Welcome to the Soudan Underground Laboratory

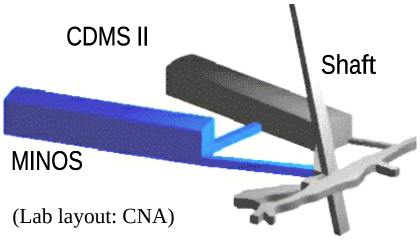
• • •

Soudan Underground Mine State Park, Soudan, Minnesota

Welcome to the Soudan Underground Laboratory, operated by the University of Minnesota in partnership with the Fermi National Accelerator Laboratory, the Minnesota Department of Natural Resources, and the CDMS II and MINOS Collaborations. This unique facility is located almost a half-mile underground, and is designed to explore fundamental questions about the structure of our universe. Not all have answers—at least not yet—but we hope this guide and your hosts can help explain how we go about asking such questions, and why we think they are important. Enjoy your visit, and visit us on the web for more information and educational resources:

http://www.soudan.umn.edu

(Headframe: J. Meier)



(Lab layout: CNA)

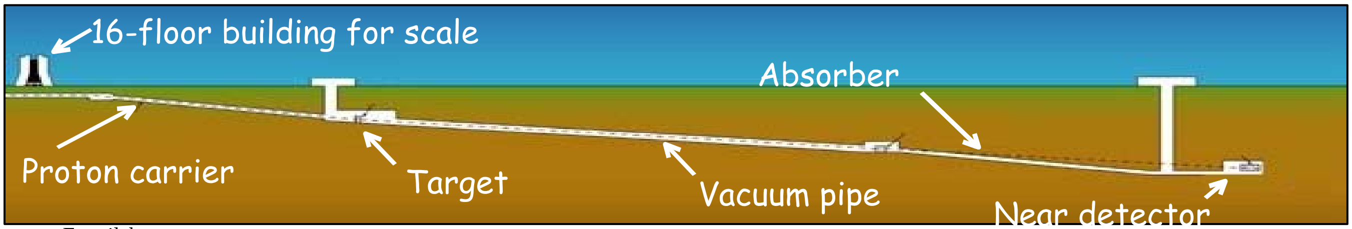
The Soudan Underground Laboratory is a general-purpose science facility, which provides the deep underground environment required by a variety of sensitive experiments. The Lab currently hosts two large projects: MINOS, which investigates elusive and poorly understood particles called neutrinos; and CDMS II, a "dark-matter" experiment which may help explain how galaxies are formed. Both were built for basic research—exploring how the universe works—but similar efforts have spawned practical (if unforeseen) byproducts, including advanced medical imaging techniques and even the world-wide web.

What is a neutrino? A neutrino is a tiny particle similar to an electron but without its electric charge. Neutrinos are produced by natural radioactive decay, inside the sun and other stars, and by scientists at particle accelerators. They don't interact very often, as they are so small they pass right through the spaces in ordinary matter. A neutrino is as many times smaller than an atom as that atom is smaller than your fingertip – one hundred million times smaller!

What is "dark matter"? Actually, no one really knows! What we *do* know (from astronomical observations) is that there is a lot of it around —perhaps 80% or more of the material in the universe. We can't see it, but we know it's there from the gravitational force it exerts. One possibility is very heavy (so-far undiscovered) particles nicknamed "WIMPs" (Weakly-Interacting Massive Particles). CDMS II searches for the WIMPs that might be providing all the extra gravity seen pulling on the stars in our own galaxy.

Why is the Laboratory so far underground? MINOS and CDMS II are extremely sensitive instruments searching for particles that (at best) are very seldom seen. At ground level, naturally occurring cosmic rays strike the surface of the earth very often – about ten per second for something the size of your head. This would completely mask the rare effects these experiments seek to see. The half-mile or so of rock above the Lab blocks almost all these cosmic rays, providing a much "quieter" research environment – about one cosmic ray per head per day.

How big is the Laboratory? The MINOS cavern is 82 meters (270') long, 15 meters (50') wide, and 13 meters (40') high. The CDMS II cavern is similar in shape but only 70 meters (230') long. The surrounding rock formation is not iron ore but Ely Greenstone, an especially strong rock which is about 2.7 billion years old. Nearly 100,000 tons were excavated to build the lab—all hoisted to the surface, six tons at a time. Some was used beneath the parking area west of the Engine House, while the rest can be seen piled southeast of the headframe.



Fermilab

Where do neutrinos come from? Most are made naturally by cosmic rays and the sun, but MINOS looks primarily for neutrinos from the Fermi National Accelerator Laboratory (Fermilab), near Chicago. There, the "Main Injector" accelerator can direct an intense beam of protons onto a special graphite target, where they produce new particles called "pions." The pions are pointed toward Soudan along a 675-meter (2,200') vacuum pipe (top illustration), where they decay to make neutrinos. Other particles are also created, but they are stopped at the end of the pipe by a 10-meter (33') thick steel absorber and 240 meters (800') of solid rock. Because neutrinos don't interact very much, virtually all simply pass straight through the absorber and rock, as well the 735 km (457 miles!) of earth between Fermilab and Soudan. They travel at nearly the speed of light and take only 2.5 thousandths of a second to make the trip. Before they leave Fermilab they have a (very) small chance of being seen in the MINOS Near Detector, so a "before-and-after" experiment can be done.

What does MINOS *mean*? MINOS is the Main Injector Neutrino Oscillation Search: "Main Injector" for the Fermilab accelerator, and "Oscillation Search" for the theory that links neutrino mass to oscillations. In Greek mythology Minos was the son of Zeus and Europa, the King of Crete and builder of the labyrinth.

How big are the MINOS detectors? The MINOS "Far Detector" at Soudan consists of two identical "super-modules." Each is an octagon (a neutrino stop sign!) 8 meters (26') across, and 15 meters (48') long. Together they weigh more than 6,000 tons (about the same as a two WW-II era destroyers). Why so large? The more atoms of iron there are, the more neutrinos will be so unlucky as to hit something, so the more we learn. The Near Detector at Fermilab is similar but smaller, about 1,000 tons.

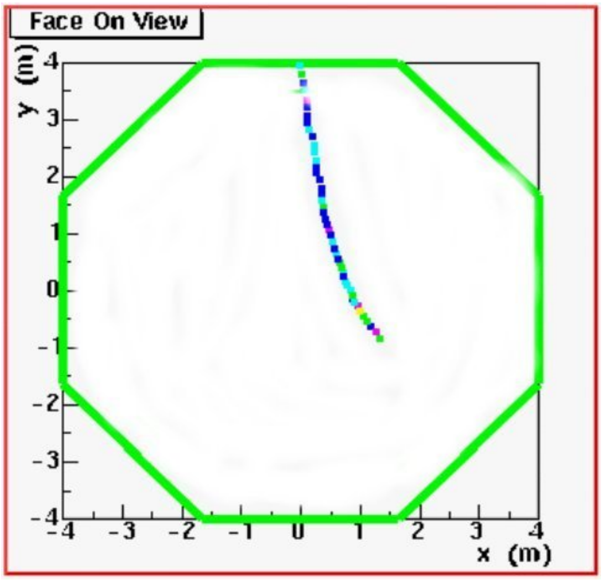
What are they made of? The MINOS detectors consists of alternating planes of 1"-thick steel and ½"-thick plastic scintillator strips. The plastic gives off light when charged particles pass through. An electric current through the middle of the detector magnetizes the steel, helping identify these particles and measure their energy. The Far Detector was completed in July 2003, and has been operating steadily ever since.

The MINOS Far Detector.

How about the Near Detector? The Near Detector (at Fermilab) is made of the same alternating steel and scintillator design. The plates are smaller and oddly shaped – the neutrino beam is only a few feet wide at the source so only the left half of the detector needs to be instrumented (although the beam has spread to a mile wide by the time it reaches Soudan!). It is also magnetized by a current through a hole in the middle. The construction was finished in July 2004.

The MINOS Near Detector, installed at Fermilab.

How does the detector "see" neutrinos? It actually never directly does! Neutrinos interact only very rarely with ordinary matter, which is why they don't need a tunnel to get from Fermilab to Soudan. The number of neutrinos in the beam is *very* large, however, so once every few hours one is unlucky enough to directly hit one of the 6000 tons of Far Detector. Even then we don't see the neutrino itself, but only the charged particles created by the collision. By watching the resulting spray of ordinary particles, the properties of the incoming neutrino can be deduced – much as you could watch a game of pool with an invisible cue ball, watch where the other balls break, then figure out where the shot came from.



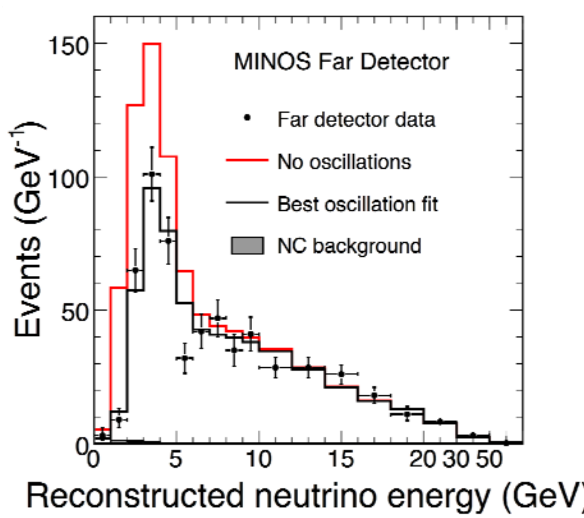
A cosmic ray muon seen in the MINOS detector, entering from the top and headed down. It curves due to the magnetic field and stops before exiting. Each "dot" in this track represents a tiny flash of light in a plastic scintillator strip created when the charged muon passes through. See the www.soudan.umn.edu website for a live display of current data!

How does it all work? When charged particles travel through the detector they create light in the plastic scintillator. This is collected by special green optical fibers. The light travels down the fiber to the edge of the detector, and into a clear fiber which carries it on to devices called photomultiplier tubes. These convert the light to electrical signals. A bank of computers records these signals for display and analysis.

What will MINOS tell us about neutrinos? Neutrinos come in at least three different types or "flavors": one paired with the electron, another with its heavier cousin the "muon," and the last with the even heavier "tau." Quantum mechanics, the physics of particles, tells us that neutrinos with mass spontaneously change from one type to another and back again (or "oscillate"). MINOS is designed to search for these oscillations. Because neutrinos were long thought to be massless, a positive signal would be tremendously important. These masses are quite small, however, so the beam must travel a long way (from Fermilab to Soudan) before anything happens. Previous experiments in Italy, Japan, and right next door in the original Soudan 2 cavern have seen these neutrino oscillations. MINOS is able to study them in detail by a before-and-after comparison of the beam using the Near and Far Detectors.

How do you tell the neutrinos apart? Neutrino type can be determined from the particles they produce. Electron-type neutrinos tend to make electrons, which create short "shower-like" patterns in the detector. Muon-type neutrinos make muons, which produce long almost-straight "tracks." The tau-type is difficult to observe directly. The beam contains primarily one type of neutrino (muon-type). If neutrinos have no mass it should look essentially the same here at Soudan as it did when it left Fermilab. Any significant difference between the "Near" and "Far" Detectors is the signature of neutrino oscillations and thus neutrino mass.

What has MINOS learned? The NuMI beam has been running since March of 2005. The first two years of operations produced ~3.4×10^{20} neutrinos, of which 848 were seen at Soudan. A graph of the number of neutrinos seen at different energies is shown below. What the Near Detector sees before the trip from Chicago to Soudan is the red line. The black crosses are what is actually seen, many neutrinos have gone missing! If the muon neutrinos are changing into the hard-to-see tau neutrinos, the black line is what would be seen. That black line matches the data. With this first look at the data, MINOS already has the best measurement in the world of this neutrino flavor changing. The beam will continue to run for at least a few more years to refine this picture.



Why are neutrinos important? Neutrinos are the most common massive particle in the universe, and are so hard to study that we know comparatively little about them. Even a tiny bit of mass per neutrino could add up to as much stuff as all the "normal" matter we see combined (although not enough to make up the Dark Matter CDMS is looking for). Neutrino mass is also something not explained by the current Standard Model of particle physics, so is something new that theorists trying to create Grand Unified Theories of Everything need to be able to explain. MINOS hopes to provide details about neutrinos to test these new theories.

How was all this equipment brought underground? Much like the proverbial ship in a bottle. Everything you see in the Lab came down the same narrow mine shaft that brought you underground. The hoist can handle equipment 1.3 x 2 x 10 m long (a little over 4' by 6' by 33'), weighing up to six tons. Each item in the laboratory was carefully designed to fit within these limits. During excavation of the cavern a full-sized front-end loader was brought underground in pieces, assembled, used for a year, and brought back out again.

How were the detector planes put together? Eight sheets of 0.5" steel are needed for each 1" thick octagon. They were “plug” welded in the open area directly below the Visitors’ Gallery, and the scintillator modules attached and tested. The crane used a special fixture called a strongback to lift the assembled plane to vertical, and to its proper location in the detector.

How long did it take to build the Laboratory? The “Soudan 1” experiment began in 1981, using an existing cavern on the 23rd level of the mine. The Soudan 2 Detector Lab was completed 1986, and MINOS Far Detector excavation began in 1999. The ceiling, walls, and floor were completed in 2000, with outfitting—steel supports, electrical, communications, and other systems—finished in July 2001. The first MINOS Far Detector plane was installed at the end the same month and it was completed in July 2003. The CDMS II enclosures were completed in spring 2002.

Who funds the projects? The U.S. Department of Energy provides primary MINOS support, with additional major contributions from the United Kingdom, the National Science Foundation, the State of Minnesota, and the collaborating universities and laboratories.
CDMS II is funded by the National Science Foundation and the Department of Energy.

How is the Laboratory related to the State Park? U.S. Steel donated the Soudan site to the people of Minnesota in 1962. The Department of Natural Resources has administered it as a State Park since then, operating and maintaining the hoist, pumps, and electrical and other systems, and escorting approximately 35,000 visitors each year underground to the last working areas of the mine. The University of Minnesota leases the Soudan Underground Laboratory from the State, and operates it under contract with the Department of Energy.

Are there other labs like this? During the past fifty years more than a dozen underground mines and tunnels have been used for physics experiments. Major active underground laboratories include Creighton (Sudbury, Canada), Boulby (northeastern England), Gran Sasso (Italy), Frejus (between Italy and France), Baksan (Russia), Kamioka (Japan), and Soudan.

What’s Next Door? The other cavern is the original Soudan 2 Laboratory. The Soudan 2 detector was about the same size as the MINOS Near Detector (1,000 tons) and was also built primarily of steel, but employed a different (gas-based) detector technology. Soudan 2 was built to look for “proton decay,” operated between 1989 and 2001, and was removed in 2005. While proton decay has not yet been observed, Soudan 2 contributed to the initial evidence for neutrino oscillations on which MINOS is based. A new Low Background Counting Facility is being built in this lab space to give scientists a place to make careful measurements of very faint radioactive sources that would be overwhelmed by the cosmic radiation if the measurement was made on the surface.

What is CDMS? The other cavern also houses the Cryogenic Dark Matter Search (CDMS). This experiment searches for dark matter, the stuff that astronomers believe constitutes most of the matter in the universe. “Cryogenic” refers to the fact that the experiment’s detectors operate at only a tenth of a degree above absolute zero (–460° F, the coldest place in Minnesota!).

How is dark matter different from normal matter?
The matter that makes up everything we are familiar with, from the air we breathe and the food we eat to the stars that shine in the night sky, is composed of the well-known elementary particles named protons, neutrons and electrons. While other particles are known to exist, such as the neutrinos studied by our MINOS neighbors and even more exotic ones made at Fermilab, *none of these could be the dark matter*. They simply don’t account for enough mass to have formed the structures like galaxies that we see in the universe. Some type of particle that neither emits nor absorbs light must be providing the gravitational “glue” that has allowed galaxies to form and persist. One of the current favorite theories in particle physics, supersymmetry, postulates the existence of just such a particle which has been given the colorful acronym WIMP, standing for Weakly-Interacting Massive Particle.

What is a WIMP?
WIMPS appear to be cousins to photons, but with a mass of 10 to 10,000 times the mass of the proton. They will only be detectable by us when they collide with an atomic nucleus. Atoms contain mostly empty space, so this rarely happens. As many as 10 trillion WIMPs should pass through one kilogram of solid material on Earth in a second, but perhaps as few as one per year will bump into anything. Hopefully, WIMPs are plentiful enough and our detectors sensitive enough that we will be able to “see” them.

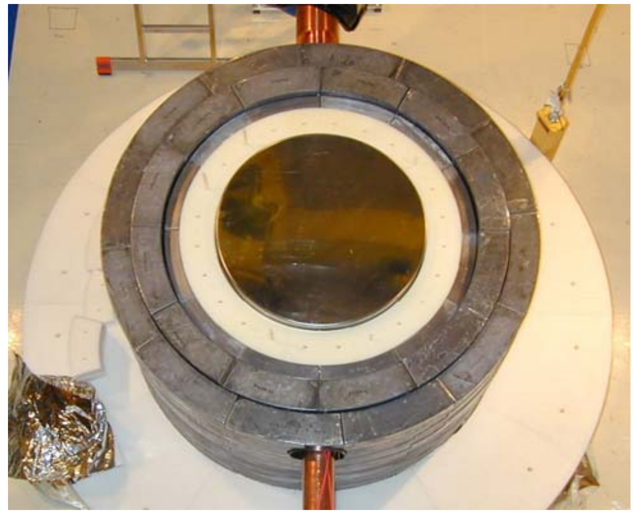
How do the detectors work?

The CDMS detectors are hockey puck-sized disks of silicon and germanium. If a WIMP hits a germanium nucleus, the nucleus recoils and vibrates the whole germanium crystal. Sensitive thermometers detect the resulting warming of the crystal. Less exotic particles such as photons and electrons, however, tend to disturb the germanium's electrons rather than the nucleus, releasing charge that can be detected with separate electrodes. The ratio of charge to heat for each event tells whether a particle struck the nucleus, as WIMPs do, or simply rattled the electrons surrounding the nucleus, as most background particles do. Incoming neutrons also strike the germanium nucleus, so they more closely resemble WIMPs. The germanium detectors sit in a stack with detectors made of silicon. A silicon atom has a smaller nucleus, and so will be hit less frequently by WIMPs. The strong nuclear force does not affect WIMPs, but it does affect neutrons and so neutrons will hit nuclei of different sizes at about the same rate. A higher collision rate in the germanium than the silicon will indicate the interaction of WIMPs.

Are there other sources of backgrounds?

Small amounts of natural radioactivity in the rock and other materials used to construct the cavern would supply a huge background of particles, blinding our detectors to WIMPs. To reduce the rate from these backgrounds we surround the detectors with a variety of different shielding materials, including lead, copper, and polyethylene. The experiment is constructed inside a clean room that filters out most of the dust particles which can carry radioactive isotopes. Also, all of the materials that we use to construct the detectors have been screened to make sure they have very low radioactive contamination. The radioactivity level of the experiment has to be far lower than the levels that are safe for humans – in fact, we humans contain far more radiation in our bodies than could be tolerated in the experiment. A single drop of human sweat on the surface of one of our detectors contains enough radioactive potassium-40 to completely mask any WIMP signal that we could hope to see.

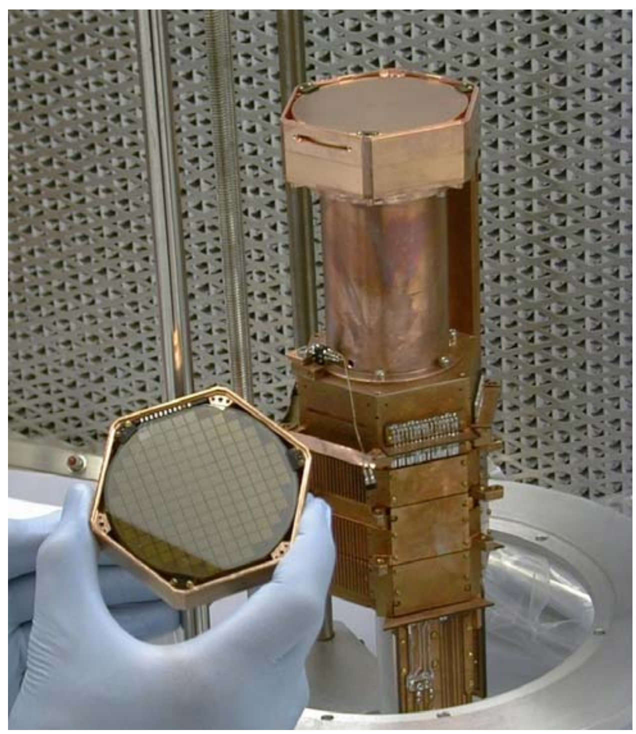
Five "towers" of 6 CDMS detectors each (from above).



This top view of a partial assembly of CDMS shows the white polyethylene that shields the experiment from neutrons and the gray lead that shields gamma rays. The can lid in the center covers the central cryostat in which the cold detectors are operated.

How long will it take to find WIMPs?

CDMS II has been running for approximately 4 years and has not yet seen WIMPs. However, the experiment is just reaching the sensitivity where most theories predict WIMPs to appear. The Germanium detector mass will be increased to 15 kg over the next two years to improve the sensitivity even further.



The hexagonal ring holds a single CDMS detector. The square grid on the detector surface shows the patterning of the metallic thermal sensors. In the background is the detector & wiring package forming a "tower".

Who does all this work? There are nine full-time UofM employees who keep the lab and experiments running. Several scientists from MINOS or CDMS will be visiting the lab at any point in time, but many more work on the projects from their home institutions. MINOS has 153 scientists, professors, students, and technicians from 28 different universities and national labs in five countries, primarily from the US and UK. CDMS currently involves 50 such physicists from 14 institutions. Typically, each member institution brings a particular expertise or capability to the experiment. By organizing themselves and working together they can accomplish a much more challenging scientific goal than if they each worked independently.

CDMS II institutions (March 2009): California Institute of Technology, Case Western Reserve Univ., Fermi

National Accelerator Lab, Massachusetts Institute of Technology, Queens Univ., Syracuse Univ., Texas A&M, Univ. of Minnesota Twin Cities, Santa Clara Univ., Stanford Univ., Univ. of California Berkeley, Univ. of California Santa Barbara, Univ. of Colorado at Denver, Univ. of Florida, and the Univ. of Zurich.

MINOS institutions (March 2009): Argonne National Lab, Univ. of Athens (Greece), Benedictine Univ.,

Brookhaven National Lab, California Institute of Technology, Univ. of Campinas (Brazil), Cambridge Univ., Fermi National Accelerator Lab, Harvard Univ., Holy Cross College, Illinois Institute of Technology, Indiana Univ., Univ. College London, Univ. of Minnesota Duluth, Univ. of Minnesota Twin Cities, Otterbein College, Oxford Univ., Univ. of Pittsburgh, Rutherford Appleton Lab, Univ. of Sao Paulo (Brazil), Univ. of South Carolina, Stanford Univ., Univ. of Sussex, Texas A&M Univ., Univ. of Texas (Austin), Tufts Univ., Univ. of Warsaw (Poland), and The College of William and Mary.

Science and art provide complementary insight into the universe of natural phenomena. The mural pictured below was created by Joseph Giannetti in order to convey one artist's impression of neutrino physics and the Soudan Mine, and includes images of people important to the development of both physics and the mining industry. Mr. Giannetti designed the mural with computer graphics, projecting his image onto a 25' by 60' rectangle prepared with 25 gallons of white primer by Laboratory staff. Mr. Giannetti and his assistants completed the installation from a movable "window washing" platform, applying approximately 50 gallons of color paint over several months' time.