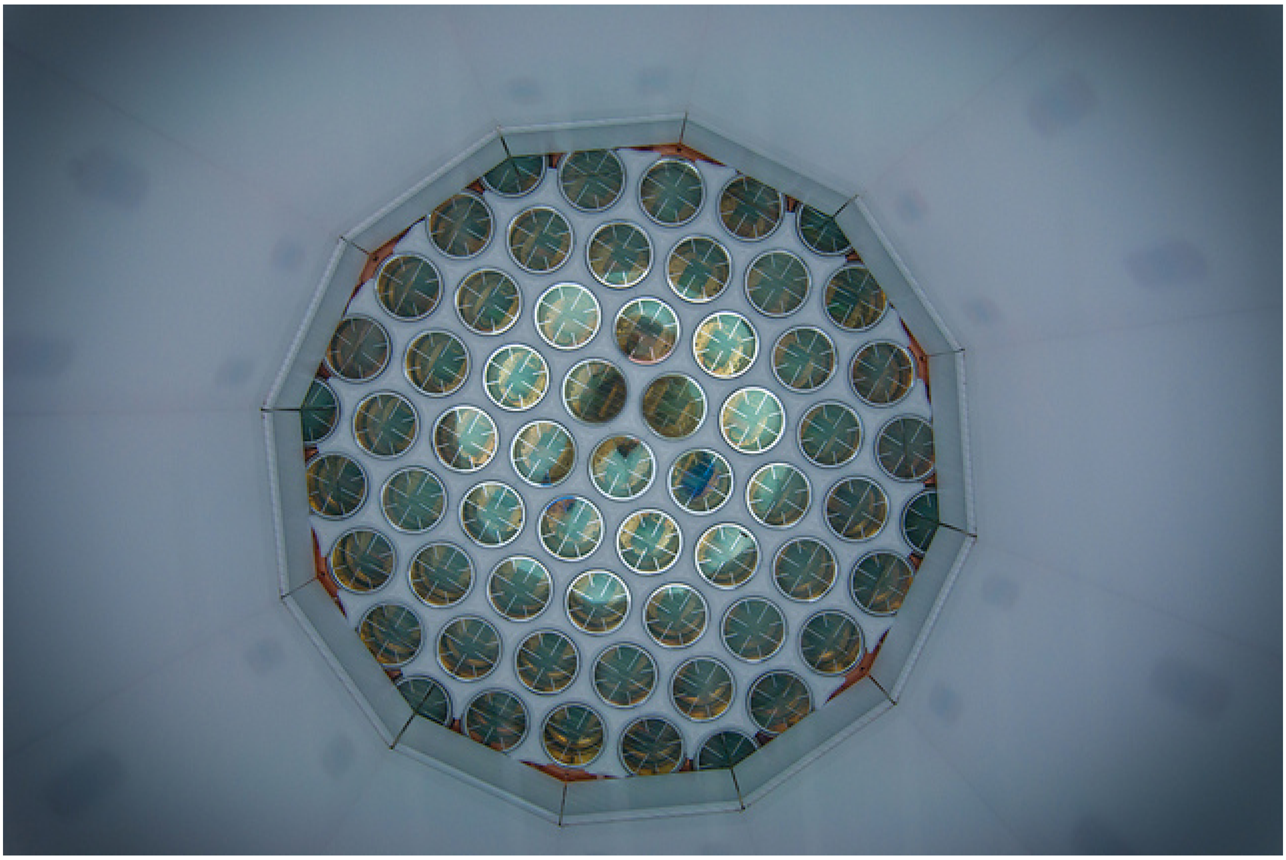
In the Hunt for Dark Matter, Promises to Keep?

By Jennifer Ouellette



A bottom-up view inside the Large Underground Xenon dark matter experiment, which is located a mile beneath the surface in the Black Hills of South Dakota.

Pity the poor physicist searching for dark matter, the exotic substance that accounts for roughly one-quarter of all the stuff in the cosmos, yet only interacts with the rest of the universe through gravity and the weak nuclear force. Hardly a week goes by, it seems, without a tantalizing new hint of a dark matter particle hovering at the threshold of statistical significance that eventually goes poof, dashing hopes yet again.

The search for dark matter involves a dizzying array of experiments, a veritable alphabet soup of acronyms, all using different techniques and technologies. This is how physicists look for something when they don't know its precise properties. The problem is that although several experiments have detected possible hints of dark matter, the hints don't agree with one another. Plot the color-coded results from various experiments onto a single graph, and it looks like abstract art.

Two years ago, Juan Collar of the University of Chicago was hopeful that dark matter was on the verge of being detected. But every subsequent new result seemed to point in a different direction. Small wonder that he opened a recent talk with a slide paraphrasing "The Big Lebowski": "We are nihilists. We believe nothing."

"We seem to be chasing our tails for the last two or three years," Collar said in an interview.

The good news is that things might be looking up again. Physicists are seeing signs in the sky and deep underground, and they are looking for others at the Large Hadron Collider, which recently launched a hunt for dark matter. The whispers of dark matter are becoming louder, with a series of signals that seem to be converging toward a narrowed range. The bad news is that those hints still don't agree exactly, and each hint on its own is "shaky," according to the University of Michigan's Kathryn Zurek. There remain many physicists who are skeptical that these will turn out to be dark matter signals. A few physicists are flirting with outright nihilism, including Collar, who said, "It's hard not to be a nihilist the way things are going."

Mysterious Matter

Ordinary visible matter — the planets, stars, galaxies and everything else that we see — makes up a mere 4.9 percent of everything in the universe. Most of the universe (68.3 percent) is made up of a form of energy dubbed dark energy, which is believed to be causing the expansion of the cosmos to accelerate. The remainder — roughly 26.8 percent of the universe — is made up of dark matter.

Physicists might not know precisely what the dark matter is, but they are confident that it exists. The notion made its debut in 1933, when Fritz Zwicky analyzed the velocities of galaxies in a certain cluster and concluded that the gravitational pull from visible matter alone could not prevent the speeding galaxies from escaping the cluster. Decades later, Vera Rubin and Kent Ford found further evidence of Zwicky's "dark matter" in the stars orbiting the outskirts of spiral galaxies. The stars should have been orbiting more slowly the farther they were from the center of the galaxies, much like the outer planets of our solar system orbit the sun more slowly. Instead, the outer stars were moving just as quickly as those near the center, yet the galaxies weren't flying apart. Something else had to be augmenting the gravitational pull.

Dark matter was not the only possible explanation. Perhaps Einstein's theoretical model for gravity needed modification. There have been many proposed alternative models, such as MOND (Modified Newtonian Dynamics). Rubin herself once favored this approach, telling New Scientist in 2005 that it was "more appealing than a universe filled with a new kind of sub-nuclear particle."


The total mass of the “Bullet Cluster’s” individual galaxies adds up to far less than the mass of the cluster’s two clouds of hot x-ray emitting gas shown in red. The blue areas, which account for even more mass than the galaxies and x-ray gas combined, show the distribution of dark matter in the cluster.

But nature doesn’t care about our aesthetic preferences. In 2006, a startling image of the so-called “Bullet Cluster” (technically 1E 0657-56) largely set the matter to rest. It showed two clusters of galaxies that had passed through each other, creating a shock wave in the shape of a bullet out of the colliding gases. The resulting analysis was striking: the hot gas (ordinary matter) clumped together at the center, where the collision took place, while what could only be the cold dark matter was concentrated on either side. When the clusters collided, the dark matter passed right through because it interacts so rarely with ordinary matter.

“I think we are highly confident that there is dark matter at this point,” said Dan Hooper, a physicist at the University of Chicago. “As far as I’m aware, there is no modified gravity theory that could explain that.”

One leading contender for a dark matter particle is a class of weakly interacting massive particle (WIMP) that is similar to another subatomic particle called a neutrino in that it rarely interacts with other matter. With the discovery of the Higgs boson last year, one era of particle physics has come to an end, and public attention is shifting from Higgs mania to the next big discovery. University of Chicago cosmologist Michael Turner told Space.com that he considers this the decade of the WIMP.

Signal to Noise

Most theorists initially favored a heavy WIMP scenario predicting a dark matter particle with a mass of around 100 giga-electron volts (GeV). (The masses of subatomic particles are measured in mass-energy units called electron volts. For comparison, a proton has a mass of 1 GeV.) But the latest evidence — which has yet to pass all the experimental tests — seems to support a light WIMP scenario, with an approximate mass between 7 GeV and 10 GeV. This makes direct detection more difficult because many of the experiments searching for dark matter rely on measuring nuclear recoil.

These kinds of experiments are usually housed deep underground — the better to block out cosmic rays, which can easily be confused with a dark matter signal — and feature a detector housing a carefully chosen target material, such as germanium or silicon crystals, or liquid xenon. Then physicists wait for a rare collision between an incoming dark matter particle and the nucleus of an atom in the target material. This should give rise to a tiny flash of light, and if that flash is strong enough, it will be recorded by the detector.

This means that in order to be detected, the dark matter particle must transfer enough energy when it knocks the nucleus for the resulting signal to go above the detector's energy threshold. A lighter WIMP is less likely to do so. New York University's Neal Weiner said the difference in the WIMP scenarios was like the difference between the collision of two bowling balls and the collision of a Ping-Pong ball and a bowling ball. "Kinematically, it is much easier for a heavier particle to transmit that energy than a lighter particle," he said.

How do physicists search for dark matter? They look for "bumps" in the data collected by those detectors. A signal's strength is determined by the number of standard statistical deviations, or sigmas, from the expected background. This metric is often compared to a coin landing on heads several tosses in a row. A three-sigma result is a strong hint, equivalent to the coin landing on heads nine times in row.

But many such signals weaken or vanish altogether as more data comes in and they turn out to be less statistically significant. The gold standard for discovery is a five-sigma result, comparable to tossing 21 heads in a row. If you have several people flipping coins at the same time, and they all come up heads several times in a row — or several experiments all find a three-sigma signal in the same mass range — even an unlikely result becomes more probable.

Some of the dark matter hints seen to date are in a tricky 2.8 sigma range. "All these promising results could go away in a week," Fermi National Accelerator Laboratory's Matthew Buckley said. "But a hint is always how these things start. As you get more data, that hint becomes more statistically significant."

Background noise makes the task more difficult. "A 'signal' is what you're looking for. 'Background' is everything else that resembles your signal and makes it difficult for you to find it," Matthew Strassler, a physicist most recently at Rutgers University, wrote in a July 2011 blog post. In a more recent post, Strassler added: "A failure to account for a small background will typically show up as a few extra low-energy collision candidates, which will then closely resemble what you'd expect for a [light WIMP]. In other words, lightweight dark matter is [also] what an *oops!* will look like."

Strassler has compared this challenge to trying to locate a group of friends in a crowded room. If your friends happen to be wearing matching bright red jackets while everyone else is wearing other colors, finding the signal is easy. But if other people in the room are also wearing bright red jackets, random clusters of strangers will obscure the signal. Now imagine that you are wrong about how many people will be wearing red jackets, or worse, that you are colorblind. Any of these scenarios will lead you to draw the wrong conclusion: that you have located your friends when in fact the "signal" is a random cluster of strangers.

The Evidence So Far

Despite these challenges, the various experiments have yielded some promising but controversial hints. Ten years ago, the DAMA/LIBRA experiment (Dark Matter/Large Sodium Iodide Bulk for Rare Processes), located deep underground in the Gran Sasso mountain in central Italy, detected tiny fluctuations in the rate of collision events over a year. The collaboration claimed that a dark matter particle had been observed, in the form of a light WIMP around 10 GeV.


The Dark Matter/Large Sodium Iodide Bulk for Rare Processes experiment is located deep underground in the Gran Sasso mountains in central Italy.

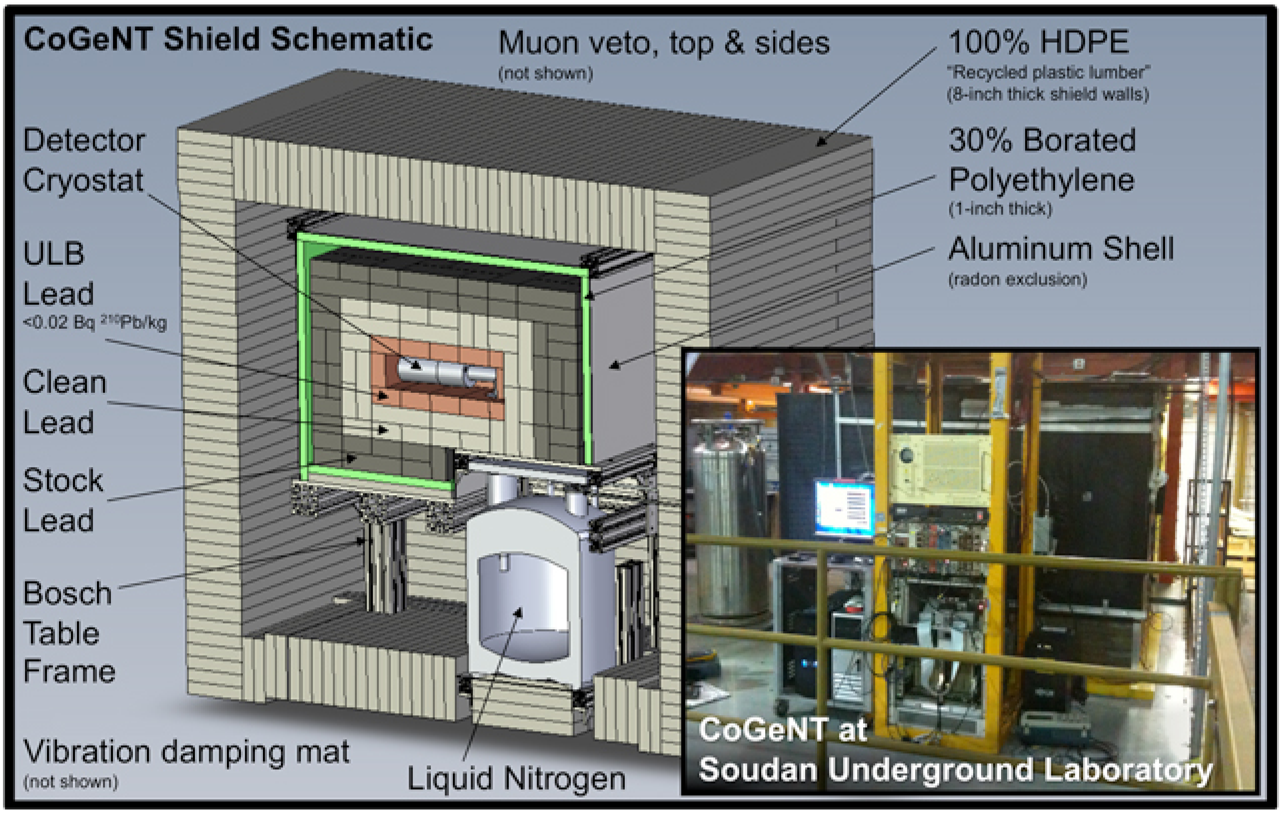
Other physicists expressed strong doubts. Although DAMA/LIBRA has an unmistakable signal, it could be evidence of something else. It didn't help that another experiment — XENON10, also located under the Gran Sasso mountain — failed to detect a signal in that energy range. As did the Cryogenic Dark Matter Search II (CDMSII), housed in a deep mine in Soudan, Minn. Both experiments are sufficiently sensitive that they should have seen a signal in that range if the DAMA/LIBRA result was, indeed, due to dark matter.

Another experiment, CRESST (Cryogenic Rare Event Search with Superconducting Thermometers), did detect a signal. However, it wasn't entirely consistent with DAMA/LIBRA, and the analysis may have failed to account for all the possible backgrounds that could mimic the signal. Additionally, DAMA/LIBRA irritated the physics community by declining to make its data public so others could analyze it.

Emotions have sometimes run high when the topic of discussion turns to the discrepancies between experiments. "You'd give a talk about dark matter and end up getting into fights with people," Buckley said.

Yet the Italian collaboration has proven surprisingly resilient. Collar, among the most outspoken critics, set out to disprove the DAMA/LIBRA findings by building his own experiment, called CoGeNT. That strategy backfired in 2011, when CoGeNT's preliminary analysis seemed to confirm the results.

"We built CoGeNT thinking we were going to blow [DAMA] out of the water, and we got stuck in the same region of parameter space," Collar said. However, a fire broke out in the Soudan mine housing the experiment in 2010, so those initial findings were based on only 15 months of data. And it is yet another 2.8-sigma signal. Collar's team is now analyzing the full three-and-a-half years of data, which should boost that signal considerably — if it is real.



The CoGeNT dark matter experiment, located at Soudan Underground Laboratory in Soudan, Minn., searches for signals from interactions of dark matter particles.

Strong doubts still linger. However, CDMSII unveiled its latest results in April, which showed three events near that same 10 GeV range. Two years ago, the two CDMSII events that looked like a dark matter signal, upon further analysis, likely were not. This time, there were "three clean events," said Zurek.

"If one were to see dark matter, this is what it would look like," she said. But because they are still at the troublesome 2.8 sigma threshold, she said, "no one is going to believe that these three events are due to dark matter until someone else sees it too." This latest evidence has already prompted the physicists on XENON10 to revisit their earlier analysis, concluding they had made an error in ruling out the hints of a light WIMP found by DAMA/LIBRA.

Suddenly, the light WIMP scenario seems at least plausible, bolstered by Hooper's analysis of gamma rays from the center of our Milky Way showing hints of a dark matter signal consistent with the lighter 10 GeV scenario.

But it's not the only scenario. WIMPs with no interesting dynamics — whatever their mass — are just the simplest possibility proposed for dark matter. There could be more than one type of dark matter particle, with many different types of interactions via dark forces, making up an entire "dark sector" of the universe that theorists like Weiner and Zurek have only begun to explore. Weiner considers dark force models to be "the most straightforward way to reconcile some of these anomalies" but cautions that this is a long way from empirical demonstration. Zurek agrees. "At the end of the day, we can write down as many theories as we want, but nature has to choose just one," she said.

Several experiments are expected to announce results relevant to many of these light WIMP signals in the next six months. So when will we know whether these hints are real? It could be within the next year if the current leads stand up to further scrutiny. If not, the search could go on much longer.

However, physicists trying to detect dark matter may soon face a more pragmatic constraint: budget cuts. Experimental variety is critical to the search. “Since we don’t know the particle physics by which dark matter interacts with normal stuff, multiple experiments minimize the chances that we miss dark matter due to a poor choice, and if multiple experiments do see something, we can start ruling out theoretical models much more quickly,” Buckley said. However, come October, all the current dark matter experiments in the United States must submit progress reports to the Department of Energy, the primary funding agency for these collaborations, and only two or three are expected to survive the cuts.

“The DOE is essentially cleaning house,” Collar said. “Variety is good, but money is limited. And if the detectors we’re building right now don’t pan out, it will be hard to find the motivation to keep going.”

The funding clock is ticking. Unless physicists zero in on their target soon, the decade of the WIMP could end not with a bang but a whimper.

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