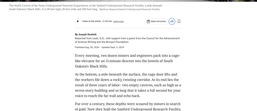
Mining for Neutrinos, and for Cosmic Answers

In a South Dakota cavern, scientists are working to unpack the most distant particles in the universe.



Alex Wright-Gottesman, left, and Ryan Dahlke, both of the Sanford Underground Research Facility, a mile underneath Lead, Dakota Territory, Black Hills. At 4,850 feet, right, the deepest underground DUNE cavern. Photos: Sanford Underground Research Facility

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Reported from Lead, S.D., with support from a grant from the Council for the Advancement and Support of Education (Rendell)
Photos by Ryan Dahlke
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Every morning, two dozen miners and engineers pack into a cage like elevator for an 8-minute descent into the bowels of South Dakota's Black Hills.

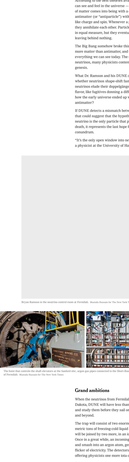
At the bottom, a mile beneath the surface, the cage door lifts and the workers file down a rocky, twisting corridor. At its end lies the Sanford Underground Research Facility, a cavernous hollow the size of a seven-story building and so long that it takes a full second for your voice to reach the far wall and echo back.

For now a century, these depths were secured by miners in search of gold. The facility, home to the Sanford Underground Research Facility, is now being repurposed for a different kind of prospecting: physicists plan to transform the nodes into the listening end of an 800-mile, $3 billion tin-can telephone. With it, they hope to hear a whispered answer to an existential question: How did we get here?

The message will be carried by interacting neutrinos — strange, elusive particles that weigh almost nothing and move almost as fast as light. At the telephone's other end, a half-mile-wide particle accelerator will fire a beam of neutrinos through Illinois, Lebanon, Joy and outside Chicago, will cross trillions of neutrinos every second in a narrow beam painted squarely at this cavern. The beam will pass through a human's hand and through their sister's skull at rated herbeck.

When the neutrinos arrive, physicists hope, they will finally explain how the Big Bang created our a slightly more matter than its opposite, antimatter — an excess that constitutes everything in the universe today.

The telephone, officially called the Deep Underground Neutrino Experiment, or DUNE, is the largest science-engineering project beneath American soil in history. It has taken a decade to reach this point, and it will take years more to finish digging. When it is all gone well, it will turn the superfluid neutrino into a known quantity, lifting a major gap in scientists' understanding of the universe and, perhaps, rewrite the United States to be brown prominent at the center of particle physics.



Excavation starting beneath Lead, Dakota Territory, underneath and beyond the Sanford Lab, a mining depot at the Homestake Mine. Underground DUNE cavern at a mile from the square's bottom. Recent Research from The New York Times

What's the antimatter

When an atom is split, its two fragments fly off at odd, oblique angles. In 1956, the physicist Wolfgang Pauli dreamed up the neutrino to explain the behavior. There must be a third, unseen bullet that whizzes off in a third direction, as fast as light that released a species. Dr. Pauli concluded.

It took decades for someone to prove him right. Neutrinos are the most abundant particles in the universe, and they are so small that they evade particle detectors as easily as they pass through bedrock. They are so slippery that they are the only particles whose mass remains a total mystery.

Moreover, whereas every other particle has an immutable identity, neutrinos change identities as they move. Neutrinos come in a Pleiadian roll-product-of-three-like set. "Neutrinos" all neutrino. But by the time those reach South Dakota, some will have morphed into a different flavor.

"It's as stark as if you turned into your grandmother as you walked to the kitchen, and then turned back into yourself as you walked back to your room," Bryan Bateman, a physicist on the project, said in his office at Fermilab, just north in Batavia, Ill. "That's essentially what neutrinos do."

Yet this "long-term, long-distance quantum effect," he added, is how DUNE will use neutrinos to explain, well, everything.

Fermilab's Short Baseline Near Detector, effectively a miniaturized version of what will go in the South Dakota cavern. Recent Research for The New York Times

The cosmic imbalance

Particle physicists hope that neutrinos can help solve a mystery of existence.

According to the best theories available, matter — everything we can see and feel in the universe — should not exist. Every particle of matter comes into being with a doppelganger, a particle of antimatter (or "antiparticle") with equal but opposite properties. When they meet, they annihilate, in a flash of energy so intense they overblown each other. Particles and antiparticles can be made in equal measure, but they eventually find and destroy one another, leaving behind nothing.

The Big Bang somehow broke this rule. It created very slightly more matter than antimatter, and that sliver of matter comprises everything we can see today. The shape-shifting properties of neutrinos, many physicists contend, may explain our existence.

What Dr. Bateman and his DUNE colleagues are trying to learn is whether neutrinos shape-shift faster than antineutrinos do. Can neutrinos slude their doppelgängers by morphing into the wrong flavor? Do they behave differently from their twins? Is that how the early universe ended up with slightly more matter than antimatter?

If DUNE detects a mismatch between neutrinos and antineutrinos, that could suggest that the hypothesis has merit. And because the neutrino is the only particle that physicists have not yet studied in depth, it represents the last hope for resolving the existential question.

"It's the only open window into new frontiers," said Jelena Maricic, a physicist at the University of Hawaii and a DUNE member.

Bryan Bateman in the neutrino-control room at Fermilab. Recent Research for The New York Times

The Fermilab particle accelerator, left, and the Sanford Lab, a mile and a half underground, in Lead, S.D. Photos: Recent Research for The New York Times

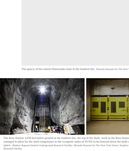
Grand ambitions

When the neutrinos from Fermilab reach the caverns in South Dakota, DUNE will have less than one millionth of a second to trap and study them before they sail on through subcoverness Wyoming and beyond.

The trap will consist of two enormous tanks, each filled with 17,000 tons of ultra-pure liquid argon. Neutrinos that enter the tanks will be joined by two more, in an identical screen down the hall. Once in a grow while, an incoming neutrino will become corporal and smash into an argon atom, generating a flash of light and a flicker of electricity. The detectors will measure these signals, offering physicists one more mess of information about neutrinos.

This rare event needs to occur many thousands of times to determine whether neutrinos and antineutrinos behave differently. So the trap must be big, so snag as many neutrinos as possible. This called for excavating two caverns, and then filling them with a dizzyingly complex array of pipes, pumps, refrigerators, electronics cross hatch, all carved down through the miner's narrow esophagus. Mike Headley, the director of SURF, compared the construction to "building a ship inside a glass bottle, except the neck of the bottle is a mile long."

Dr. Bateman said that "DUNE will be essentially the perfect large-baseline neutrino oscillation experiment." He added, "If you gave us a billion years, we would spend all the time in the world, it's hard to see how we would do better."



A panel at Fermilab explores the basics of the DUNE experiment. Recent Research for The New York Times

But the project's grand ambition has brought grand challenges, not all of them between.

The infrastructure of the mine shaft had to be overhauled before the lab could get the racks out and the experiment in, delaying the project by years. Meanwhile, the Fermilab particle accelerator that's to be upgraded — a billion-dollar expense — to deliver enough neutrinos to the detector. In 2022 the Department of Energy gave the lab a halting performance grade, and in 2023 it requested the lab's management contract to new bidders. In 2024 the lab's director, Lia Merminga, resigned concerns and was severely injured. Work was halted for the remainder of the year, allowing the lab "to look at all our procedures and ensure the safety of our people," Lia Merminga, Fermilab's director, said.

Even the DUNE pre-project — a free measurement using the detector in the first screen — was originally positioned to be completed in 2032 at around $3 billion. It's now scheduled for completion by 2040 at $3.1 billion. This does not include the billion dollar accelerator upgrade or the two additional detectors that will be installed in Japan, at a cost of roughly $1 billion and 1 million. All dell, the cost to American taxpayers for the entire undertaking could approach $5 billion.

Criticism in the scientific press has been harsh nothing, and it gave pause to some of the 1,400 scientists who had hitched their future to DUNE.

"The press, as it came out, was something I had to really think about," said Jonathan Paramo, a physicist at Fermilab and a DUNE life. Dr. Bateman said: "I've grown up extremely furiously cancer elsewhere to believe my interests." Were DUNE to be cancelled, he said, "then I would have essentially made the wrong bet."

The main cavern of the current Homestake mine at the Sanford Lab. Recent Research for The New York Times

The Sanford Lab, a mile and a half underground, in Lead, S.D. Photos: Recent Research for The New York Times

Ron Ray, DUNE's deputy project director, dismissed the critics. "Yeah there's some noise out there, but the people who are writing these things don't really know what they're talking about," he said. Dr. Paramo said the project was "inflicted by overwhelming optimism that every process is fine."

He argued that DUNE's unexpected costs and delays were normal for a scientific endeavor of this size. He pointed to the Kamio Wide Space Telescope, which was launched in December 2022 after years of delays and cost overruns and now regularly breaks cosmic ground. "There's no remedy this success," Dr. Ray said.

Yet Dr. Bateman, giving up on DUNE now "would mean that we would that America does not want to lead in particle physics anymore." He pointed to the Chinese Jiangmen Underground Neutrino Observatory experiment, which is now under construction and scheduled to begin operating in 2025 Like DUNE, JUNO, Hyper-K will use a newly excavated cavern to hold its detector, and it will use neutrinos from a newly excavated chamber in a mine. But it is simpler and sleeker, a modest step up from existing technology compared with DUNE. It is likely to progress faster and make the first, rough estimate of the imbalance between neutrinos and antineutrinos.

"Anything worth doing involves competition," Sam Zeller, a physicist at Fermilab, said. But this isn't a simple horse race, she added. Each experiment has its own strengths and potential collaborations. Besides, she said, DUNE has additional goals, which include looking for dark matter, the unseen substance that makes up most of the universe and exploding neutrinos from the explosion of stars in the sky.

Behind the scenes, DUNE scientists say that they have made steady progress toward performing the liquid-argon detector, which was still a nascent technology in 2012 when DUNE's designers gambled on it. "I look at the whole list of things that could have turned out differently and it's like all the stars are aligning," Dr. Zeller said.

A turning point

Dave G. Brooks, a senior engineer/contractor coordinator with Fermilab, in a hardwood drift, at upward, during the groundbreaking for DUNE at the Sanford Lab, a mile beneath Lead, Dakota Territory Underground Research Facility

DUNE received a major morale boost in December. A panel of 22 prominent particle physicists, charged with ranking the field's priorities for the coming decade, gave a top slot to the project's second phase.

"Why did the responsibility," said Karsten Heeger, a physicist at Yale and deputy chair of the panel, which is known as the Pa Particle Physics Project Prioritization Panel. "It was a daunting, scary task."

In the end, Dr. Heeger said, the scientific stakes were too high not to endorse the project. "This is a real opportunity for the U.S. to lead the world and to become the center of neutrino physics for the coming decades," he said.

The report arrived at a mandate to "finish what we started," Dr. Paramo said. The project's leaders have spent the last two years more pleased with the outcome." She concluded that Fermilab had faced real challenges in recent years and added: "We've almost put it behind us."

On Feb. 1, after more than a decade of planning and construction, the experiment officially transitioned from building to being dynamite. The hole is there, now all the physicists — and the universe — must do to fill it.

A correction was made on Sept. 2, 2026. An earlier version of this article misspelled the surname of a project official: He is Mike Headley, not Hendy. Picture captions, for the article, mistakenly transposed the name of a detector: It is the Short-Baseline Near Detector, not the ICARUS detector.

How we handle corrections

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