World's most sensitive detector tightens the net on elusive dark matter

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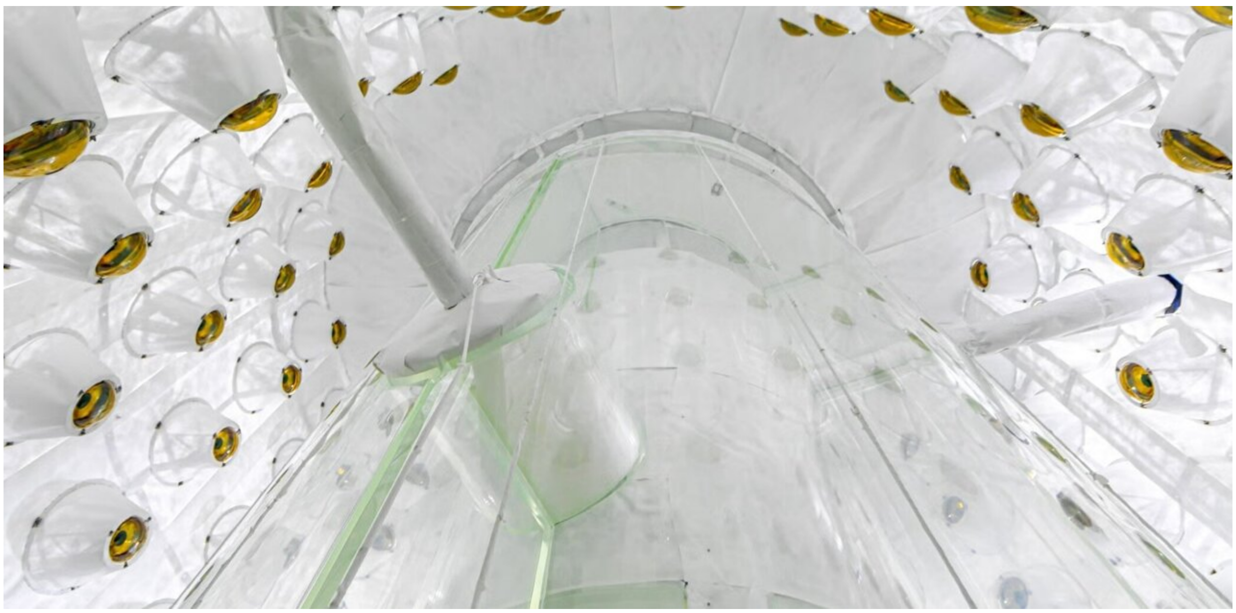


The outer detector of the LZ dark matter experiment. Credit: Matt Kapust/Sanford Underground Research Laboratory

Determining the nature of dark matter, the invisible substance that makes up most of the mass in our universe, is one of the greatest puzzles in physics. New results from the world's most sensitive dark matter detector, LUX-ZEPLIN (LZ), have narrowed down the possibilities for one of the leading dark matter candidates: weakly interacting massive particles (WIMPs).

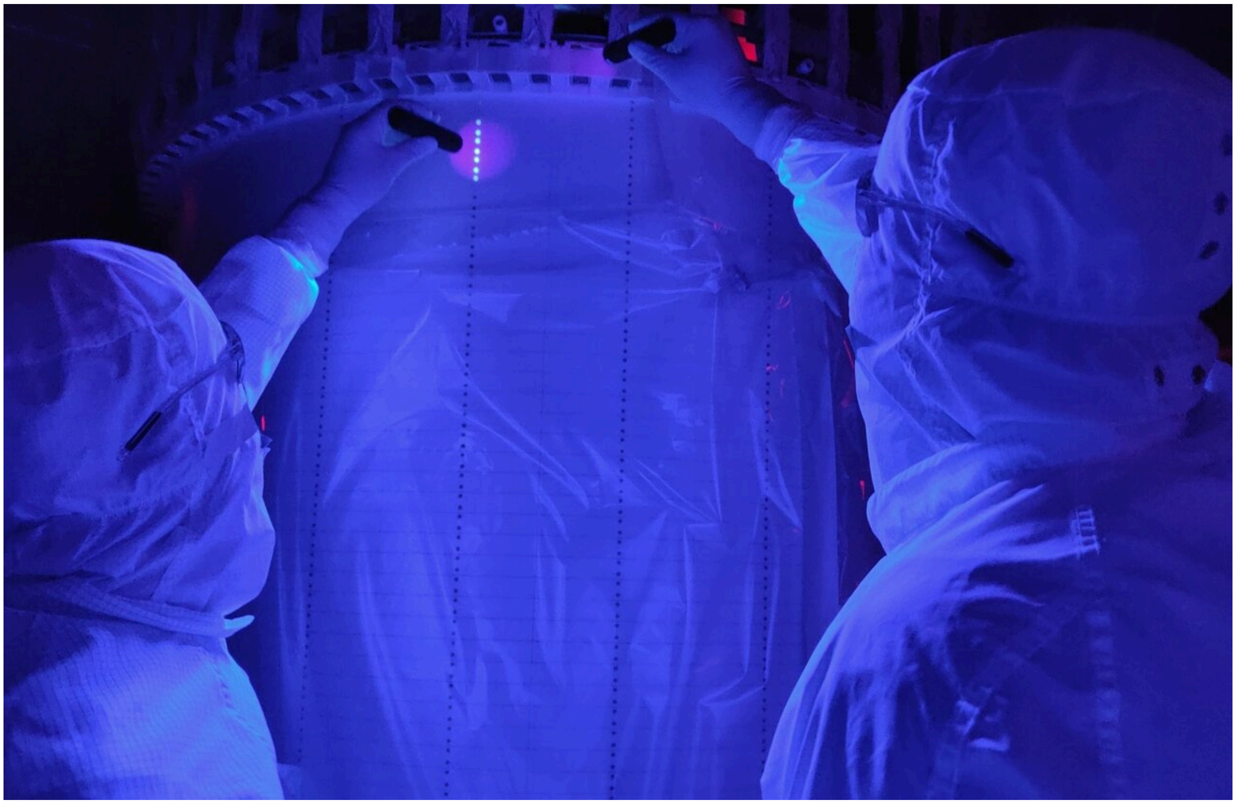
"While we always hope to discover a new particle, it is important for particle physics that we are able to set bounds on what the dark matter might actually be," said UC Santa Barbara experimental physicist Hugh Lippincott. Scientists have suspected the existence of dark matter for decades, but it remains a mysterious substance—one that nevertheless plays a fundamental role in the structure of the universe

LZ hunts for dark matter from a cavern nearly one mile underground at the Sanford Underground Research Facility (SURF) in South Dakota. The experiment's new results explore weaker dark matter interactions than ever searched before and further limit what WIMPs could be.

The results, published in *Physical Review Letters*, analyze 280 days' worth of data: a new set of 220 days (collected between March 2023 and April 2024) combined with 60 earlier days from LZ's first run. The experiment plans to collect 1,000 days' worth of data before it ends in 2028.

The inner portion of the LZ detector consists of two nested titanium tanks filled with 10 tons of transparent pure liquid xenon, which is so dense it creates a highly isolated environment, free from the "noise" of the outside world and perfect for capturing the faintest of faint signals that could be indicative of a WIMP.

The hope is for a WIMP to knock into a xenon nucleus, causing it to move, much like a hit from a cue ball in a game of pool. By collecting the light and electrons emitted during interactions, LZ captures potential WIMP signals alongside other data. This liquid xenon core is surrounded by a much larger Outer Detector (OD)—acrylic tanks filled with gadolinium-loaded liquid scintillator.



Researchers use UV light to scan for possible dust contamination at the detector's time-projection chamber. Dust can be a source of background noise. Credit: Nicolas Angelides/University of Zurich

LZ's sensitivity comes from the myriad ways the detector can reduce backgrounds, the false signals that can impersonate or hide a dark matter interaction. Deep underground, the detector is shielded from cosmic rays coming from space.

To reduce natural radiation from everyday objects, LZ was built from thousands of ultraclean, low-radiation parts. The detector is built like an onion, with each layer either blocking outside radiation or tracking particle interactions to rule out dark matter mimics. And, sophisticated new analysis techniques help rule out background interactions.

UCSB was one of the founding groups in LZ, led by UCSB physicist Harry Nelson, who hosted the first LZ meeting at UCSB in 2012. The team currently consists of faculty members Lippincott and Nelson, postdoctoral researchers Chami Amarasinghe and TJ Whitis, and graduate students Jeonghwa Kim, Makayla Trask, Lindsey Weeldreyer, and Jordan Thomas.

Other contributors to the result include recent Ph.D. recipient Jack Bargemann, now a postdoctoral researcher at Pacific Northwest National Laboratory, and former undergraduate researcher; Tarun Advaith Kumar, now a graduate student at the Perimeter Institute. The physics coordinator for the result was Scott Haselschwardt, who received his Ph.D. from UCSB in 2018 and is now an assistant professor at the University of Michigan.

Neutrons, subatomic particles that exist in every atom save hydrogen, are among the most common confounders of WIMP signals. Nelson and UCSB led the design of LZ's Outer Detector, the critical component that allows the collaboration to rule out these particles and enable a real discovery.

"The tricky thing about neutrons is that they also interact with the xenon nuclei, giving off a signal identical to what we expect from WIMPs," Trask said. "The OD is excellent at detecting neutrons, and confirms a WIMP detection by not having any response." Presence of a pulse in the OD can veto an otherwise perfect candidate for a WIMP detection.

Radon is also a WIMP mimic, for which the scientists must be vigilant. "Radon undergoes a particular sequence of decays, some of which could be mistaken for WIMPs," Bargemann said. "One of the things we were able to do in this run was look out for the whole set of decays in the detector to identify the radon and avoid confusing them for WIMPs."

To enable a strong result and eliminate unconscious bias, the LZ collaboration applied a technique called "salting," which adds fake WIMP signals during data collection. By camouflaging the real data until "unsalting" at the very end, researchers can avoid unconscious bias and keep from overly interpreting or changing their analysis.

"We're pushing the boundary into a regime where people have not looked for dark matter before," said Haselschwardt. "There's a human tendency to want to see patterns in data, so it's really important when you enter this new regime that no bias wanders in. If you make a discovery, you want to get it right."

With these results, the field of possibilities for what WIMPs may be has narrowed dramatically, allowing all scientists searching for dark matter to better focus their searches and reject incorrect models of how the universe operates. It's a long game, with more data collection in the future and one that will do more than accelerate the search for dark matter.

"Our experiment is also sensitive to rare events with roots in diverse areas of physics," Amarasinghe said. "Some examples are solar neutrinos, the fascinating decays of certain xenon isotopes, and even other types of dark matter. With the intensity of this result behind us, I'm very excited to spend more time on these searches."

"The UCSB Physics Department has a long history of devising searches for dark matter, starting with one of the first published results of a search in 1988," Nelson said. Previous faculty members include David Caldwell (now deceased), and Michael Witherell, now director of the Lawrence Berkeley Laboratory. David Hale (now retired) pioneered many of the techniques for suppressing fake dark matter signals which are now employed throughout the field of dark matter searches.

"UCSB, through the Physics Department, the College of Letters and Science, the administration, and through private donations, has strongly supported the dark matter effort for decades, and made substantial contributions to LZ."

LZ is a collaboration of roughly 250 scientists from 38 institutions in the United States, United Kingdom, Portugal, Switzerland, South Korea, and Australia; much of the work building, operating, and analyzing the record-setting experiment is done by early career researchers.

The collaboration is already looking forward to analyzing the next data set and using new analysis tricks to look for even lower-mass dark matter. Scientists are also thinking through potential upgrades to further improve LZ, and planning for a next-generation dark matter detector called XLZD.

More information: J. Aalbers et al, Dark Matter Search Results from 4.2 Tonne Years of Exposure of the LUX-ZEPLIN (LZ) Experiment, *Physical Review Letters* (2025). DOI: 10.1103/4dyc-z8zf

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