota has committed nearly $130 million to the facility, including a $70 million donation from philanthropist T. Denny Sanford. *Photo: Reidar Hahn*

The LUX dark-matter detector, which scientists assembled and tested in a clean room above ground, is one of two physics experiments that will be installed 4850 feet underground in the new science facility this summer. *Photo: Matt Kapust*



The LUX detector features two arrays with 61 slots each for photomultipliers. When in operation, the arrays will be surrounded by 350 kilograms of xenon. *Photo: Carlos Faham*



The ultrasensitive photomultipliers of the LUX experiment can detect the rare photons emerging from the collisions of dark-matter particles with a xenon nucleus. *Photo: Carlos Faham*

In July 2010, engineer Wendy Zawada stands on the last pile of rock that needed to be removed from the cavern for the LUX experiment, 4850 feet underground. *Photo: Matt Kapust*

Construction workers are turning the former gold mine into a state-of-the-art underground research facility. The tunnel to the right provides secondary access to the Davis cavern, which will house the LUX experiment. The doorway to the left is the entrance to the Transition cavern, which will house the Majorana Demonstrator experiment and provide primary access to LUX. *Photo: Matt Kapust*

The floor of the Davis cavern is designed to support the heavy, cylindrical water tank that will surround the LUX detector. *Photo: Matt Kapust*

The LUX detector hall is ready for the installation of the large water tank. The lid of the tank, assembled from stainless steel plates, lies on the concrete floor. *Photo: Matt Kapust*

Construction workers built the water tank starting from the top. A temporary gantry was used to lift the lid off the ground, and welders attached the cylindrical walls below the lid, one ring at a time. *Photo: Matt Kapust*

The stainless steel tank, completed in January 2011, will hold 71,600 gallons of purified, deionized water to protect the LUX detector from naturally occurring radioactive decays. Technicians will lower the detector into the water this summer. *Photo: Matt Kapust*

LUX scientist Simon Fiorucci inspects the progress of the underground construction. Before joining the LUX collaboration, he worked on the EDELWEISS and XENON dark-matter experiments at Gran Sasso, Italy. *Photo: Matt Kapust*

The LUX control room, at right, is located on the second floor of the LUX detector hall, above the water tank. Data taking could begin as soon as October 2012. The tunnel leads to the Majorana Demonstrator experiment. *Photo: Matt Kapust*

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