TO CATCH A SUPERNOVA

BY CALLA COFIELD

New 3-D simulations of Supernova 1987A show rings of material leaving the star at 62 million miles per hour. Observations of 1987A were the first to confirm that core-collapse supernovae emit neutrinos.
Image: European Southern Observatory/ L. Calçada

SOME EXPLODING STARS RELEASE BURSTS OF ODDBALL NEUTRINOS. SCIENTISTS WITH THE LONG BASELINE NEUTRINO EXPERIMENT ARE EAGER TO CATCH THOSE NEUTRINOS AND MILK THEM FOR DISCOVERIES. BUT THEY MUST WEIGH THE BENEFITS OF DOING THAT AGAINST THE RISK THAT NOTHING WILL HAPPEN—NO SUPERNOVA, NO NEUTRINO BURST—DURING THE EXPERIMENT'S 50-YEAR LIFETIME.

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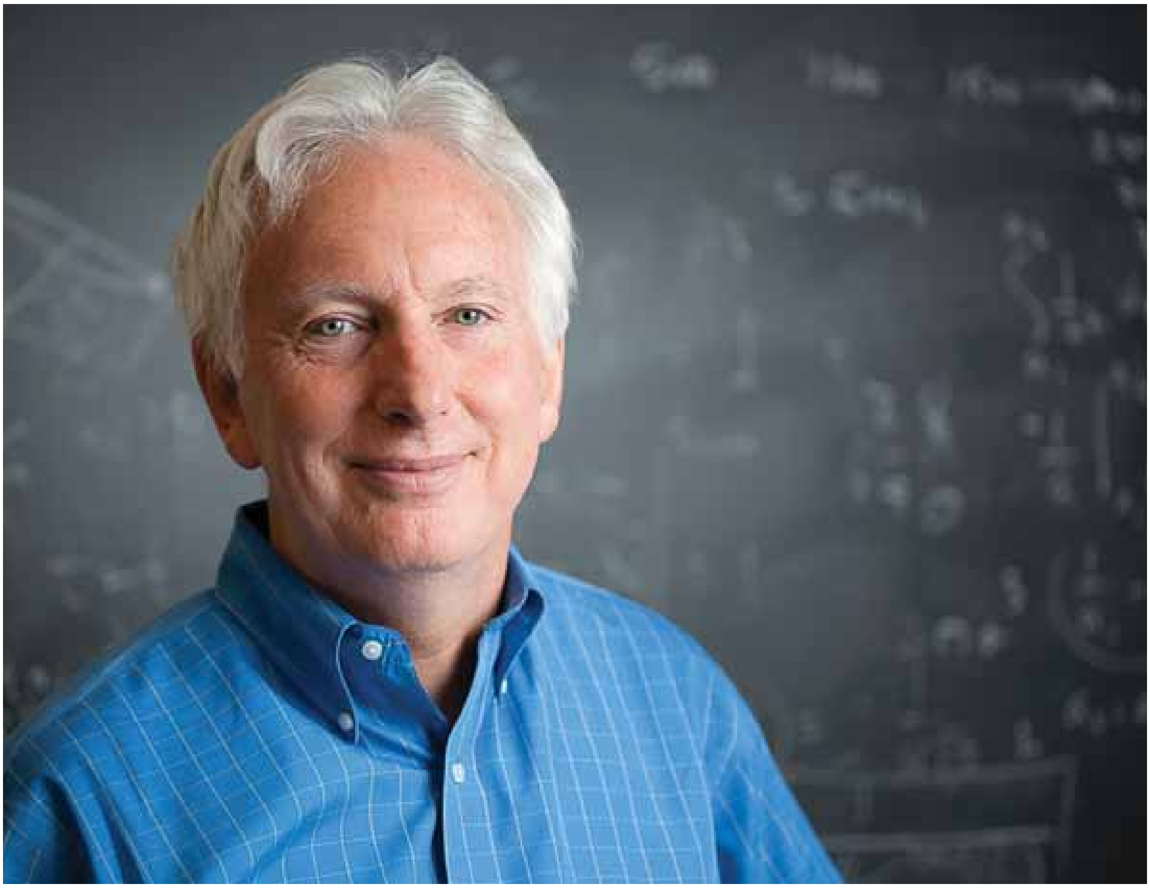


Bob Svoboda is a physicist at the University of California, Davis, co-spokesperson for the Long Baseline Neutrino Experiment, and supernova neutrino hunter.
Photo: Bradley Plummer, SLAC

IN THE WEE HOURS OF THE MORNING ON MARCH 7, 1987, BOB SVOBODA WAS COMBING THROUGH DATA, LOOKING FOR THE ANSWER TO A QUESTION ABOUT ONE OF THE MOST EXOTIC EVENTS IN OUR UNIVERSE.

Normally, such an answer reveals itself gradually over time; but this night was different. Around 2 a.m. he picked up the phone and started waking his colleagues.

Svoboda was a postdoctoral researcher at the University of California, Irvine working on the Irvine-Michigan-Brookhaven, or IMB, nucleon detector and neutrino observatory. IMB was set up to detect proton decay, but the apparatus doubled as a neutrino detector. Neutrinos are perhaps best known as the subatomic particles that rarely interact with other forms of matter; the steady flow of them produced by the sun passes through the Earth like a parade of ghosts. Out of those many trillions of trillions of neutrinos, IMB collected about two a day.

But on one fateful night, researchers had reason to think this number had abruptly increased.

On February 23 the International Astronomical Union's Central Bureau for Astronomical Telegrams had reported a star explosion—a supernova—just outside the Milky Way galaxy. Telescopes quickly turned to watch the star's violent death in the Southern Hemisphere. It was the first supernova in 383 years that could be seen with the naked eye. Dubbed 1987A because it was the first supernova of that year, this was a core-collapse supernova, meaning its massive outer shell, weighing nearly 10 times the mass of the sun, had come crashing down onto the star's burnt-out core. The impact of the collapse would release a mind-boggling amount of energy, and at the time some models of supernovae predicted that this energy might convert into neutrinos. The only way to know for sure was to directly observe neutrinos coming from a supernova burst.

Svoboda and the UC Irvine group were the first IMB collaborators to respond to the news. They requested data from the detector site, an old Morton salt mine outside Cleveland, Ohio. When it finally arrived by FedEx, the group spent four days in the lab, barely sleeping, combing the data from February 23 onward for a sign of a neutrino spike. They found nothing.

Their hopes rose when they got a tip that the Large Scintillation Detector in Italy had picked up a neutrino signal. But again they found nothing (and, in fact, no one was ever able to confirm the LSD findings). This was a bitter disappointment, considering that supernovae go off in the Milky Way, on average, only once every 50 years, and the last recorded supernova visible from Earth was in 1604. IMB seemed to have missed a once-in-a-lifetime event.

Svoboda's wife suggested they try to relieve the disappointment out on the ocean; March is peak whale-watching season in California. It was there that Svoboda realized that he and the team had not looked at a period of time when one of the detector's power supplies had failed. The analysis software automatically skipped over such periods, so to see it, one would have to alter the software. When the boat docked he hurried back to the lab.

Svoboda was working on the software when he got word that the Kamiokande neutrino detector in Japan had detected a burst precisely during the power supply failure time. With the altered software he immediately ran the data from the correct time, and saw what he'd been hoping for.

"I didn't even have to analyze it," said Svoboda. "It was obvious we had a neutrino burst."

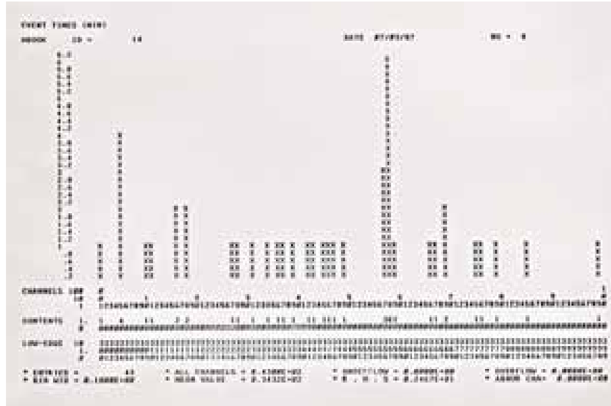
At 2:35 a.m. on February 23, eight neutrinos had collided with the detector in a matter of six seconds.

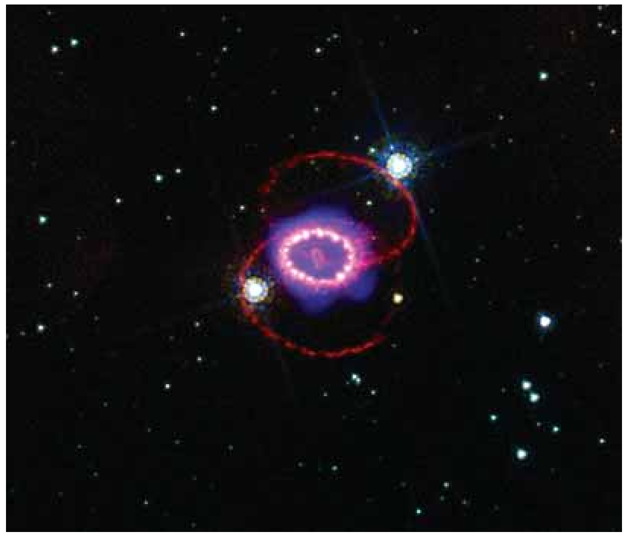
The team once again assumed a schedule of barely sleeping, rushing to get their observations ready for publication. To ensure that the work would be published simultaneously with that of their colleagues at Kamiokande II, they had a messenger fly from California to New York and hand deliver the draft.

A total of 24 neutrinos had been collected—eight by IMB, 11 by Kamiokande II in Japan, and five by the Baksan Neutrino Observatory in Russia. The news of the supernova was on the cover of most major newspapers, and a cover story in *Time* magazine mentioned the neutrino search.

The neutrino data shook astrophysics and rippled through the larger physics community. Any theoretical model of supernovae that didn't take into account neutrino emission had to be scrapped. For astrophysicists studying supernovae, the neutrino data was a revelatory shaft of light. In the 23 years since its publication, hundreds of papers have been written about those 24 particles.

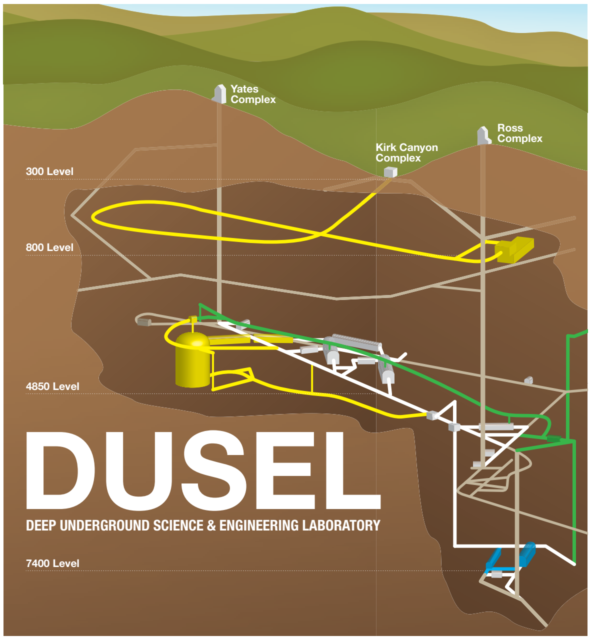
If two dozen supernova neutrinos could do that, imagine what tens of thousands could do.

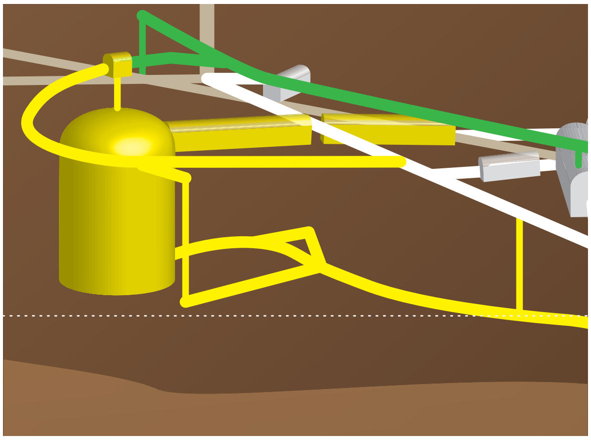




Top: Framed on Bob Svoboda's office wall is an actual IMB data chart from February 23, 1987. A spike in the neutrino count is clearly visible at the moment that IMB captured supernova neutrinos from 1987A.

Bottom: Combined optical images from the Hubble Space Telescope and X-ray images from the Chandra X-ray Observatory illuminate the remnants of 1987A. *Image: (X-ray) NASA/CXC/PSU/S. Park and D. Burrows.; (Optical) NASA/STScI/CfA/P. Challis*





Only about one in 10^{16} neutrinos will interact with a neutrino detector such as LBNE. The proposed DUSEL facility will protect detectors from cosmic rays and other stray particles that could obscure the faint neutrino signal. *Image: Sandbox Studio*

THE NEXT DETECTOR

A lot has changed since 1987. Astronomical telegrams go out over email, and large data sets travel almost instantly over the Internet. Svoboda is now a physics professor at the University of California, Davis, a leader in the field of neutrino physics, and co-spokesperson for the Long Baseline Neutrino Experiment, or LBNE, which would be one of the most ambitious neutrino experiments ever undertaken.

The plan is to build a neutrino detector with ten times the neutrino-sensitive material of any that exists today, and install it in the proposed Deep Underground Science and Engineering Laboratory, DUSEL, which would be the deepest science facility in the world. LBNE would collect and study neutrinos from a beam generated at Fermilab, which, when built, would pack in more neutrinos per square inch than any neutrino beam before, allowing an unprecedented rate of data collection.

Besides being one of the most elusive particles in the universe, neutrinos are also one of the most abundant, and our understanding of neutrinos is a critical part of our understanding of the universe as a whole. Many of LBNE's scientific goals will address basic questions about neutrinos, such as those surrounding their masses. Via this advanced study of neutrinos, the collaboration will also take a crack at other major questions in modern physics, including the fundamental relationship between quarks and leptons (and hints at a grand theory of unification) and CP violation (how did matter survive after the big bang?). It may also look for relic neutrinos left over from the many core-collapse supernovae that have been going off in the universe almost constantly since the beginning of star and galaxy formation.

Now LBNE is approaching a critical moment: deciding what kind of detector it should build. Three basic designs exist, although LBNE will have the opportunity to add its own details. Groups of LBNE scientists around the country are evaluating how each design could benefit the areas they wish to study.

One of those scientific areas, much to Svoboda's delight, is supernova neutrino physics. A team of researchers led by Kate Scholberg of Duke University is conducting simulations to determine the best design for catching supernova neutrinos and figure out how to wring the most information out of them.

"Right now we're trying to reduce that vast landscape of possibilities into something that's very concrete," says Svoboda. "It's a combination of what science we would like to do and what we can afford."

The next time a core-collapse supernova goes off in our galaxy, LBNE and other major neutrino detectors around the world stand to collect hundreds of thousands of neutrinos. But physicists want more than a neutrino headcount. They're after detailed readings on the energies of neutrinos, and that requires special equipment capable of receiving short, strong bursts of particles, the ability to glean a great deal of information from them, and the computing power and data storage capacity to record it all. And that will cost money.

The LBNE construction budget is not yet finalized, but will land above $1 billion. The 300 or so LBNE collaborators plan to present their scientific report, including a rough budget estimate, to major funding agencies in December—one step in the lengthy process of getting construction approval. Svoboda and his LBNE co-spokesperson Milind Diwan, a researcher at Brookhaven National Laboratory, will include supernova neutrino burst capabilities in their pitch in December. Many of the requirements are already built into the LBNE plan because they enable other science goals of the machine, and Diwan says ultimately the financial investment for catching supernova neutrino bursts is relatively modest. Right now, he says, “it looks like the collaboration would like do that. That’s not such a big deal.”

The monetary investment may be small, but LBNE has a serious risk to consider: there is no guarantee that a supernova will go off within the lifetime of the experiment and send neutrinos flying into the specially equipped detector.

An estimated 20 supernovae go off in our galaxy every 1000 years (or about one every 50 years), but there is no mechanism driving this estimate or formula for predicting when the next one might occur. What’s more, only one type of supernova—a core-collapse—generates such large bursts of neutrinos, and that burst must occur within the Milky Way; otherwise only a handful of neutrinos would reach detectors on Earth. To make the investment worth the risk, the data set would have to be something very special.

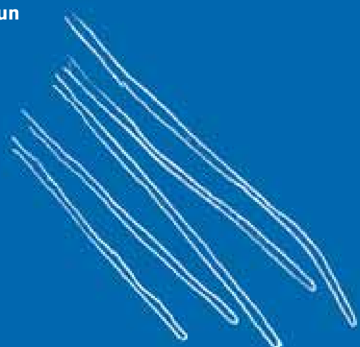
A TREASURE CHEST OF DATA

In 1987 scientists weren’t even sure if supernovae emitted neutrinos. Now these neutrinos may unlock mysteries in particle physics, astrophysics, and nuclear physics.

A neutrino carries a certain amount of information about the event that produced it. Through the study of solar neutrinos, scientists have deduced a great deal about the inner workings of our sun, including exactly what kind of nuclear processes keep it burning. Supernova neutrinos hold the promise of

THE DOUBLE LIVES OF NEUTRINOS

Neutrinos from the sun



Neutrinos from a supernova

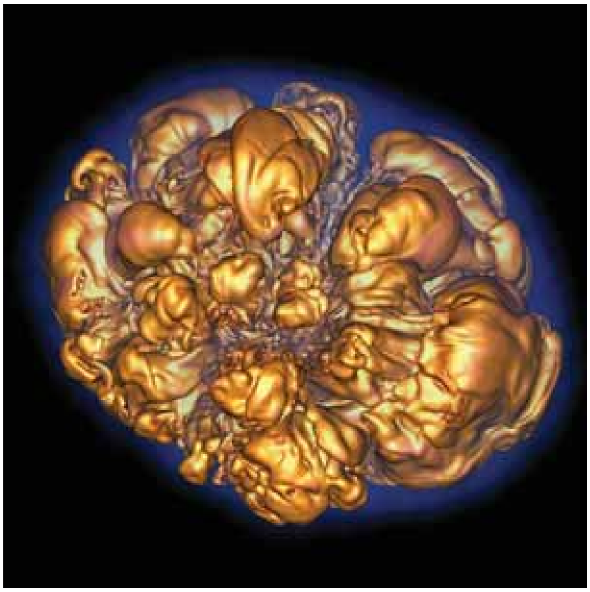
Image: Sandbox Studio

To get an idea of what scientists are up against when studying supernova neutrinos, imagine that a piece of string connects each neutrino to its point of origin. As the particle heads out into space, we can follow the string to see where the neutrino came from and where it has been. Because neutrinos from the sun don’t interact with other matter or with each other, their strings are straight, smooth, and easy to follow.

But supernova neutrinos are another story, because they do interact with each other. When two neutrinos interact, or “couple,” their strings tangle together. Each neutrino goes on to couple with a series of other neutrinos, until the imaginary strings of all 10^{58} neutrinos twist and knot into a mess that would make untangling Christmas lights seem like a walk in the park.

And it gets more complicated. These interactions fundamentally alter the way a neutrino changes flavor, or transforms from one of the three basic neutrino types into another, which normally takes place independently.

Simulating the behavior of the nice neat neutrinos coming from the sun is what’s called a linear problem; the behavior changes in a simple, predictable way. But the path of a supernova neutrino is a non-linear problem, meaning small changes in the environment can cause drastic, complicated changes in the behavior of the subject. “That’s sort of the legacy of non-linear systems,” says George Fuller of the University of California, San Diego, “They’re squirrely.”



New supernova simulations reveal "convective blobs" that emerge from the star's core as it explodes. The energy deposited by the neutrinos as they course out of the core drive these blobs. This particular supernova has the potential energy of 25 trillion trillion nuclear weapons.
Image: A. Burrows and J. Nordhaus, Princeton; H. Childs, UC Davis

carrying similar information about what goes on inside an exploding star. Those explosions are thought to produce all the heavy elements in our universe—elements crucial for life as we know it—but major uncertainties surround this theory. Learning about the processes taking place inside a supernova might settle some of the debate. This information will most certainly increase scientists' understanding of those intense nuclear reactions and feed into the study of nuclear physics, which has applications in energy research.

This multidisciplinary appeal is one of the central reasons that Diwan thinks funding agencies will get behind the necessary upgrades to the LBNE.

"Anytime some science is of interest to multiple disciplines there is something interesting going on there," Diwan says. "We really need to understand why and how this thing works, because nobody has a complete picture."

For years after 1987A shook up the study of supernovae, scientists have tried to create a picture of what is going on inside these dying stars, and what life there might be like for neutrinos. In the late 1980s George Fuller was a graduate student in neutrino physics, and saw the field suddenly receive the attention not only of the public, but of both particle physicists and astrophysicists. The result, he says, were a lot of projections about supernova neutrinos that were "just plain wrong."

Fuller drifted away from the field for a few years, but returned as a population of specialized supernova neutrino physicists began to emerge. He was there at the turn of the 21st century when he and his colleagues began to suspect that something very peculiar was happening to supernova neutrinos. And when computer technology finally caught up with theory and supernova neutrino computer models were created, Fuller saw the first shocking results.

Neutrinos, it turns out, lead double lives. The neutrinos we know on Earth—those that come from the sun, from radioactive material in the Earth, or from cosmic ray collisions in the upper atmosphere—are ghostly, anti-social individuals. Most of them pass right though our bodies, cars, buildings, and indeed through the center of the Earth without interacting with other matter. That's why a detector like LBNE can record only about one in 10^{16} (ten thousand trillion!) neutrinos. This is a characteristic no other subatomic particle exhibits to such an extreme degree.

So imagine physicists' surprise when they began to realize that if neutrinos are packed together tightly enough, they become social, interactive party animals.

This unusual behavior can only take place in an extreme environment—the inside of a supernova is currently the only one we know of, and may be the only one we are ever able to detect. The models of core-collapse supernovae show that when the outer layers of the dying star come crashing down, 99 percent of that energy turns into neutrinos. If the sun provides a shower of neutrinos and a man-made neutrino beam is a neutrino fire hose, then a supernova burst is a veritable neutrino tsunami. The force of the collapse packs the particles together so tightly that for a moment there are more neutrinos per cubic inch than electrons. In that intensely crowded environment, the neutrinos no longer act like their typical selves. They begin to scatter off each other, touching and colliding much as other forms of matter do.

This scattering induces another odd behavior: neutrino coupling, in which the neutrinos don't just collide, but become linked. After two coupled neutrinos part ways, they may each couple with another neutrino, connecting all four of them. As the coupling continues, the entire body of 10^{58} neutrinos becomes connected.

When neutrino flavor changing, or the spontaneous switching of identities from one of the three types of neutrino to another, is taken into account, coupling increases to such a degree that large clumps of neutrinos may all change flavor together, rather than randomly, as individuals. But is there a connection between the flavor-changing behavior of neutrinos and their peculiar coupling? What can this tell us about neutrino physics, or about other events that release neutrinos?

"We don't know all the answers right now, and we don't have predictions for the supernova neutrino signal that are set in stone," says Alexander Friedland, a supernova neutrino physicist at Los Alamos National Laboratory in New Mexico. "I predict in the next couple of years there will be a lot more interesting results found, and we'll gain a more definite picture of supernova neutrinos. But right now we have this wonderful Wild West period of discovery."

The unique journey that neutrinos take on their way from a supernova to Earth may deeply impact LBNE. (See illustration, page 21) In order to deduce what happened at the neutrinos' source, scientists must be able to untangle the neutrinos' paths and understand how scattering and coupling may have altered these particles. Supernova neutrino physicists like Friedland, Scholberg, and Fuller, along with colleagues including Huaiyu Duan, now a professor of physics at the University of New Mexico, will guide LBNE in this regard. Fuller and his group at the University of California, San Diego have accomplished one major step in this process by untangling the path of a single supernova neutrino. Although there is more work to be done to refine their results, their computer models can now tell LBNE physicists what to expect from supernova neutrinos, and how to be better prepared to catch them.

LOOKING FORWARD

Svoboda thinks the field is ready for a new set of data from hundreds of thousands of supernova neutrinos, and that LBNE is the best machine to gather it. Talking to Svoboda about the possibility of catching a supernova blast is like talking to a kid anticipating Christmas. His enthusiasm for the subject, for the possibilities this data might hold and for the chance to follow up on the discovery that started it all, is infectious. Diwan doesn't have the personal connection that Svoboda has to supernova neutrinos, but he arrives at the same conclusion: the impact that the last batch of supernova neutrinos had on the physics community was deep and long lasting, and the benefits of preparing LBNE to catch another batch are, he says, "crystal clear."

To maximize the chance of doing that, scientists plan on running the LBNE detector for at least 50 years. But that will be a policy decision, up for re-evaluation every ten years or so.

Over the course of those decades, LBNE will operate two separate detectors, with at least one of them running at any given moment. Friedland expresses a deep anxiety of his field when he says it would be too bad if LBNE never saw a core-collapse supernova go off in the Milky Way, "but it would be a tragedy if one went off while LBNE wasn't prepared."

His sentiment rings true for the small community of supernova neutrino scientists around the world, who love the field they study but will always run the risk of never seeing another real data set in their lifetimes.

Fuller, who is working with Scholberg on her detector analysis, is hungry for data, and aware that the rarity of supernovae poses a significant challenge to getting it.

"A funding agency will never give us a stand-alone supernova neutrino detector," he says. "And we accept that this machine should have a day job, so to speak." LBNE will essentially moonlight as a supernova neutrino detector, leading a double life not unlike those of the neutrinos Fuller hopes it will catch.