The search for dark matter

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The Large Underground Xenon (LUX) experiment was one of the biggest efforts to directly detect dark matter. It was located a mile deep in a former gold mine to minimize radioactive "noise." . Credit: C.H. Faham. Courtesy of LUX Dark Matter experiment

At least a quarter of the universe is invisible.

Unlike x-rays that the naked eye can't see but equipment can measure, scientists have yet to detect dark matter after three decades of searching, even with the world's most sensitive instruments. But dark matter is so fundamental to physics that scientists supported by the Department of Energy's Office of Science are searching for it in some of the world's most isolated locales, from deep underground to outer space.

"Without dark matter, it's possible that we would not exist," said Michael Salamon, a DOE Office of Science High Energy Physics (HEP) program manager.

The Office of Science supports a comprehensive program in the hunt for dark matter and other phenomena that help scientists better understand how the universe functions at its most fundamental level.

Traces of Dark Matter's Influence

What we do know about dark matter comes from the ways it's influenced the universe nearly as far back as the Big Bang. Like paw prints left by an elusive animal, the cosmos is full of signs of dark matter's existence, but we haven't actually seen the creature itself.

Astronomer Fritz Zwicky discovered dark matter in 1933 when he was examining the Coma Cluster of galaxies. He noticed they were emitting much less light than they should have been, considering their mass. After running some calculations, he realized that the majority of the cluster's mass wasn't emitting light or electromagnetic radiation at all.

But it wasn't just that cluster. Today, we know that visible matter accounts for only five percent of the universe's total mass-energy. (As Einstein's famous equation, E=mc2, tells us, the concepts of matter and energy are intrinsically linked.) Dark matter makes up about a quarter of the total mass-energy, while dark energy comprises the rest.

Since Zwicky's initial discovery, scientists have found a number of other tell-tale signs. Examining the rotation of galaxies in the 1970s, astronomer Vera Rubin realized that they don't move the way they "should" if only visible matter exists. Her discovery of the galaxy rotation problem provides some of the strongest evidence for dark matter's existence. Similarly, cosmic background radiation, which has a record of the early universe imprinted on it, reflects dark matter's presence.

Scientists think dark matter is most likely made up of an entirely new elementary particle that would fall outside the Standard Model that all currently known particles fit into. It would interact only weakly with other known particles, making it very difficult to detect. There are two leading particles that theorists have postulated to describe the characteristics of dark matter: WIMPs and axions.

Weakly Interacting Massive Particles (WIMPs) would be electrically neutral and 100 to 1,000 times more massive than a proton. Axions would have no electric charge and be extraordinarily light – possibly as low as one-trillionth of the mass of an electron.

On the Hunt for Dark Matter

Not only does dark matter not emit light or electromagnetic radiation, it doesn't even interact with them. In fact, the only means by which scientists are confident dark matter interacts with ordinary matter is through gravity. That's why millions of dark matter particles pass through normal matter without anyone noticing. To capture even the tiniest glimpse, scientists are using some of the most sophisticated equipment in the world.

The Large Underground Xenon Experiment and Direct Detection

The Large Underground Xenon (LUX) experiment, which ran for nearly two years and ended in May 2016, was one of the most significant efforts to directly detect dark matter.

Directly detecting a dark matter particle requires it bump into a nucleus (the core of an atom) of ordinary matter. If this occurs, the nucleus would give off just a little bit of detectable energy. However, the probability of these particles colliding is staggeringly low.

The Alpha Magnetic Spectrometer on the International Space Station is supported by more than 20 different research institutions and was funded in part by DOE. It is designed to detect dark matter by measuring cosmic rays that may result from dark matter particles colliding with each other. Credit: US Department of Energy

In addition, Earth's surface has an extraordinary amount of radioactive "noise." Trying to detect dark matter interactions aboveground is like trying to hear someone whisper across the room of a noisy preschool.

To increase the chances of detecting a dark matter particle and only a dark matter particle, LUX was massive and located more than a mile underground. With a third of a ton of cooled liquid xenon surrounded by 72,000 gallons of water and powerful sensors, LUX had the world's best sensitivity for WIMPs. It could have detected a particle ranging in mass from a few times up to 1800 times the mass of a proton. Despite all of this, LUX never captured enough events to provide strong evidence of dark matter's presence.

LUX was what HEP calls a "Generation 1" direct detection experiment. Other "Generation 1" direct detection experiments currently running and supported by the Office of Science are taking a slightly different tack. The PICO 60, Darkside-50, and SuperCDMS-Soudanexperiments, for example, search for WIMPs, while the ADMX-2adetector hunted for the other potential dark matter candidate, the axion.

There are also "Generation 2" direct detection experiments currently in design, fabrication, or commissioning, including the LUX-Zeplin (LZ), Super CDMS-SNOLAB, and ADMX-Gen2.

The Alpha Magnetic Spectrometer and Indirect Detection

In addition, there are experiments focusing on indirect detection.

Some theorists propose that colliding dark matter particles could annihilate each other and produce two or more "normal" particles. In theory, colliding WIMPs could produce positrons. (A positron is the positively charged antimatter counterpart to the electron.) The Alpha Magnetic Spectrometer on the International Space Station captures cosmic rays, bits of atoms accelerated to high energies by exploding stars. If the AMS detects a high number of positrons in a high-energy spectrum where they wouldn't normally be, it could be a sign of dark matter.

"AMS is a beautiful instrument," said Salamon. "Everyone acknowledges this is the world's most high-precision cosmic-ray experiment in space."

So far, the AMS has recorded 25 billion events. It's found an excess of positrons within the appropriate range, but there's not enough evidence to state definitively where the positrons originate. There are other possible sources, such as pulsars.

In addition to the AMS, DOE also supports the Fermi Gamma-Ray Space Telescope, which analyzes gamma-rays as it circles the globe and may offer another route to dark matter detection.

Dark matter Production at the Large Hadron Collider

In theory, a particle accelerator could create dark matter by colliding standard particles at high energies. While the accelerator wouldn't be able to detect the dark matter itself, it could look for "missing" energy produced by such an interaction. Scientists at the Large Hadron Collider, the world's largest and most powerful particle accelerator, are taking this approach.

Lessons Learned and the Future of Research

So far, not a single experiment has yielded a definitive trace of dark matter.

But these experiments haven't failed – in fact, many have been quite successful. Instead, they've narrowed our field of search. Seeking dark matter is like looking for a lost item in your house. As you hunt through each room, you systematically eliminate places the object could be.

Instead of rooms, scientists are looking for dark matter across a range of interaction strengths and masses. "As experiments become more sensitive, we're starting to eliminate theoretical models," said Salamon.

The search for dark matter is far from over. With each bit of data, we come closer to understanding this ubiquitous yet elusive aspect of the universe.

Provided by US Department of Energy