symmetry
dimensions of particle physics

A joint Fermilab/SLAC publication

issue 1

volume 7

February 2010

SCIENCE GOES UNDERGROUND
2 Editorial
A US deep underground lab would allow this country to be a leader in many areas of science. Our magazine tends to focus on particle physics, but we recognize that geology, geomicrobiology, and other fields also need a deep science facility to progress, and we discuss some of those possibilities in this issue.

3 Commentary: Lucia Votano
Underground physics has a glorious past at its back. Here at Gran Sasso, we see a future just as bright ahead, with the potential for unique contributions to the discovery of the laws of nature and the understanding of the evolution of the universe.

4 Signal to Background
Sonic Booooum shakes art world; Neanderthal crashes SNOLAB; China dreams deep; L’Aquila science center appeals for donations; kids reach out to kids after earthquake; letters.

8 symmetrybreaking
A summary of recent stories published online in symmetrybreaking, www.symmetrymagazine.org/breaking

On the cover
Deep underground, physicists set traps to catch dark matter, neutrinos, rare particle decays, and other exotic phenomena. These protected subterranean lab spaces are highly valued by scientists in a number of fields for their isolation and their easy access to depths where geological and microbial processes help shape the Earth and the nature of life itself.
10 DUSEL: Big Plans for Deep Science
Plans are under way to turn the former Homestake mine in South Dakota into the first US national laboratory for underground science and engineering—the largest and deepest facility of its kind in the world.

18 EXO Takes Clean to an Extreme
Some particle physics experiments require an extraordinary degree of cleanliness and quiet. How far will they go to achieve this? Try etching tools with acid, setting up shop in a deep salt bed, putting equipment on stilts, and choreographing a 2100-kilometer truck ride so not a moment would be lost.

24 Gran Sasso: A Tale of Physics in the Mountains
In an epic story of fairy-tale beauty and world-leading science, human courage and determination confront adversity and Gran Sasso laboratory comes forth to see the stars once more.

32 Bringing Dark Life to Light
The stunning realization that up to half of life on Earth may exist underground has transformed biologists’ thinking about the origin and evolution of life here and on other planets. They’re hoping to take the search for “dark life” to new depths at a proposed underground laboratory.

38 Day in the Life: Soudan Lab
Just before 7:30 on a bitter cold morning in northern Minnesota, engineer Jim Beaty begins the last leg of his daily commute. He steps into a dark brown metal box with five coworkers. Someone slides the door closed. In pitch dark, with its engine thundering, the elevator shudders as it travels a half mile below ground.

42 Accelerator Application: Mining
Looking for ways to get more metal out of ore, scientists are turning to a technology born in particle accelerator research—the synchrotron lightsource. These machines also play a role in analyzing mine waste and developing safe ways to dispose of it.

C3 Logbook: Neutrino Oscillation
In June 1998, the Super-Kamiokande collaboration revealed its eagerly anticipated results on neutrino interactions at the Neutrino ’98 conference in Japan. They presented strong evidence that three known types of neutrinos apparently transform into each other, a phenomenon known as oscillation.

C4 Explain it in 60 Seconds: Shielding
Shielding refers to layers of material that block radiation. We don’t need shielding from cosmic rays; but this steady background radiation does bedevil scientists and their experiments because it can drown out the nearly imperceptible signals of rare subatomic processes.
Science opportunities
depth underground

If you’re a dark matter particle or a neutrino, it’s a constant struggle to make
yourself heard. The universe is an exceptionally noisy place, filled with
a rain of cosmic-ray particles—mainly high-energy protons. One of the few
places to escape the noise is deep underground, where the rock, earth,
or water above shields against cosmic rays and allows other particles to tell
whatever they are trying to say.

If we’re going to listen to them, we need to work underground. But working
underground is not easy. It requires a significant investment in resources
to build an underground laboratory, which not only has to be deep, but also
clean. Experiments there need extra attention in their design, construction,
and transport. Due to the expense of digging deep, most underground
laboratories around the world piggyback on some other facility like a mine,
tunnel, or underground storage facility.

Currently in the United States, there are a few underground facilities.
However, none lie at the depths required to block enough cosmic rays to
let us hear the signals of ultra-rare particle events that hold the key to
discovering the fundamental nature of the universe. Many experiments
are conducted in existing shallow US facilities, but those requiring greater
depths are installed in underground labs overseas, where they typically
come second to the domestic science priorities of host countries.

A US deep underground lab would allow this country to be a leader in
many areas of science. Our magazine tends to focus on particle physics, but
we recognize that geology, geomicrobiology, and other fields also need
a deep science facility to progress, and we discuss some of those possibilities
in this issue.

The US Department of Energy and the US National Science Foundation
are exploring ways that they might work together to develop a deep
underground laboratory for science and engineering research. If created as
proposed, it would be a world-leading facility, offering enough space for a
wide range of experiments addressing fascinating and important scientific
questions. We hope that such a facility will be constructed and help drive
US and global physics, geology, and biology.

David Harris, Editor-in-chief
An auspicious time for Gran Sasso

In September 2009, I began my new assignment as director of the Gran Sasso National Laboratory, the biggest underground laboratory in the world devoted to neutrino and astroparticle physics. I couldn’t help thinking that 2009 was an auspicious year. It marked the thirtieth anniversary of the official birth of the project and the twentieth anniversary of the first experimental data published by Gran Sasso’s MACRO experiment.

I reflected on the scientific path of these past 30 years and on the advances we have made in understanding the fundamental laws of nature and the evolution of the universe. I thought about the extraordinary growth in this type of physics, which connects elementary particle physics, astrophysics, and cosmology. The community of astroparticle physicists has increased considerably, along with the dimensions, complexity, and technology of the experiments.

The Gran Sasso National Laboratory, one of the four laboratories of Italy’s Istituto Nazionale di Fisica Nucleare, or INFN, has maintained a leading role throughout these transformative years. At least two earlier Gran Sasso experiments represent major milestones in the scientific activity of the lab. GALLEX/GNO, a radiochemical experiment, measured the flux of neutrinos from the sun and made a decisive contribution to solving the famous solar-neutrino puzzle. The MACRO experiment provided the worldwide limit on the flux of magnetic monopoles and, together with the Japanese experiment Kamiokande, measured the effect of atmospheric neutrino oscillation.

Currently, our laboratory is at the height of its activity and I can say I have inherited a rich scientific legacy. Gran Sasso hosts more than a dozen experiments devoted to neutrino physics, dark matter, neutrinos from the sun and galactic collapsing stars, geoneutrinos, nuclear astrophysics, geophysics, and environmental and seismic monitoring.

Despite all the recent progress, fundamental questions remain. What is the microscopic nature of the unknown elementary particles that make up dark matter? Theoretical physicists have proposed a roster of possibilities, among them weakly interacting massive particles (WIMPS) such as neutralinos, candidates for direct detection in the laboratory. Researchers are using many different techniques based on scintillating crystals, cryogenic detectors, and noble liquids in search of a definitive dark-matter signature. Because the expected detection rate is so low—one event per day per 100 kilograms of target material—the hunt for dark matter through direct detection can succeed only in an underground laboratory using radioactively ultra-pure detector materials. The dark-matter mystery is so compelling that capturing dark-matter particles could well be the discovery of the century.

Another fundamental question may be: Why does neutrino physics matter? Neutrino oscillations may be a result of physics beyond the Standard Model of particle physics at energy scales not otherwise reachable. They could be a window on a new fundamental theory and on the evolution of the universe. The next generation of neutrino experiments could determine the absolute scale of neutrino masses, discover matter-antimatter asymmetry in neutrinos, and establish whether neutrinos are their own antiparticles. Physicists might even discover so-called sterile neutrinos, interacting with ordinary matter only through gravity. How do neutrinos relate to the matter-antimatter asymmetry of the universe?

If, for example, neutrinos are their own antiparticles, it could mean they played an essential role in the survival of matter in the early universe.

Underground experiments looking for what physicists call neutrinoless double beta decay are the only ones that can determine if neutrinos are their own antiparticles. The next generation of these experiments will begin in the very near future. To complete the experimental overview, huge underground detectors will be able to dig deep into neutrino physics using neutrino beams from accelerators, as well as neutrinos raining in from the cosmos or generated below ground. At the same time, they will shed light on proton decay.

Underground physics has a glorious past at its back. Here at Gran Sasso, we see a future just as bright ahead, with the potential for unique contributions to the discovery of the laws of nature and the understanding of the evolution of the universe.

Lucia Votano is director of the Laboratori Nazionali del Gran Sasso.
French artist Nelly Ben Hayoun is no stranger to science. Her portfolio of work includes explorations of brain plasticity in snails, a scheme for generating dark matter in a kitchen sink and a recliner in which people can experience the first 10 minutes of a Russian Soyuz rocket’s lift-off sequence.

She may have outdone herself with her latest project, though. For Super K Sonic Booooum (top photo), she constructed a flashy version of Japan’s Super-Kamiokande neutrino observatory in London’s Shunt Lounge, a labyrinth of abandoned railway tunnels beneath the London Bridge train station that’s been turned into an underground performance space.

“I’m really obsessed with large-scale scientific experiments,” Hayoun says. “The project was born from the idea of giving everyone access to the Super-K detector.”

The installation consisted of a 49-foot-long channel filled with nearly 4000 gallons of water and lined with 600 balloons representing Super-K’s thousands of photomultiplier tubes (left photo). Visitors rowed through two at a time in a small dinghy, accompanied by physicists from Imperial College London and Queen Mary, University of London. Every 10 minutes, loud booms and bright flashes of blue light simulated interactions between incoming neutrinos and the atoms of water—the events that the real Super-K is designed to detect.

There was no question about the installation’s popularity. According to physicist Francesca di Lodovico of Queen Mary, one of the presenters at Super K Sonic Booooum, people lined up for more than an hour to go through the faux observatory. Fifteen hundred attended during an 11-day run in November.

“It was really amazing,” she says.

Nicholas Bock
Underground, good stories are found

Prior to 2002, very few non-scientists knew that Sudbury Neutrino Observatory laboratory, or SNOLAB, existed. But these days, the laboratory must regularly turn away people who want to visit, even though entering the underground facility requires a long ride down a mine shaft, a sanitation shower, and a full body suit to keep contaminants out of the lab.

SNOLAB rests in the Vale Inco Creighton nickel mine in Sudbury, Ontario. Two kilometers below the surface, it is the deepest underground laboratory in the world.

It was the novel *Hominids*, by Robert J. Sawyer, that turned the lab into such a desirable destination.

In Sawyer’s book, there exists a universe parallel to our own, where Earth is much the same except that Neanderthals survived and humans died out. The Neanderthals conduct quantum computing experiments in the location equivalent to SNOLAB for the same reasons that humans picked the mine for neutrino experiments: In addition to protection from cosmic rays, the mine has significantly lower levels of background radiation, which can interfere with highly sensitive experiments, than most underground sites. The novel begins with a Neanderthal passing through a portal into our world, shattering a 30-foot-wide acrylic sphere that was part of the lab’s first neutrino experiment.

Sawyer says he grounds all of his work in scientific fact, and that using a real laboratory location adds to a book’s credibility. “SNOLAB gave me all kinds of opportunities,” Sawyer says. “It’s a fascinating place to write about.”

His novel *FastForward*, which takes place at the Large Hadron Collider, has been adapted for television. Other novels feature TRIUMF, Canada’s national laboratory for nuclear and particle physics research, and the Perimeter Institute for Theoretical Physics.

*Hominids* has been published in 15 languages and won the Hugo Award, the world’s top science-fiction honor. “It gives us a welcome opportunity to discuss the science we’re doing,” SNOLAB Director Nigel Smith says, “and to help people try and understand the extreme efforts we’re going through to do it.”

Calla Cofield

World’s deepest lab proposed in China

Chinese scientists have carved out a space in the heart of a mountain where a search for dark matter will soon begin. It’s just the first taste of what they hope to do there: Create the world’s largest, deepest underground laboratory.

The China Jinping Deep Underground Laboratory, or CJPL, would piggyback on a giant hydroelectric project that’s under construction in a rugged, remote area of Sichuan province. Engineers are building two dams and drilling tunnels to carry road traffic and water from the Yalong River 17 kilometers straight through Jinping Mountain.

The project’s two traffic tunnels caught the attention of physicists, because they offer easy access to the mountain’s core. Most of the 2513 meters of overlying rock is marble, whose low level of natural radioactivity would provide ideal shielding for physics experiments. If completed, this lab would surpass the proposed 2400-meter-deep DUSEL laboratory in the United States and the current record-holder, Canada’s SNOLAB, which goes down two kilometers. Chinese researchers say the lab would be open to scientists from around the world.

Proponents acknowledge that the giant lab is far from a done deal. The project will need approval from the National Development and Reform Commission, a process that could take several years, says Hesheng Chen, director of the Institute of High Energy Physics in Beijing.

In the meantime, Tsinghua University scientists have excavated an initial lab space, six by six by 40 meters, with the aid of $4 million in US dollars from the university and the Chinese Ministry of Education and help from the Ertan Hydropower Development Company. They are installing detectors there and plan to start searching for dark matter by mid-2010. And they plan to apply for funding to carry out a bigger dark-matter experiment, as well as to study the feasibility of excavating the “huge cavity”—size yet to be determined—that would house the deep lab of their dreams.

Glennda Chui
Plans for science center in quake-damaged L'Aquila

Many towns have public science centers. But it’s difficult to think of one so close to the geographic, spiritual, and cultural heart of a city as one being planned in L’Aquila, Italy.

The 7.5-acre Parco del Sole (Park of the Sun) science center will sit at the center of L’Aquila in a park filled with towering trees and wide lawns. Next door stands a symbol of the medieval city, the church of Santa Maria di Collemaggio, whose roof partially collapsed in an earthquake that ravaged the town and the region last April. A destination for pilgrims, it housed the body of Pope Celestine V and is considered by many to be the site of the first Papal Jubilee.

Tying the two together, a statue with Pope John Paul II’s declaration, “Science and faith are both God’s gifts,” would stand at the Parco del Sole entrance.

A small planetarium and exhibit hall would showcase the work of nearby Gran Sasso National Laboratory, the world’s biggest underground laboratory and a partner in the project.

The plan grew out of a suggestion by town leaders who appreciated Gran Sasso’s long history of science outreach. Still, the offer caught then-laboratory director Eugenio Coccia off guard. “I was impressed that just by a spiritual center could be a scientific center like this park,” he said from his University of Rome office.

Planning for the project was already under way when the April 6 earthquake struck. More than 60,000 people lost their homes, and much of the daily business of the town has had to relocate to Rome and other places.

“So this project is going on slowly now,” Coccia says, “but I am confident that it is so good that it will go on.”

The National Italian American Foundation is collecting donations to move the project forward. The project Web site, www.parcodelsole.org, has this message: “Completion of this project will symbolize a renaissance for the town as well as a scientific inspiration for future generations.”

Tona Kunz

The crayon connection: A lot of families lost their homes when an April 6 earthquake hit near Italy’s Gran Sasso National Laboratory. Kids at the Fermilab daycare center collected art supplies and sent them to the kids of Gran Sasso, along with drawings and a letter of support. They received heartfelt thank-you drawings in return.
Don’t make us guess
In the latest symmetry, I read that, “The two-mile-long linear accelerator at SLAC National Accelerator Laboratory is the second-longest building in the world.” OK. I give up. You opened the question and gave no answer: What is the longest building in the world now?
John Michael Williams, Silicon Valley Technical Institute

The editors respond:
We didn’t mean to tease! When Beijing International Airport Terminal 3 opened in 2008, it took the title of longest building in the world. It is 3.25 km long, edging out the SLAC klystron gallery at a “mere” 3073 meters. Visiting the SLAC klystron gallery is an item on our physics life list (Aug 07).

Shining Cherenkov’s light on Vavilov
The article on Cherenkov light in “Explain it in 60 seconds” (Aug 09) provides a concise and helpful explanation of Cherenkov radiation to readers.

Of course, the Cherenkov radiation is named to honor the Russian physicist Pavel Alekseyevich Cherenkov and this term is commonly used by the physics community. But Vitaly Ginzburg, the Russian physicist who died recently, always called the radiation Vavilov-Cherenkov radiation to give credit to the other co-discoverer, Sergei Ivanovich Vavilov.


The 1958 Nobel Prize in physics was awarded to Cherenkov, Il’ja Mikhailovich Frank, and Igor Yevgenyevich Tamm “for the discovery and the interpretation of the Cherenkov effect”. It would be not acceptable for Ginzburg that the Nobel committee did not include Vavilov’s name in the headline of the announcement. Vavilov died in 1951, and Nobel Prizes are not given to dead persons.

It is worthy of mentioning that the relationship between Vavilov and Cherenkov was teacher-student. In 1933 Vavilov proposed the PhD topic "The luminescence of the uranyl salt solutions under the influence of hard gamma radiation" to Cherenkov. As a consequence of Cherenkov’s hard work, their study turned out to be two papers published in 1934. One paper was on experimental results by Cherenkov, and the other was by Vavilov in which he proposed, correctly, that the origin of the new phenomenon was fast electrons.

Min-Liang Wong, National Chung-Hsing University, Taiwan

An eye for type
Could you please tell me the name of the font family that you use for the print edition of symmetry? From what I can tell, the slanted terminals on the c, e, and s and the forms of many of the numbers don’t match Helvetica or Arial. It’s a very striking font; it reminds me of the old NYC subway signage. I would guess that it’s based on Akzidenz Grotesk or one of its derivatives such as Standard or Basic Commercial. Am I right?

Although it may seem unorthodox for a scientist to say, I have long observed that design is an important element of scientific communication. Many of the more successful experimental particle physicists that I know habitually take extra care in preparing their presentations and graphics from the standpoint of aesthetics and clarity. Obviously, there are some very successful people who are a total mess, but there is in my experience a correlation between attention to design issues in presentations and personal success. Akzidenz is probably a good font for presentations. It’s clean, easy to read at a distance, and distinctive.

Matthew Moulson, INFN Laboratori Nazionali di Frascati

The editors respond:
We are often asked about the typeface we use in symmetry. As Matt correctly guesses, it is indeed Akzidenz Grotesk. The typeface was created in 1896, but we feel it still looks modern and retains all its good qualities for print that made it popular a century ago. The more recent typeface Helvetica is based on it, and both Univers and Folio take inspiration from it.
New MINOS results "strongly disfavor" sterile neutrino, neutrino decay
February 2, 2010
In the search for a better understanding of neutrinos, the Main Injector Neutrino Oscillation Search, MINOS, recently put forth results that help rule out a theorized fourth neutrino and strengthen the case against the hypothesis of neutrino decay.

CERN's new LHC plan: Two years at 3.5 TeV
February 1, 2010
CERN's new plan for the next phase of the Large Hadron Collider: run the accelerator for up to two years at an energy of 3.5 TeV per beam. The run, expected to start at the end of this month, would end no later than December 2011 and be followed by a long shutdown to prepare the accelerator to run at its full energy of 7 TeV per beam.

Strongly interacting dark matter ruled out by observations
January 22, 2010
The possibility that dark matter could be made of heavy, strongly interacting particles has been ruled out by neutrino observations at the IceCube detector. Scientists said the result closes the window on the possibility of a massive version of the SIMP, or Strongly Interacting Massive Particle, called the simpzilla.

Easy listening and learning with Deep Science podcasts
January 15, 2010
Check out this selection of physics podcasts on the science that could occur in the Homestake Mine in South Dakota. Scientists explain how biologists hope to study extreme forms of life, theories about the origin of the universe, and how the LUX experiment will search for dark matter.

Ground-breaking neutrino R&D gets government boost
January 14, 2010
The Department of Energy has given the Long-Baseline Neutrino Experiment a key level of approval known as Critical Decision-o, invigorating US and international collaborators. The experiment will aim the world's most intense beam of neutrinos from Fermilab to a distant detector.

US sends first ILC-type cavities to Japan
January 12, 2010
A Fermilab shipment of cavities to KEK lab in Japan marks a major milestone in the advancement of US particle accelerator technology. SRF cavities allow very energy-efficient acceleration of particle beams. They'll be needed for future experiments into the origins of the universe and the nature of matter, including the proposed International Linear Collider and Project X.

Fermi telescope closes in on mystery of cosmic-ray acceleration
January 7, 2010
Cosmic rays are some of the most energetic and enigmatic particles in the universe. A new result from the Fermi Gamma-ray Space Telescope offers insight into how the universe accelerates these particles to such high energies. They appear to be coming from the remains of exploded stars.

Expanding girls’ horizons
December 28, 2009
Ever thought that a physics class would teach you how to make your own comet with dry ice, water, and sand? Or that math could be a gateway to the world of computing science behind applications like Google? For the 250 girls who attended the first European...
Expanding Your Horizons conference in Geneva, these and many more exciting topics were on the menu.

**ATLAS’ wonderwall**
December 24, 2009

At CERN, traveling artist Josef Kristofoletti is painting an enormous mural that will represent the Large Hadron Collider’s ATLAS detector almost in 3D.

**Dark-matter experiment results announced**
December 17, 2009

Scientists from the Cryogenic Dark Matter Search have detected two events that have characteristics consistent with the particles that physicists believe make up dark matter. While this result does not pass the stringent statistical test needed to claim a dark matter discovery, it has caused considerable excitement in the scientific community.

**Fueling the future: Using accelerator-driven systems to recycle nuclear waste**
December 14, 2009

The superconducting radio frequency technology that Fermilab scientists are helping to develop could one day pave the way to cleaner nuclear power, by producing fuel and recycling nuclear waste.

**FlashForward: Science fact vs. science fiction**
December 11, 2009

In the December 3 episode of ABC’s *FlashForward*, researchers from a fictional organization called the National Linear Accelerator Project announced that they might have caused a worldwide blackout that killed 20 million people by conducting “proton-driven plasma-wakefield acceleration” experiments. In real life, plasma-wakefield experiments at SLAC National Accelerator Laboratory aim to find a cheaper, more efficient way to accelerate particles, with potential benefits for thousands of particle accelerators in everyday use around the world.

**How a new muon experiment can advance physics**
December 9, 2009

While many signs point to the existence of physics outside the realm of current knowledge, a treasure map doesn’t exist, and a new particle’s discovery won’t necessarily include clues to how it fits into the rest of the particle zoo. A new Fermilab-based experiment, the Muon-to-Electron Conversion experiment, or Mu2e, could shine light on those gray areas, aiding researchers at the Large Hadron Collider in Europe and likely the next generation of collider experiments.

**We found the Higgs; it was in Greenwich Village**
November 20, 2009

Aspiring physicist Heidi Baumgartner is certainly destined for physics fame after successfully finding the Higgs boson on October 31, 2009. While the rest of the scientific community toils away building multi-billion-dollar machines like the Large Hadron Collider to search for the much-coveted Higgs in the wreckage of particle collisions, Baumgartner says she found it quite by accident, amid the chaos of New York City’s Greenwich Village Halloween parade.
BIG PLANS FOR DEEP SCIENCE

LEAD
SOUTH DAKOTA
When the Homestake mine closed in 2003 after producing 42 million ounces of gold, it left a colorful gold rush history, tall steel headframes looming over a town of 3000 people, and an enormous hole in the ground: North America’s largest and deepest underground mine.

Now scientists are rushing to Lead, South Dakota, to claim the empty space the miners left behind. A meeting to discuss potential experiments, held in 2008, brought together 350 researchers from around the world. Plans are now under way to turn Homestake into the first national laboratory for underground science in the United States—and the largest and deepest facility of its kind in the world.

“The deeper the better,” says Robert Svoboda, a physics professor at the University of California, Davis, who has worked on underground neutrino experiments in Japan and Europe for the last two decades. Together with 200 collaborators, he hopes to use the lab in South Dakota for an experiment to find out what role neutrinos played in the evolution of the universe. It is one of more than 40 scientific experiments scientists already have proposed for the new laboratory.
Physicists seek out deep places for their research because they offer shelter from cosmic rays, the steady rain of particles hitting Earth. We don't feel them as they pass through our bodies, but their constant background patter is enough to drown out the rare, faint signals stemming from things like the decay of an atom, particles of dark matter, or neutrinos spat out by an exploding star. The more rock that scientists put between their experiments and the sky, the greater their chance of making a discovery.

Several countries, including Canada, Italy, and Japan, already have extensive deep-science programs. But the rising worldwide interest in underground science and engineering has led to a shortage of underground lab space, especially at very great depth. In the United States, existing underground facilities, such as the Soudan Underground Laboratory operated by the University of Minnesota, have limited space and are not deep enough. Each additional 1000 feet of overlying rock reduces the number of incoming muons—cosmic-ray particles that are a major problem for ultra-sensitive physics experiments—tenfold.

STARK SUPPORT
Over the past decade, a dozen independent reports from the National Academies and multi-agency government committees have emphasized the need for a deep underground laboratory in the United States. In 2007, the National Science Foundation selected the 8000-foot-deep Homestake mine in the Black Hills of South Dakota as its top choice for the potential site of the Deep Underground Science and Engineering Laboratory, or DUSEL. The following year, a particle physics advisory group of the Department of Energy and the National Science Foundation, known as the P5 panel, urged the funding agencies “to make this facility a reality as rapidly as possible!” The panel recommended “that DOE and NSF work together to realize the experimental particle physics program at DUSEL.” In response, the two agencies established a joint oversight group to help advance the DUSEL plans. The group is modeled after the successful joint oversight group for the US contributions to the Large Hadron Collider at the European Laboratory CERN.

If the DUSEL project goes forward, it would almost double the world’s present underground-laboratory space, with enough floor space to cover almost two football fields and caverns large enough to hold the Mount Rushmore carvings of the heads of four US presidents. The space would house clean rooms, lab benches, cryogenic equipment, and the world’s largest neutrino detectors, along with locker rooms and a lunch hall. The mine’s roughly 400 miles of tunnels would give geologists, biologists, and other scientists unprecedented access to rock formations, geological processes, undisturbed groundwater, and ancient, deep-living microbes that may hold clues to the origin and evolution of life here and on other planets (see story on page 32).

NOBEL HISTORY
The former gold mine already has a reputation for Nobel Prize-winning research. In 1965, physicist Ray Davis started an experiment at the 4850-foot-level of Homestake to look for neutrinos emitted by the sun, using a tank filled with 600 tons of fluid to catch the invisible, ghost-like particles. Over a period of 30 years his experiment succeeded in capturing a couple of thousand solar neutrinos and proving that nuclear fusion processes account for the energy our sun and other stars radiate. In 2002, Davis and Masatoshi Koshiba, founder of the Kamioka neutrino experiment in Japan, shared half of the Nobel Prize for Physics for their pioneering contributions in astrophysics and the first observations of neutrinos from extraterrestrial sources.

“Homestake is the birthplace of neutrino astrophysics,” says UC Berkeley physicist Kevin Lesko, who worked for years on an experiment to detect solar neutrinos with the Sudbury Neutrino Observatory, located more than a mile underground in a Canadian nickel mine.

The state of South Dakota has embraced the DUSEL idea and started the process of rehabilitating the Homestake mine, which had begun to fill with water. To prepare the mine for its proposed mission, the state has turned the mine into the Sanford Underground Science and Engineering Laboratory, with the help of a $70 million donation from banker and philanthropist T. Denny Sanford.

“New discoveries, new ideas, and the knowledge and education that will result from future research and experiments are more valuable than gold,” Governor Michael Rounds of South Dakota said at the dedication of Sanford Lab in June 2009.
Photos: Bill Harlan, Sanford Lab, and Steve Babbitt, Black Hills State University
If the NSF approves the final DUSEL proposal—a decision that will be made in 2011—the new laboratory is expected to absorb Sanford Lab and greatly expand its surface campus and underground space, adding caverns and laboratories at the 4850- and 7400-foot levels of the mine.

**THE SCIENCE BEGINS**

Scientists have started to scope out the mine’s microbial wildlife and groundwater flow, as well as explore whether the vast mine would make for a good gravity-wave detector. Geologist William Roggenthen of the South Dakota School of Mines & Technology has installed a seismic array with sensors at several levels of the mine to measure the motions of rock. This three-dimensional view will help improve models of rock motion that were based purely on surface measurements.

“The science is beginning,” says Jose Alonso, who served as director of Sanford Lab for two years until his retirement in October 2009. Miners began excavating the new underground space for Sanford Lab last fall, blasting away the first layers of rock in September. “Rehiring the people and miners familiar with the mine has been a tremendous success,” Alonso says. The construction, which includes the expansion of the Davis cavern, will add underground space equivalent to the size of three tennis courts.

**SETTING UP DARK-MATTER TRAPS**

Scientists will use the expanded Davis cavern to set up a dark-matter detector, the heart of the Large Underground Xenon experiment. LUX scientists will try to trap the mysterious, invisible matter that accounts for 80 percent of all matter in the universe.

Astrophysicists postulated the existence of dark matter when they discovered that the gravitational forces stemming from the ordinary matter we can see with our eyes and telescopes were not enough to explain the shapes and motions of galaxies. But dark matter’s origin and composition remain a mystery.

To detect dark-matter particles that drift through the earth, the LUX scientists will use liquid xenon, a transparent liquid that is three times denser than water. And they will use a lot of it—more than 700 pounds—to increase the chance that a dark-matter particle will collide with a xenon atom and produce a faint signal that can be picked up by photodetectors.

A former Homestake warehouse, converted into a lab with clean room and cryogenic equipment, already serves as staging area for the LUX experiment and allows scientists to get ready for the underground installation of their experiment this year.

A second physics experiment in preparation at Sanford Lab, called the Majorana Demonstrator, will explore a long-standing mystery: Are neutrinos their own antiparticles? Scientists have known for a long time that every elementary particle has a partner with the opposite electric charge—its antiparticle. For instance, the electron’s antiparticle is the positron.

Since neutrinos have no electric charge, physicists face the possibility that a neutrino and its antineutrino are the same particle—or, conversely, that they are two distinct types of particles, like electrons and positrons. Theorists have developed mathematical frameworks that explain either one of these two scenarios. Once underground, the Majorana Demonstrator will help determine which theory is correct by testing several detector technologies that measure the properties of neutrinos in the decay of germanium atoms.

Eventually, the Majorana scientists hope to build at DUSEL, in collaboration with scientists from the European GERDA experiment, a one-ton germanium detector to solve this neutrino puzzle once and for ever. Another experiment, called EXO, that is aimed at solving the same puzzle has been proposed for DUSEL as well; its first phase is being tested in another below-ground lab in New Mexico (see story on page 18).

**PLANNING GOES FORWARD**

The competition for underground lab space is fierce. Last summer, a committee winnowed the long list of proposals for underground research in physics, engineering, geosciences, and biology at DUSEL down to 16. These proposals—including the neutrino physics proposal by Svoboda and his colleagues—are now under consideration for the initial suite of experiments that DUSEL could host. Proposals for other experiments will have to wait until the laboratory is up and running.

A team at UC Berkeley, led by Lesko and South Dakota’s Roggenthen, is developing the preliminary design of DUSEL’s extensive surface and underground facilities and
the overall plan for the scientific, engineering, and educational goals of the laboratory. The NSF will review their report before the end of the year.

Last fall, Lesko and Roggenthen invited scientists to the city of Lead for a meeting of future DUSEL users. About 150 senior scientists attended, including researchers representing more than two dozen experiments that had not been chosen for the initial round. One of the main goals of the meeting was to begin to identify the infrastructure the new facility must include to accommodate a wide range of science.

“We are pursuing some of the most exciting aspects of several different disciplines simultaneously,” Lesko says. “We will exploit the synergies among those different disciplines.”

THE FIRST ROUND OF PHYSICS

Nine proposals are under consideration for the initial suite of physics experiments at DUSEL, and scientists have received $21 million in NSF funding to refine them. The proposals cover four areas of research:

- What is the nature of dark matter? (Proposals for LZ3, COUPP, GEODM, and MAX)
- Are neutrinos their own antiparticles? (Majorana, EXO)
- How do stars create the heavy elements? (DIANA)
- What role did neutrinos play in the evolution of the universe? (LBNE)

In addition, scientists propose to build a generic underground facility (FAARM) that will monitor the mine’s naturally occurring radioactivity, which can interfere with the search for dark matter. The facility also would measure particle emissions from various materials, and help develop and refine technologies for future underground physics experiments.

But why are there four separate proposals for how to search for dark matter? Not knowing the nature of dark-matter particles and their interactions with ordinary matter, scientists would like to use a variety of detector materials to look for the particles and study their interactions with atoms of different sizes. The use of different technologies would also provide an independent cross check of the experimental results.

“We strongly feel we need two or more experiments,” says Bernard Sadoulet of UC Berkeley, an expert on dark-matter searches. “If money were not an issue, you would build at least three experiments.”

The largest experiment intended for DUSEL is the Long-Baseline Neutrino Experiment (see graphic), a project that involves both the DOE and NSF. Scientists would use the LBNE to explore whether neutrinos break one of the most fundamental laws of physics: the symmetry between matter and antimatter. In 1980, James Cronin and Val Fitch received the Nobel Prize for the observation that quarks can violate this symmetry. But the effect is too small to explain the dominance of matter over antimatter in our universe. Neutrinos might be the answer.

The LBNE scientists would generate a high-intensity neutrino beam at DOE’s Fermi National Accelerator Laboratory, 800 miles east of Homestake, and aim it straight through the Earth at two or more enormous neutrino detectors in the DUSEL mine, each containing the equivalent of 100,000 tons of water.

Studies have shown that the rock at the 4850-foot level of the mine would support the safe construction of these caverns. In January, the LBNE experiment received first-stage approval, also known as Mission Need, from the DOE.

Lesko and his team now are combining all engineering studies and science proposals into an overall proposal for review.

“By the end of this summer, we hope to complete a preliminary design of the DUSEL facility and then integrate it with a generic suite of experiments,” Lesko says. “While formal selection of the experiments will not have been made by that time, we know enough about them now that we can move forward with the preliminary design. The experiments themselves will be selected through a peer-review process, as is common in the NSF.”

If all goes well, Lesko says, scientists and engineers could break ground on the major DUSEL excavations in 2013, marking the start of a new era for deep underground research in the United States.
Long-Baseline Neutrino Experiment

Neutrinos are among the most abundant particles in the universe, yet we know very little about these mysterious particles and their role in the evolution of the cosmos. The proposed Long-Baseline Neutrino Experiment would help determine whether neutrino interactions could explain the dominance of matter over antimatter in our universe. LBNE would generate a beam of neutrinos at Fermilab in Batavia, Illinois, and examine the behavior of those neutrinos as they traveled through the Earth to a proposed underground particle detector in the Homestake mine in Lead, South Dakota.

General cross section of the Homestake Mine

The former Homestake mine is 8000 feet deep and contains 370 miles of tunnels. Excavation is under way to enlarge the 30-by-60-foot Davis cavern and create additional underground space for experiments. Scientists have proposed turning the mine into a national laboratory for deep science and engineering research with a surface campus, several underground labs and large caverns for neutrino detectors.
ENRICHED XENON OBSERVATORY 200

EXO

TAKES CLEAN TO AN EXTREME
Some particle physics experiments require an extraordinary degree of cleanliness and quiet. How far will they go to achieve this? Try etching tools with acid, setting up shop in a deep salt bed, putting equipment on stilts, and choreographing a 2100-kilometer truck ride so not a moment would be lost.

By Lauren Knoche
Just before midnight on November 3, 2009, a large truck loaded with 40 tons of cargo pulled away from the Stanford University campus. It carried the last shipment of laboratory equipment from Stanford to New Mexico for a high-energy physics experiment that will begin taking data this year.

Moving complicated experimental equipment is always a delicate process, but in this case the task was more challenging than usual. The experiment, called the Enriched Xenon Observatory 200, or EXO-200, is designed to look for an ultra-rare phenomenon that could reveal key secrets about the nature of the neutrino. This process is so rare that detecting just a few signals over the course of a year would be a triumph. Scientists have no hope of seeing these faint signals unless they eliminate every possible source of background radiation that could get in the way. Yet sources of radiation are everywhere—from cosmic ray particles that rain down from space to materials as common as copper, everyday tools, ordinary rocks, even the human body.

It had taken the 70 scientists and engineers of the EXO collaboration six years to design and assemble their detector—a tank that would hold 200 kilograms of liquid xenon cooled to a very low temperature and heavily shielded by onion-like layers of components. A fanatic degree of cleanliness prevailed at every step. Most of the components were not only assembled in clean rooms, but also shipped in those same clean rooms, shielded and sealed against contamination. Even so, the team choreographed and practiced every move to make sure those containers spent as little time as possible in the open air.

The truck that left Stanford that night was headed for a salt deposit in New Mexico at the US Department of Energy’s Waste Isolation Pilot Plant, where the last piece of apparatus would be lowered to its new home 700 meters below ground. “You go underground because you want to suppress cosmic rays,” says EXO spokesperson Giorgio Gratta of Stanford. “Cosmic rays can be energetic enough that they are essentially unstoppable with reasonable amounts of matter, so you need lots of matter to filter them out. Whether it’s a salt mine is not essential, but you generally need about one kilometer of ground above.”

**Cleanliness starts from scratch**

Ensuring that there is no residual radioactivity in the detector began with material selection. EXO designers ordered candidate materials from “clean” manufacturers—companies aiming to create products free of radioactivity—and screened all of them to make certain that every piece of material incorporated in the experiment was “clean.”

Samples were inserted into a nuclear reactor to expose them to radioactivity, then tested to see how they responded, says Jesse Wodin, a postdoctoral researcher working on EXO-200 from Stanford and SLAC National Accelerator Laboratory. Any material exposed to radioactivity will become slightly radioactive itself, but some retain this property longer than others; “We chose the cleanest material we could.”

After finding the best materials, including ultra-pure copper, Teflon, and lead, construction began in clean rooms at Stanford’s End Station III. These were not just the usual clean rooms intended to prevent contamination by dust and other particulate matter. They also needed to prevent contact or proximity with anything that has low-level radioactivity, which means most everyday materials. The facility sports a five-foot-thick concrete roof that helps to block harmful background radiation. Here the EXO team tackled challenges in maintaining cleanliness during construction of the project.

Given the need to use only carefully selected non-radioactive materials, “solder might as well be pure uranium,”
says Stanford and SLAC graduate student Nicole Ackerman. So rather than soldering components together, the designers used springs made from special screws and bent washers. These "clean" springs were used for every connection in the detector, which is called the time projection chamber, or TPC.

Each tool used in construction of the EXO-200 experiment had to be submerged in acetone and alcohol and sonicated, a process that uses high-frequency sound waves to disrupt any impurities on the surface of the tool. The tools were then rinsed with water and dried before double-bagging for transport to the clean room where they would be used. The outer bag, having seen a "dirty" environment in transport, was removed in a transition room so that only the inner bag and tool entered the clean room.

If the tool was to come in direct contact with the TPC, an additional precaution was taken, called acid etching. In this technique, the tool was immersed in a strong acid that effectively removed the outer layer of molecules from the tool. Because the acid could harm the ultra-pure materials, acid etching was followed by multiple washes in distilled water and ethanol.

An extra-speedy truck trip
As construction finished, plans for shipping the EXO-200 components were finalized. Cosmic rays are more intense at airplanes’ flight altitudes than at ground level. While not harmful to humans at this level, they would do irreparable damage to the experiment’s components by causing some atoms to become radioactive. That meant the experiment could not be taken by plane; every piece of equipment had to be driven by truck to New Mexico. It took five separate trips in 2007 and 2008, as well as the final shipment of the detector in November 2009, to bring the entire experiment to WIPP.

Cleanliness was the top priority every step of the way, from extracting each container from the Stanford lab to loading it onto the truck, unloading it at WIPP, and lowering it into the mine. Each shipment was planned and carried out with extreme precision and caution, but the team took extra precautions with the detector.

“Certain portions needed to be transferred as fast as possible,” Wodin says. “If atmospheric radiation hits copper, it can make a little impurity that undergoes radioactive decay two years later. The TPC was placed in a 60,000-pound concrete vault and the entire container was closed up at Stanford to go to WIPP.” In addition, the TPC set off on its 30-hour trek at 11 p.m. so it would arrive in the morning of the second day, giving the team a full span of daylight to safely maneuver the detector underground and not leave it above ground any longer than necessary.

Two drivers took turns at the wheel so the truck would not have to stop for rest breaks; those extra hours would have left the TPC vulnerable to harmful amounts of cosmic ray exposure. With such delicate equipment on the 18-wheeler, the organizers also worried about vibrations and acceleration forces.

“We used an air-ride truck,” Gratta says. “We also installed accelerometers so that we could check what kind of accelerations or vibrations our load was subject to.”

The TPC is made of both metal and plastic components, which shrink and expand at different rates when temperatures change. This could easily damage the detector by placing tension on wires and connections. So the team waited until fall, when temperatures are more moderate, to ship the detector, and took other precautions as well.

“We painted the container with special reflecting paint to help keep it cool,” Ackerman says.

Snuggling into the salty depths
The truck drivers took the detector more than 2100 kilometers before rolling into the WIPP site, a storage facility for
nuclear waste maintained by the US Department of Energy. Crews quickly unloaded each container from the truck and put it on a rail car that glided into the cage of a waste conveyance—an elevator intended for lowering nuclear waste into the mine. Its large size helped efficiently lower the loads delivered for the EXO-200 project, but space was tight. The EXO team built each container to fit the dimensions of the elevator with about one centimeter to spare.

The detector and its surrounding layers weighed 40 tons, the heaviest load that the conveyance can lower. The innermost layer is a copper drum that would be filled with 200 kilograms of pure liquid xenon. The drum is surrounded by HFE fluid, which acts like antifreeze to keep the xenon at the ideal temperature of minus 103 degrees Celsius. A copper can holds the fluid, and the can is encased in 25 centimeters of lead.

The lead protects the experiment from background radiation emitted by the ground in which the machine is buried. Additionally, salt has naturally lower background radiation than many of the Earth’s other common materials. Common low-energy emission elements—such as uranium and thorium—that occur in hard rock were filtered out in the geochemical process that formed the salt bed, leaving the site with a lower concentration of these elements. “Roughly speaking, the salt is about 1000 times less contaminated with uranium and thorium than a hard-rock mine,” Gratta says. “But shielding more of this radiation would not have been a big deal. If we were in a regular mine less clean than WIPP, we could have used roughly 40 centimeters of lead.” The salt environment’s natural protection means the physicists don’t need to use as much lead shielding as they would in some other underground location.

**Seeking a rare, revolutionary decay**

Shielded from background radiation, researchers hope to detect a theorized phenomenon called neutrinoless double beta decay by the footprints it leaves in the tank of liquid xenon.

In normal double beta decay, two neutrons become protons, ejecting two electrons and two antineutrinos in the process. Neutrinoless double beta decay is theorized to be very similar, except that no antineutrinos would be emitted. But in order for this to happen, the neutrino would have to be its own antiparticle. It would be the first particle with mass that is known to have this property.

Finding this rare decay would be a revolutionary discovery about the fundamental components that make up the universe.

“Discovering that there are particles that have this funny property is a big deal,” Gratta says. “Part of the interest is that we would be discovering a new way for particles to behave, and that’s very important.”

A second draw for studying the neutrino is to better identify its mass. Researchers know the neutrino has a mass of less than two electronvolts, making it at least 250,000 times lighter than the electron. But thus far, physicists have been unable to pinpoint a more accurate mass. The Standard Model of particle physics, a theoretical framework that allows scientists to calculate many interactions, does not predict masses of particles and was built around the idea that neutrinos are massless like photons, the particles of light.

“There is no theory that ties together masses and then explains, for example, why an electron is lighter than a proton,” Gratta says. “Neutrinos are very strange because they are incredibly light, so it is possible that understanding a little bit more about how neutrino masses come about will allow us to understand masses in general and how particle masses are produced.”

But catching a neutrinoless double beta decay is no easy task. “These events are as rare as they make them,” Gratta says. “It’s possible that it is so rare that it doesn’t
exist. This is slightly funny, but it’s the right answer because the rarer the decay is, the smaller the neutrino mass. So if this thing is infinitely rare, the neutrino mass is infinitely small.”

Salt air, bunny suits, and clean rooms on stilts

The WIPP site employees were nervous about the tight squeeze down the elevator, and had practiced every maneuver with a large dummy box before containers began arriving. Planning and practicing paid off. Each container fit, allowing the cage door to close and the containers to be lowered 700 meters into the salt deposit.

This is no stereotypical rattling-and-shaking mine shaft elevator; it was designed for lowering delicate cargo.

“The conveyance is actually very smooth and excruciatingly slow on the scale of mines,” Gratta says.

The EXO-200 underground experiment area is like a long highway tunnel, apart from the copious amounts of salt and dust, Gratta says. The experiment’s zone is far from the nuclear waste site.

“People may wonder how come we want to do this low-radioactivity experiment in this place where they have all this radioactive waste,” Gratta says. “But the radioactive waste is a kilometer away, and of course this shields it plenty. In fact, we’ve got lots of help to go there because the facility is happy we are living proof that their storage facility is not a problem.”

At Stanford, the team had built one large clean room with dividers. As shipping began, the area was sectioned into six smaller clean rooms. These were closed up individually, encasing their contents, and transferred one at a time to WIPP. Once underground, the rooms were reassembled with one difference—they were put on stilts.

“The advantage of being in salt is that it has lower radioactivity than hard rock,” says Gratta. “The bad thing about salt is that it moves.” Because salt is incredibly soft, it will slowly creep under pressure, like that provided by the weight of six clean rooms and an 80-ton cryostat surrounded by lead shielding. “That means the floor comes up, so we have our clean rooms sitting on stilts with hydraulics and every few months we re-level them,” Gratta says, appearing undaunted by the idea that the salt is constantly shifting around the $15 million experiment.

“Eventually this thing will collapse, but eventually means more than 20 years and we will hopefully be done by then.”

High amounts of salt in the air at WIPP also pose a threat to the EXO experiment. To keep salt dust from entering the experiment rooms, the air is thoroughly filtered and scientists must enter the experimental chamber through a number of airlocks.

Only six clean rooms were needed to house and ship the EXO experiment, but two additional clean rooms were used to ship extra materials and tools. These two rooms were kept underground and serve as transition rooms for scientists entering or leaving the experiment.

As physicists enter the mine, they don coveralls over their clothes. In transition rooms, the scientists remove the salty coveralls, wash their hands and faces, and change into bunny suits before entering the experiment.

The TPC is now installed, and tests are under way to prepare the experiment to start up in mid-2010, Wodin says.

After years of preparation, the EXO team’s hard work to protect their experiment from ever-present background radiation is about to be put to the test.
Gran Sasso: A Tale of Physics in the Mountains
By Judith Jackson

In an epic story of fairy-tale beauty and world-leading science, human courage and determination confront adversity and Gran Sasso laboratory comes forth to see the stars once more.

"Somewhere," wrote MFK Fisher, the late American writer on food and other human appetites, "there must surely be a folk saying, not in Poor Richard's Almanack, perhaps, but of equal logic and simplicity, about how every life has at least one fairy palace in its span."

Fisher's fairy palace, encountered at the age of ten, was the Pig 'n' Whistle, a stylish ice cream parlor in 1918 Los Angeles where Mother occasionally took her for a treat. In the realm of underground laboratories, for some physicists that magical palace of a lifetime must be the Laboratori Nazionali del Gran Sasso. The largest underground science laboratory in the world casts an extraordinary spell.

Of course, the logic of enchanted castles decrees a quota of dragons to slay before all can live happily ever after. And in true enchanted kingdom form, Gran Sasso has battled epic perils that have sometimes come scarily close to breaching the castle gates. The unfolding story of this remarkable mountain laboratory has all the drama of a tale by the Brothers Grimm.
Snow, sheep, spaghetti, science
What is it that makes Gran Sasso so magical? For one thing, it's beautiful. At 1000 meters, in the heart of a national park in Italy's highest mountain range south of the Alps, the snow-capped peaks of the Abruzzo mountains ring the campus, outlined against the sky. Weathered tile roofs climb the steep streets of tiny stone towns, and flocks of sheep would block traffic on the mountain roads if there were any traffic. It's only a 130-kilometer trip from car-choked Rome, but Gran Sasso is a world away.

For another, there's the food. Those sheep? Think cheeses so local they're unknown beyond the next valley, and tiny “burn-your-fingers” lamb chops that taste of mountain mint and thyme. The Abruzzesi make their characteristic pasta with a wire device called a chitarra, because it looks like a guitar. And although the region doesn’t produce a lot of it, olive oil from the Abruzzo is claimed to be the best in Italy. After work, in Maria’s restaurant five minutes up the mountain from the lab, everyone—lab people, townspeople, the mayor—knows everyone else, the children fall asleep in a heap on a couch in the corner, and people eat the way MFK Fisher would want them to.

Having breathed the mountain air and eaten magnificently, it's time to do science. To reach the underground experiments at Gran Sasso, unlike the case for many other underground laboratories, scientists don't take an elevator. They hop in the car. Gran Sasso, one of four Italian national laboratories funded by the Istituto Nazionale di Fisica Nucleare, or INFN, is among the few underground laboratories (Canfranc and Modane are others) with drive-in access. From the above-ground campus near the hamlet of Assergi (population 524), physicists and visitors take the expressway west through a 10-kilometer tunnel underneath the Gran Sasso mountain. A “lab-only” turn-off shunts them back eastward through the tunnel to a special exit for the underground galleries. And what underground galleries they are—three huge, bright experimental galleries, each about 100 meters long, 20 meters wide, 18 meters high, for a total volume of 180,000 cubic meters. First-time visitors catch their breath. Wow.

Drive-up window on the universe
A drive-in laboratory has distinct advantages. Most strikingly, experimenters can truck in giant detector components and materials, rather than sending tiny pieces, ship-in-bottle style, down a narrow elevator shaft for reconstruction below. Experimenters can easily come and go, and the laboratory avoids the costs, maintenance, and safety concerns of elevators. Overhead, Gran Sasso’s 1400 meters of rock shelter the experiments, reducing cosmic-ray noise from space by a factor of a million. Thanks to the low level of natural radiation in the native rock, the rate of neutron interactions in the galleries is a thousand times less than on the earth’s surface.

Protected from bombardment, Gran Sasso experimenters investigate dark matter, nuclear astrophysics, and the physics of neutrinos. For some of these experiments, observing three or four events per year would constitute a scientific breakthrough. To hear these whispered intimations of discovery, experimenters must escape the deafening background chatter of billions of particle events on the earth’s surface. For underground physicists, experimental design, techniques, materials, and location all aim at one goal: victory over backgrounds. The underground galleries provide the cosmic peace and quiet that these physicists need in order to have a hope of detecting incredibly rare interactions. For Gran Sasso’s 750-plus scientific users, underground physicists from 24 countries including the United States, the laboratory might be paradise.

Gran Sasso isn’t paradise, of course. At times, over the past two decades, it has seemed less like il Paradiso and more like l’Inferno. Perhaps ironically, most of Gran Sasso’s severest troubles have come from the same sheltering mountain and convenient highway that make it such a remarkable place for underground science.
At Maria’s restaurant, five minutes from the laboratory campus, lab people, townspeople, and families share meals of extraordinary “cucina Abruzzese.”

Top photo: Luigi Ottaviani; photo below: Attanasio Candela
Troubled waters

The laboratory shares Gran Sasso mountain not only with the high-speed A24 expressway linking Rome to the Adriatic, but also with a major aqueduct that sends some 1500 liters of water per second rushing into giant pipes that supply drinking water to the city of Teramo, 40 kilometers down the mountain to the east. Construction of the highway began in 1969 and finished in 1982, with the associated laboratory and aqueduct construction complete in 1988. From the earliest days of construction, changes in the local water table attracted the attention of Italian environmentalists.

A 2005 paper by Italian university geologists in the *Giornale di Geologia Applicata* summed up the issue:

“Tunnels, although being built for different uses, may drain groundwater even after completion of their lining. In some instances, it is extremely difficult or impracticable to restore the original hydrodynamic equilibrium, with consequent risks of exhaustion of springs, change in the relations with adjacent hydrogeological structures, depletion of groundwater reserves, etc. Tunnel construction also can alter water supply for drinking, irrigation and industrial uses, with major economic and social repercussions on wide neighbouring areas.” (Italics added.)

The laboratory had been experiencing those repercussions for more than a decade when, in August 2002, environmental calamity struck. As they were filling the detector for the Borexino solar neutrino experiment, two US collaborators spilled 50 kilograms of pseudocumene, a liquid scintillator with a strong characteristic odor. The physicists contained the spill and the lab reported it to local authorities, but not before some of it drained into a nearby creek, where picnickers smelled it. A dead fish turned up at the scene. The citizens of Teramo reacted with rage, and the spill became a cause célèbre for environmental activists all over Italy and beyond. They took the matter to the Italian courts and in May 2003, a court-ordered report found that the drainage systems of the laboratory and the highway were not leak tight and could contaminate water supplies. In July 2003, the Council of Ministers declared a state of emergency for all Gran Sasso facilities, including the highway, the laboratory, and the water system. The laboratory immediately shut down any and all underground operations that involved liquids. Some in the science community feared that Gran Sasso might never open its doors to experiments again.

End of a tunnel

Meanwhile, the motorway, Gran Sasso’s other underground tenant, was causing another problem for the beleaguered laboratory. The highway that provides such easy access for scientists is the only way in—and the only way out. In the event of a traffic blockage in the west-bound tunnel of the A24, experimenters would be stuck in the laboratory with no means of escape. And, in fact, in May 2004, a truck fire in the tunnel stopped traffic for hours.

To address this safety issue and to provide a direct route between the underground lab and the surface campus, the Italian government had long planned to construct a third tunnel, above the existing two. Along with the new tunnel, plans called for enlarging the underground laboratory space. Not surprisingly, environmentalists opposed the project, and after the establishment of the national park in 1992, new construction within it became very difficult. During the state of emergency following the Borexino spill, the government used funds originally intended for the tunnel to address the immediate water-related problems. By 2004, given the controversy surrounding the existing structures and the diversion of funds, building another tunnel had become, in the words of one Gran Sasso physicist, not so much a third tunnel as a political third rail. The laboratory had to accept that it would probably never be built, and that the underground space for science at the Gran Sasso site would not expand.
A special exit from the A24 motorway tunnel brings scientists to Gran Sasso’s underground galleries. Photo: Luigi Ottaviani

The laboratory shares Gran Sasso mountain with an aqueduct that supplies water to neighboring communities. Photo: Luigi Ottaviani
**Incipit vita nova: The new life begins**

Those difficult days marked the start of a major turn-around effort for the laboratory and its funding agency, INFN. Following the Borexino spill, Gran Sasso took immediate steps to seal off the laboratory’s drains and water systems from the aqueduct. Beginning in 2004, they leak-proofed the floors and installed new leak containment wells, part of a completely new drainage system. Along with new water ducts in the freeway, these changes ensured that laboratory operations could never again contaminate local water supplies. Installation of a second independent ventilation system provided the means to bring fresh air into the laboratory in case of a tunnel fire. New highway lighting and better traffic monitoring and control were all aimed at making the laboratory and the highway as safe and environmentally sound as possible.

Laboratory policy increasingly emphasized environmental responsibility, with the central tenet “to develop knowledge of nature in its more intimate structure while respecting nature itself.” Relations with neighboring communities have taken a U-turn for the better, thanks in part to an extensive program of science education and outreach to communities in the Abruzzo region and beyond. Programs for students and the public draw some 8000 visitors a year. Gran Sasso’s annual physics summer school sends 20 Abruzzo students to Princeton University for three weeks of physics immersion. With INFN support, Gran Sasso scientists worked with the Teramo provincial and city governments to create the Galileium, a stylish and accessible astroparticle physics museum near the city’s railroad station. Good relationships with the community are a priority, says Gran Sasso’s new director, particle astrophysicist Lucia Votano, who took over in September 2009.

The Borexino experiment resumed operations in 2005 and began taking data in May 2007. In late August 2006, CERN sent the first beam of muon neutrinos from its Super Proton Synchrotron accelerator to Gran Sasso for detection by the OPERA experiment. Soon, the scientific world expected to hear that OPERA had caught muon neutrinos in the act of morphing into tau neutrinos during their three-millisecond trip from Geneva—the first direct observation of the appearance of one type of neutrino from a beam of another type. The largest concentration of world-leading dark matter experiments made their home at the laboratory.

Things at Gran Sasso were definitely looking up.

**Thence they came forth...**

Then, at 3:32 on the morning of April 6, 2009, a magnitude 6.3 earthquake struck the Abruzzo, its epicenter near the medieval city of L’Aquila, 20 kilometers from Gran Sasso. The quake caused an average 25-centimeter lowering of the surface in a 12-square-kilometer region around the city. More than 300 people died, some 15,000 were injured, more than 60,000 people lost their homes, and L’Aquila lay in ruins. While subsequent inspections revealed that the laboratory itself had sustained little damage, and normal operations resumed on May 4th, some 80 percent of staff lost their homes. Almost immediately, INFN went into action, working with the laboratory to find temporary staff housing in nearby hotels and even in specially adapted shipping containers on the Gran Sasso campus. Flexible work schedules, financial help, and an on-site children’s center supported laboratory families as they attempted to cope after the earthquake. Nearly a year later, their lives are far from returning to normal.

“Now,” Votano says, “the April earthquake has raised another big challenge, the need to contribute to the new beginning of the social and economic life of L’Aquila territory in which the laboratory is based.”

As part of the effort to rebuild the city, with support from corporate and individual donations, Gran Sasso laboratory and the city of L’Aquila have joined forces to develop a new planetarium and science center for the city. It will take shape in the Parco del Sole, adjoining the badly damaged 13th-century Santa Maria di Collemaggio, L’Aquila’s most famous and beloved church.

For its inspiration, the Parco del Sole project turned to Dante’s *Divine Comedy*: “And thence we came forth to see the stars once more.” It’s a good motto for Gran Sasso Laboratory too. Here mountains and water, neutrinos and dark matter, scientists, students, lovers of nature, not to mention some of the best food in Italy, come together to create a unique human vantage point on the mysteries of the universe. Through trials and triumphs, the laboratory and its people have come forth to see the stars once more. In the end, better than a magic palace, Gran Sasso is an utterly human place, entirely of the real world, a meeting point for science and civilization.
Generation Gran Sasso

I joined Gran Sasso laboratory in October 1994, when the lab was in its infancy. The science was vibrant; we were in the hottest time for the solar neutrino problem. The possibilities for new ideas and new projects seemed endless. The contrast between the rural atmosphere of the little town of Assergi and the lab was striking—the white blanket of snow in winter, the scorching heat of the summer, the lunar landscape of Gran Sasso. Sheep over Campo Imperatore, old farmers moving crops on donkeys’ backs, and, hundreds of meters below your feet, an ultramodern lab gazing at the deepest secrets of the cosmos. No surprise that so many scientists fell in love with it, among them the young Italian scientists who took the baby steps of their careers at Gran Sasso.

I am part of a generation of scientists trained by INFN at Gran Sasso that ended up filling physics departments and labs all around the Western world.

In my 16 years of work at Gran Sasso, I witnessed transformation. Old physics problems have been solved, and even more intriguing questions have opened up. The very rural Abruzzo I met in 1994 is now long gone. L’Aquila morphed into a vibrant town, with a pleasant downtown and an interesting night life. It all came to a sudden stop on April 6, 2009. The earthquake brought endless grief, and yet more transformation. The little town of Assergi, unmodified for centuries and untouched by the earthquake, is now booming with new construction to accommodate hundreds of displaced inhabitants from L’Aquila.

I take pride in my ongoing association with Gran Sasso. With so many open problems in particle astrophysics, it is still the place to be. My love affair continues with the region that adopted me and that now I call home.

Cristiano Galbiati, Princeton University

Photo: Pier Oddone, Fermilab
Bringing dark life to light

The stunning realization that up to half of life on Earth may exist underground has transformed biologists’ thinking about the origin and evolution of life here and on other planets. The search for “dark life” could go to new depths at a proposed underground laboratory.

By Kathryn Grim
Scientists found these bacteria 112 meters below ground in the Åspö Hard Rock Laboratory. They belong to the genus Desulfovibrio. These bacteria use sulfate as an oxidizing agent, reducing it to sulfide. This can threaten underground construction and radioactive waste canisters, as sulfide is corrosive to metals.

In 1988, a team of Swedish scientists drilled 1000 meters into the ground to gather rock and groundwater samples for a study aimed at improving the disposal of nuclear waste. They were looking for microorganisms that might interact with buried waste canisters, and they expected to find only a few.

Instead the scientists stumbled upon an entire ecosystem of undiscovered microbes, flourishing beneath their feet.

Scientists had imagined that life could exist underground, but what startled microbiologist Karsten Pedersen were the number, variety, and liveliness of organisms living so deep underground that they were cut off from anything touched by the sun. “They were active; they were happy,” he says. “We didn’t understand how, since they were so isolated.”

Microbe hunting has been around for centuries. In the 1670s, Dutch microscope hobbyist Antonie van Leeuwenhoek first discovered bacteria and swimming protozoa, which he described as “animalcules” and “wretched beasties.” But until the 1980s, scientists literally had only scratched the surface of the world of these invisible creatures. Scientists have since found signs of life down as deep as they have looked, about four kilometers beneath the surface. Through their studies they have pioneered a new field of research: geomicrobiology. Now some biologists estimate that there may be just as much “dark life” beneath the surface of the Earth as there is sun-based life above it.

Pedersen calls the microbes his team found “the toughest organisms on the planet.” They live anywhere with liquid water, which can be “as acidic as vinegar… more alkaline than washing powder, boiling hot, or freezing cold as the Antarctic,” he wrote for a museum exhibition in Sweden.

Biologists postulate that many of the microorganisms living deep beneath the Earth’s crust are much older than any human alive. Based on the rate at which they feed, these tiny creatures appear to mature slowly over the course of a thousand years. They live on compounds such as sulfides, iron oxide, carbon dioxide, and ammonium, and even elements like uranium, hydrogen, or arsenic—not something most of us would like to find in our breakfast cereal. If they find themselves without food, they can sleep as soundly as Rip Van Winkle for years at a time until nourishment returns.

Scientists hope studies in geomicrobiology could lead to the development of new drugs and biofuels and improved methods of sequestering carbon dioxide and purifying contaminated groundwater. The field also has the potential to revolutionize the search for life on other planets, as well as offer clues to the origin and evolution of life on Earth.
Yet most geomicrobiological studies to date have taken place in less than ideal circumstances, piggybacking on mining or oil drilling operations or radioactive-waste disposal programs. These types of arrangements allow scientists only limited access to their subjects and introduce the threat of contamination.

Soon, though, some biologists hope to have a space of their own in one of the deepest underground laboratories in the world. The Deep Underground Science and Engineering Laboratory, proposed for a former gold mine in Homestake, South Dakota, would include space for biologists along with nuclear and particle physicists, geologists, hydrologists, geoengineers, and biochemists.

The main driver behind the proposed lab is particle astrophysics, which needs quiet, sheltered spaces to search for dark matter and study rarely interacting subatomic particles like neutrinos. But seven of the initial 16 research proposals being developed with funding from the National Science Foundation are for studies in other fields, including biology.

From their base in the lab's lowest level, more than 2000 meters underground, biologists would drill even farther into the Earth. Having a dedicated space would allow them to develop long-term studies of the slow-moving, long-living microbes below.

So many microbes, so difficult to reach
Like their counterparts above ground, dark microbes can be difficult to cultivate in a lab; 99 percent cannot grow in a Petri dish. Many would still be invisible to science if not for techniques that allow researchers to probe the environment for bits of genetic material and use it to identify microbial species.

Scientists have just begun to sequence the genetic codes of the microorganisms they are discovering underground. Already they have recorded in an international database the RNA gene codes of more than one million microbes, only a quarter of which scientists have grown in the laboratory. The number of species of microorganisms scientists continue to find has not even begun to plateau, says Jim Tiedje, distinguished professor of microbial ecology at Michigan State University.

“We’re always coming up with new ones,” he says. “Naming them is a problem right now; we just use letters and numbers.”

Biologists have many unanswered questions about these organisms: How long have they been there? How far can they travel? How long do they live? How do they affect their environments? Are their populations controlled by the availability of food, or the prevalence of bacteria-infecting viruses or predators?

These questions can be difficult to answer, under the circumstances. The dearth of locations in which to conduct long-term studies keeps the number of scientists studying the deep biosphere low, says biologist T.C. Onstott of Princeton University. He estimates that the entire field comprises only about 300 scientists, most of whom study life below the seafloor with the help of international drilling ships.

Nature show
One of the few spaces in the world dedicated to long-term studies in geomicrobiology is located in Äspö, Sweden. Today Pedersen works there in a laboratory that resembles a large shipping container more than 450 meters underground in a mine operated by the Swedish Nuclear Fuel and Waste Management Company.

The laboratory is accessible by elevator or by car; “My cave is paved,” Pedersen says. It also comes equipped with a climate-control system, a coffee machine, a refrigerator, and phone and Internet connections. But most importantly, it allows Pedersen to observe microscopic life in the wild.

Sometimes, Pedersen and his small team collect samples and data to bring back to their laboratories on the surface. They don hard hats, boots, and reflective gear; pack a carful of bottles, tubes, filters, and electrodes;
Microbial biofilm—a community of microbes encased in protective slime—from 2 km deep in a South African platinum mine. It contains star-shaped bacteria that had never been seen before. Their habits and relationships to known organisms are under study.

Pedersen and his team can guide microbes from the same population into multiple pipes, which they can manipulate in different ways and compare. “We can add food, take away food, see how different compounds affect the systems,” Pedersen says. “We can test our ideas, so it’s more like classical lab work. No one else is doing these types of studies.”

On borrowed time

However, most biologists studying deep life must make do without a dedicated underground space.

Like many in the field, Onstott studies microbes in a working mine, visiting South Africa about once a year for a few long days of field research. “Many mines in the US are frankly not deep enough for my interests,” he says. “I go to South Africa because the mines are so deep that you get into temperatures of up to 70 degrees Centigrade. That’s good for us. We like nice, hot organisms.”

On a typical day of prospecting, he enters the Tau Tona Au mine with the miners at 7 a.m. They take the first cage elevator, which drops down the shaft at about 30 to 40 kilometers per hour. At the bottom of that shaft, they exit and enter another. It drops and then they enter a third cage. After that, they start to walk. They have travelled more than 3.7 kilometers underground.

“It takes about two hours to finally get to your spot,” Onstott says. “You spend about an hour there, then start getting your way back to the cage.”

In this situation, the miners—and their profitable business—come first. “If we say we need 12 people to set up an experiment and we’ve got about 500 pounds of gear, we might get on the schedule six months from now,” Onstott says. “If we need to drill, we need to arrange with a contractor and can only drill after they finish. It’s just a long, slow, tedious process.”

Adding to the frustration, a particular research area may be available for only a month before the miners tunnel right through it. “On one trip, we found a star-shaped bacterium,” Onstott says. “That was pretty neat. We’ve been trying to figure out why the hell it would be shaped like that. But we haven’t been able to get back to the spot where we found it again.”

The origins of life, here and elsewhere

Like Pedersen, Onstott stumbled upon geomicrobiology in the 1980s while investigating ways to better dispose of nuclear waste—in his case, radioactive compounds left over from nuclear weapons manufacturing. He was responsible for ascertaining the origins of the microbial flora scientists found in a post-Cold War study by the Department of Energy’s environmental management office.

He was amazed at the organisms’ diversity and abundance. “Everyone thought that beneath the soil zone, life stopped,” he says.
When he travelled to Africa, Onstott discovered that some families of microorganisms had spread surprisingly far and wide. “I was finding that species of bacteria you can find deep in the subsurface of Africa are also present in the seafloor—tens of thousands of kilometers apart from one another, but the same species,” he says. “But the surface of South Africa has not seen the ocean in two billion years.”

These microorganisms appeared to have been isolated from the surface for millions or perhaps tens of millions of years, he says. “It begs the question: Where did they come from in the first place?”

Scientists initially speculated that life arose on the Earth’s surface, moved underground and survived there during an especially violent period when the young planet faced a bombardment of meteors, volcanic eruptions, and radiation from space.

However, many geomicrobiologists wonder if the origins of life can instead be traced to the shelter of the subterranean.

“What makes people think that life had to go underground?” Pedersen says. “Maybe the question is: When did life go to the surface? When was life strong enough to leave the safe and protective underground with no wind, solar radiation, or thunderstorms?”

These discoveries also raise the question of whether microbial life exists beneath the surfaces of other planets or their moons, Onstott says.

“Any world in our solar system where the surface is definitely uninhabitable—even by microorganisms—may still hold a refuge for life at depth,” he says. “Temperature always increases with depth. You can eventually reach liquid water down there.”

Pedersen agrees: “You could take away the sun from our planet, and as long as heat, water, and hydrogen are still coming from underground, microbial systems could run for a very long time, even if the surface were deep-frozen.”

The natural radioactivity of rock, heat left over from a planet’s formation, or even tidal forces raised by a large body nearby can toast the center of a planet to a life-sustaining temperature. Pedersen hopes scientists will one day probe beneath the surface of Mars or Europa, one of the moons of Jupiter, in search of alien life.

For now, Onstott says, scientists are still in the dark about life deep within our own planet: “I don’t think we realize yet how complex life could really be down there.”
Making a place for physics in the deep
By Kathryn Grim

Just before 7:30 on a bitter-cold morning in northern Minnesota, engineer Jim Beaty begins the last leg of his daily commute. He steps into a dark brown metal box with five coworkers. Someone slides the door closed. In pitch dark, with its engine thundering, the elevator shudders as it travels a half mile below ground.

The sun has yet to rise, and it will have set by the time Beaty returns from the depths at 5:30 p.m. But when he steps out of the elevator into the Soudan Underground Laboratory, it makes no difference what conditions are like on the surface. Down here the air is kept at 71 degrees Fahrenheit and it’s as bright as a cloudy day in late fall, just like it was the day before and will be on the day to come.

The laboratory is built into Minnesota’s first iron ore mine, which operated from 1882 until 1962. The rock walls provide high-energy physicists with a shelter, for better or worse, from the Minnesota elements. They also shield experiments from cosmic rays and other particles that shower the surface of the Earth. By blocking some of the distracting subatomic debris from the sky, physicists
can better watch for particles that rarely interact with matter.

Beaty’s job, as he describes it, is to provide the scientists who come here with whatever they need. “I have a degree in mechanical engineering,” Beaty says. “That doesn’t necessarily mean I’m an engineer every day. I was sweeping floors this morning. We do whatever needs to be done.”

He is on a crew of about eight people who keep the laboratory running. Many of them also helped to build it. Beaty, a former construction worker, has been working at Soudan for more than 20 years. “It started as a temporary, two-week job, and it kept going,” he says.

His story is similar to those of many of the laboratory’s employees, including lab manager Bill Miller. Miller took a temporary job in the mine 25 years ago during the downtime most construction workers face in cold climates. He has worked at Soudan ever since.

“Most of us have been here a long time,” Miller says. “We were all in the construction business building houses and things like that. Now we’re just building different things than we used to. There’s no one else in the world that knows how to do the things we do, because we’re the ones that built everything down here.”

When Miller first began, the cavern was incomplete, and his desk sat behind a 50-horsepower air compressor. “The only way you could talk on the telephone was to have headphones on so you could knock out the sounds,” he says.

He later moved to a desk next to the 6000-ton steel detector for the Main Injector Neutrino Oscillation Search experiment, or MINOS, which studies a beam of particles called neutrinos that zip straight through the ground from their source at Fermi National Accelerator Laboratory in Batavia, Ill. Today he works in an office built against the rock, which is painted white to match the other walls. He sits beneath a bulletin board covered in ticket stubs from hundreds of concerts and music festivals and a map of North America tracking the road trips he and his wife have taken with their two dogs in a fiberglass camper. “We haven’t quite hit all the states yet, but we’ve hit most of them,” Miller says.

Everything in the high-energy physics laboratory—from Miller’s roadmap to the hulking MINOS detector—had to come down in the same elevator, piece by piece. And all of the rock the crew removed to carve out a space for the lab had to take the same elevator up.
“We once actually had a list of how many trips we were taking,” Beaty says. “It was a couple of thousand a year.”

Recently Beaty has spent most of his time helping to upgrade the Cryogenic Dark Matter Search experiment. The CDMS experiment uses germanium and silicon detectors cooled to nearly the lowest possible temperature, minus 273 degrees Celsius, to listen for signals of dark matter particles. It sits in an area carefully guarded from most environmental contaminants. “I’m servicing the cryogen tanks and the cryogen system, repairing anything that needs to be repaired, fixing, building whatever they want,” Beaty says. “We’ve got a machine shop here. If they want something, they sketch it out.”

He pulls from his desk what appears to be a dehydrated wet wipe onto which someone has scrawled an engineering design. “They can’t bring paper and pens in there,” he says. “It’s a clean room.”

When Beaty works in the clean room, he covers himself from head to toe in a “bunny suit,” a white coverall made of anti-static material. Scientists slip plastic covers over their shoes, latex gloves over their hands and surgical masks over their faces to keep oil from their skin or hair from touching the CDMS detector. Contaminants on the detector can attract radon, a natural form of radiation emanating from the rock walls of the cave, and muddy the data collected.

Today Beaty is wearing a flannel shirt, jeans, and boots. He walks through a section of the cavern toward his office. In places the ceiling stretches 40 feet above his head. A small brown bat emerges from the shadows and flies straight toward him at waist height, only to cut a 90-degree turn at the last moment and zip back into the dark. Most of the cavern’s estimated
20,000-40,000 Little Brown Myotis bats live in an area 1000 feet up the elevator shaft.

“If you see a bat flying around down here, chances are it’s on its last legs,” Beaty says. “There’s no food down here. There’s very little water.”

A graduate student once proposed bringing mosquitoes into the mine to save the few starving critters who find their way to the bottom. Understandably, the rest of the researchers said no. Another student tried to catch and release the lost bats, but that presented too much of a safety hazard. None of the laboratory employees has been bitten, as far as Beaty can remember.

Beaty climbs a set of metal stairs and steps into his 20- by 30-foot office, lit by daylight-mimicking full-spectrum light bulbs but otherwise just the same as any other workplace. He has a desk, a phone, a printer, and shelves full of manuals. “Two of us hauled almost this entire room down, and we helped erect it,” he says.

Just outside of Beaty’s office sits one of the stranger items to make its way down the Soudan elevator: a ping-pong table. “A graduate student and I set this up one night when we were having to be here late,” Beaty says. “We were waiting for a fridge to cool for one of the experiments. We found the old net, set it up, and we had a great time.”

Beaty says he remembers the days when laboratory employees had a scorecard and kept track of the reigning ping-pong champion. But many of the experiments in the Soudan Underground Laboratory are coming to a close in the next few years, and fewer people spend their days in the mine. “Now it’s kind of hard to get a game,” he says.

Eventually, Beaty, Miller, and the rest of the crew will dismantle the laboratory they built and bring it to the surface, one dark elevator ride at a time.
Mining with light

Mining involves a lot of what you might call "bucket chemistry:" mine workers grind up ore and put it in a vat of acid to dissolve the metal. They might add cyanide or a detergent-like chemical that bonds with the metal and draws it out of the solution, so it can be refined and purified.

The devil is in the details. For instance, if certain minerals are present, they form deposits on the surface of gold that keep it from dissolving, says Allen Pratt, a surface chemist with the mining branch of Natural Resources Canada.

Miners sometimes add lead nitrate to prevent this and speed things along. But is there a way to fine-tune the process to get more metal out of the ore?

For that, Pratt turns to a technology born in particle accelerator research—the synchrotron lightsource.

Lightsources are circular particle accelerators that generate intense beams of light for examining all kinds of materials in fine detail; think of them as microscopes on steroids. One big advantage they have over microscopes is that there is no need to slice samples thin or alter them in any way. This ability makes lightsources perfect for the kinds of analysis done in mining.

"We literally pick the sticks and leaves out of samples of ore or mine waste, and they're ready to go," says Jeffrey Cutler, director of industrial science at the Canadian Light Source.

What's more, Pratt says, researchers can tune the lightsource beam to penetrate a sample at specific depths without destroying it. "It's quite beautiful, really," he says, "and you can start to bring out some of the subtleties in these surface layers" that can't be seen with other lab techniques.

As these processes become more efficient and metal prices go up, it may become worthwhile to go back to piles of old mine waste and extract small amounts of metal, so-called "invisible gold," that were left behind, Cutler says. This metal is no longer in its original form; processing has tied it up in various chemical complexes. Lightsources offer the only way to directly identify those complexes, the first step in learning the best way to get the metal out.

In today's mines, though, the biggest role lightsources play is in analyzing tailings—liquid, rocky, and sludgy waste—and finding safe ways to dispose of them.

For instance, tailings may contain arsenic, which naturally occurs in areas where gold and other heavy minerals concentrate. Depending what chemical form it takes, it can be highly poisonous or inert and harmless. One well-accepted way of defanging the toxic form of arsenic is to add ferric iron, or rust, to form a compound that can't be absorbed by living things.

When AREVA Resources Canada Inc. needed a new version of this process to treat waste from a $500 million, state-of-the-art uranium mill in Saskatchewan, it turned to lightsources at the Canadian Light Source and Argonne National Laboratory in Illinois. Research there helped to develop the process, and later demonstrated to regulators that it worked.

"You have to immobilize the arsenic into a form that's stable over the long term. We're talking 25,000 years," says John Rowson, AREVA's vice president of environment, science, and technology. "We use the lightsource to demonstrate that we actually have that stable structure. The lightsource is the only technology I know that can do that."

Chris Knight and Glennda Chui
In June 1998, the Super-Kamiokande collaboration revealed its eagerly anticipated results on neutrino interactions to 400 physicists at the Neutrino '98 conference in Takayama, Japan. A hearty round of applause marked the end of a memorable presentation by Takaaki Kajita of the University of Tokyo that included this slide. He presented strong evidence that neutrinos behave differently than predicted by the Standard Model of particles: The three known types of neutrinos apparently transform into each other, a phenomenon known as oscillation.

Super-K’s detector, located 1000 meters underground, had collected data on neutrinos produced by a steady stream of cosmic rays hitting the Earth’s atmosphere. The data allowed scientists to distinguish between two types of atmospheric neutrinos: those that produce an electron when interacting with matter (e-like), and those that produce a muon (μ-like). The graph in this slide shows the direction the neutrinos came from (represented by cos theta, on the x-axis); the number of neutrinos observed (points marked with crosses); and the number expected according to the Standard Model (shaded boxes).

In the case of the μ-like neutrinos, the number coming straight down from the sky into the detector agreed well with theoretical prediction. But the number coming up through the ground was much lower than anticipated. These neutrinos, which originated in the atmosphere on the opposite side of the globe, travelled 13,000 kilometers through the Earth before reaching the detector. The long journey gave a significant fraction of them enough time to “disappear”—shedding their μ-like appearance by oscillating into a different type of neutrino. While earlier experiments had pointed to the possibility of neutrino oscillations, the disappearance of μ-like neutrinos in the Super-K experiment provided solid evidence.

Kurt Riesselmann
Shielding refers to layers of material that block radiation: that lead apron we wear during dental X-rays, the thick walls around a nuclear reactor, and even those cool, UV-blocking sunglasses all shield us from biologically damaging forms of radiation.

We don’t need shielding from cosmic rays—high-energy particles that continually rain in from outer space. But this steady background radiation does bedevil scientists and their experiments because it can drown out the nearly imperceptible signals of rare subatomic processes. Cosmic rays crashing into the atmosphere spawn secondary particles such as muons, which pass through normal layers of shielding with ease. High-energy muons can penetrate more than a kilometer of solid rock.

To search for the dark-matter particles thought to fill the universe, explore the mysterious properties of neutrino interactions, or look for neutrinos from the sun or a supernova, scientists need shelter from cosmic rays and the muons they produce. So they’re taking their experiments underground, to special-purpose laboratories such as SNOLAB in Ontario, Canada, which is under about two kilometers of rock and the deepest lab operating today. Each 300 meters of overlying rock reduces the rate of incoming muons by a factor of ten. In these subterranean refuges, sensitive instruments await the first faint whispers of new physics.

Hamish Robertson, University of Washington