Revolutionary Neutrino Detector

A revolutionary new kind of neutrino detector, designed in part by scientists from the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, sits at the heart of the MicroBooNE experiment at DOE's Fermi National Accelerator Laboratory (Fermilab). [40]

Researchers in Germany have started collecting data with a 60 million euro ($71 million) machine designed to help determine the mass of the universe's lightest particle. [39]

By analyzing data collected over eight years ago, scientists at the U.S. Department of Energy's (DOE) Argonne National Laboratory and Fermi National Accelerator Laboratory have made a potentially groundbreaking discovery. [38]

Now, in a new result unveiled today at the Neutrino 2018 conference in Heidelberg, Germany, the collaboration has announced its first results using antineutrinos, and has seen strong evidence of muon antineutrinos oscillating into electron antineutrinos over long distances, a phenomenon that has never been unambiguously observed. [37]

The Precision Reactor Oscillation and Spectrum Experiment (PROSPECT) has completed the installation of a novel antineutrino detector that will probe the possible existence of a new form of matter. [36]

The MINERvA collaboration analyzed data from the interactions of an antineutrino—the antimatter partner of a neutrino—with a nucleus. [35]

The inclusion of short-range interactions in models of neutrinoless double-beta decay could impact the interpretation of experimental searches for the elusive decay. [34]

The occasional decay of neutrons into dark matter particles could solve a long-standing discrepancy in neutron decay experiments. [33]

The U.S. Department of Energy has approved funding and start of construction for the SuperCDMS SNOLAB experiment, which will begin operations in the early 2020s to hunt for hypothetical dark matter particles called weakly interacting massive particles, or WIMPs. [32]

Thanks to low-noise superconducting quantum amplifiers invented at the University of California, Berkeley, physicists are now embarking on the most sensitive search yet for axions, one of today's top candidates for dark matter. [31]

The Axion Dark Matter Experiment (ADMX) at the University of Washington in Seattle has finally reached the sensitivity needed to detect axions if they make up dark matter, physicists report today in Physical Review Letters*. [30]*

Now our new study – which hints that extremely light particles called neutrinos are likely to make up some of the dark matter – challenges our current understanding of its composition. [29]

A new particle detector design proposed at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) could greatly broaden the search for dark matter—which makes up 85 percent of the total mass of the universe yet we don't know what it's made of—into an unexplored realm. [28]

University of Houston scientists are helping to develop a technology that could hold the key to unraveling one of the great mysteries of science: what constitutes dark matter? [27]

This week, scientists from around the world who gathered at the University of California, Los Angeles, at the Dark Matter 2018 Symposium learned of new results in the search for evidence of the elusive material in Weakly Interacting Massive Particles (WIMPs) by the DarkSide-50 detector. [26]

If they exist, axions, among the candidates for dark matter particles, could interact with the matter comprising the universe, but at a much weaker extent than previously theorized. New, rigorous constraints on the properties of axions have been proposed by an international team of scientists. [25]

The intensive, worldwide search for dark matter, the missing mass in the universe, has so far failed to find an abundance of dark, massive stars or scads of strange new weakly interacting particles, but a new candidate is slowly gaining followers and observational support. [24]

"We invoke a different theory, the self-interacting dark matter model or SIDM, to show that dark matter self-interactions thermalize the inner halo, which ties ordinary dark matter and dark matter distributions together so that they behave like a collective unit." [23]

Technology proposed 30 years ago to search for dark matter is finally seeing the light. [22]

They're looking for dark matter—the stuff that theoretically makes up a quarter of our universe. [21]

Results from its first run indicate that XENON1T is the most sensitive dark matter detector on Earth. [20]

Scientists at Johannes Gutenberg University Mainz (JGU) in Germany have now come up with a new theory on how dark matter may have been formed shortly after the origin of the universe. [19]

Map of dark matter made from gravitational lensing measurements of 26 million galaxies in the Dark Energy Survey. [18]

CfA astronomers Annalisa Pillepich and Lars Hernquist and their colleagues compared gravitationally distorted Hubble images of the galaxy cluster Abell 2744 and two other clusters with the results of computer simulations of dark matter haloes. [17]

In a paper published July 20 in the journal Physical Review Letters, an international team of cosmologists uses data from the intergalactic medium— the vast, largely empty space between galaxies—to narrow down what dark matter could be. [16]

But a new hypothesis might have gotten us closer to figuring out its identity, because physicists now suspect that dark matter has been changing forms this whole time - from ghostly particles in the Universe's biggest structures, to a strange, superfluid state at smaller scales. And we might soon have the tools to confirm it. [15]

Superfluids may exist inside neutron stars, and some researchers have speculated that space-time itself may be a superfluid. So why shouldn't dark matter have a superfluid phase, too? [14]

"The best result on dark matter so far—and we just got started." This is how scientists behind XENON1T, now the most sensitive dark matter experiment world-wide, commented on their first result from a short 30-day run presented today to the scientific community. [13]

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

SIMPs would resolve certain discrepancies between simulations of the distribution of dark matter, like this one, and the observed properties of the galaxies.

In particle physics and astrophysics, weakly interacting massive particles, or WIMPs, are among the leading hypothetical particle physics candidates for dark matter.

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Author: George Rajna

The Big Bang

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

Extracting signals of elusive particles from giant chambers filled with liquefied argon

Neutrinos are subtle subatomic particles that scientists believe play a key role in the evolution of our universe. They stream continuously from nuclear reactions in our Sun and other stars but pass through almost everything—even our bodies and Earth itself—without leaving a trace. Scientists who want to study these peculiar, lightweight particles must build extremely sensitive detectors.

A revolutionary new kind of neutrino detector, designed in part by scientists from the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, sits at the heart of the MicroBooNE experiment at DOE's Fermi National Accelerator Laboratory (Fermilab). In two new papers, the MicroBooNE collaboration describes how they use this detector to pick up the telltale signs of neutrinos. The papers include details of the signal processing algorithms that are critical to accurately reconstruct neutrinos' subtle interactions with atoms in the detector.

According to physicist Xin Qian, leader of Brookhaven Lab's MicroBooNE physics group, "The work summarized in these papers, which include comparisons of recently collected experimental data with simulations of detector signals and noise, demonstrates an excellent understanding of MicroBooNE's millimeter-resolution detector performance. This understanding provides a solid foundation for using this detector technology for precision physics measurements not just in MicroBooNE but also in future experiments, such as the Deep Underground Neutrino Experiment."

Dynamic detector

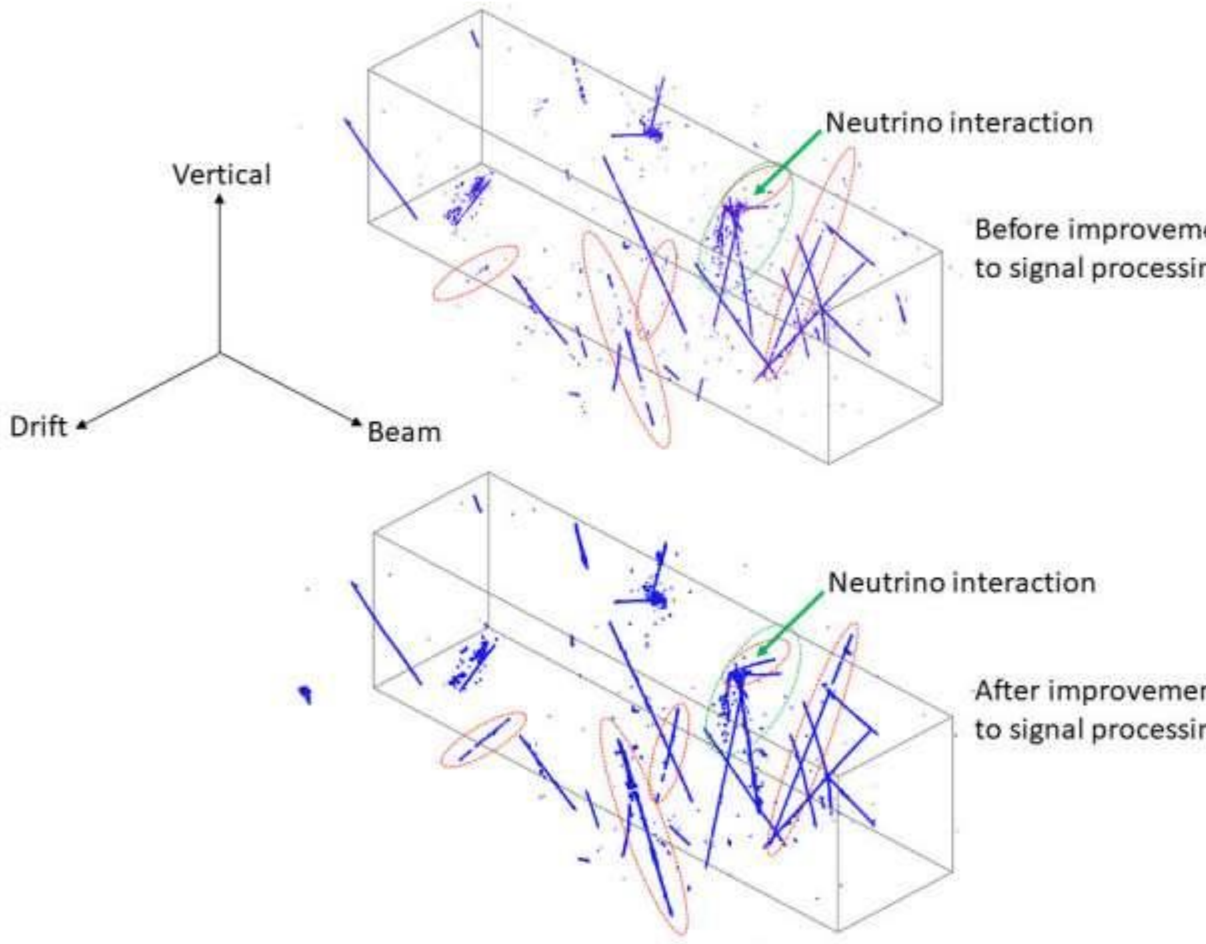
The central piece of the MicroBooNE detector is a liquid-argon time projection chamber (LArTPC)—a bus-sized tank filled with argon (kept liquid at a biting -303 degrees Fahrenheit) and lined with electronics designed to operate in that extremely cold environment. This assembly acts like a powerful tomographic 3-D digital camera to capture the trajectories of particles generated when neutrinos interact with argon atoms in the tank.

The neutrinos, which come in three "flavors" (electron, muon, and tau), originate from a proton accelerator at Fermilab. Mostly they sail on through the detector. But occasionally, a neutrino strikes an argon nucleus in the LArTPC. That interaction produces a number of other particles, some of which carry electric charge. As these charged particles zip through the tank, they ionize, or kick electrons off, other argon atoms in their path. The ousted electrons get caught in the powerful electric field surrounding the tank and drift toward an array of wires neatly arranged in three differently oriented planes at one end—the anode. Electronics inside the tank collect and amplify signals generated by electrons striking the wires and send those signals out to be recorded. By tracking the timing and locations of these signals, the detector can construct images of the electrons' trajectories to reveal information about the energy and flavor of the neutrino that triggered each chain of events.

"Unfurling the ionization signal at the anode plane is analogous to processing photographic film in a dark room, except instead of chemical agents and solutions physicists apply signal-processing algorithms to reconstruct the picture of the neutrino interaction," said Brooke Russell, a Yale University graduate student currently stationed at Brookhaven Lab.

Signal processing

But just as it's important to get the chemistry right when processing film, neutrino-tracking scientists face challenges in developing their algorithms.



The latest improvements in MicroBooNE Time Projection Chamber (TPC) signal processing result in more completely reconstructed 3D particle tracks (bottom) than earlier techniques (top), which left gaps in the 3D images (see red circled areas …more

For one thing, the currents induced by drifting ionization electrons are generally small in magnitude and can be reduced further if the electrons arrive at the wires over a prolonged period of time. In addition, the "waveform" of current produced by one set of drifting electrons might be canceled out by that of another set of electrons arriving later—like ocean waves that get flattened out when the high crests of one wave line up with the low points of another. This makes it particularly difficult to discriminate the tiny signals from background "noise"—electronic distortions generated by excess charge stored on the wires used to carry the signals, the external power supplies that generate the detector's electric field, or other sources.

Keeping some of the electronics inside the liquid argon chamber helps to minimize noise by reducing the distance signals have to travel before being read out. As Brookhaven Lab postdoctoral research associate Brian Kirby noted, these low-noise "cold electronics," designed by Brookhaven's Instrumentation Division, are a crucial technology for large LArTPCs. "They simplify detector design and provide the electronic noise performance required to make a full use of induction wire plane signals," he said.

A second challenge is that drifting electrons can induce current over an expanse of several nearby wires, introducing the possibility that the waveform produced by electrons passing by a particular wire can cancel one produced by electrons passing a nearby wire. These cancellations depend on the distribution of ionization electrons, leading to highly complex signals.

To address this challenge, the MicroBooNE collaboration developed a novel algorithm to extract the distribution of electrons from the measured induced current on the wires. The foundation of the algorithm is a mathematical technique called deconvolution, which greatly simplified the "signal" by removing the very complex induction response of the liquid argon chamber, so scientists can extract the location and distribution of electrons arriving at the wire planes.

This deconvolution is performed in two dimensions (2-D). According to Brookhaven postdoctoral research associate Hanyu Wei, the first 'D' is a common mathematical analysis of the waveform over time, and the second 'D' takes into account the long-range effect of the induction signals across multiple wires. By identifying specific "regions of interest" in the signal, the scientists can also mitigate the magnification of low-frequency noise from the deconvolution technique.

MicroBooNE is the first detector able to match the number of detected electrons across the three wire planes of a LArTPC.

"Since the same clusters of drifting electrons are detected by each of the wire planes, you'd expect to measure the same amount of charge from each plane," said Michael Mooney, a former Brookhaven Lab postdoctoral research associate who is now a new faculty member at Colorado State University. But because of the complexity of the signals in the induction wire planes, no previous LArTPC detector has been able to do this.

"Our data-driven demonstration that local cross-plane matching of charge is feasible in a LArTPC opens doors to new types of reconstruction techniques that aim first to create a 3-D image of the neutrino-argon interaction—and could greatly improve our ability to precisely determine the properties of the neutrino," Mooney said.

The school-bus-size MicroBooNE Time-Projection Chamber. Credit: Fermilab

Simulations vs. data

The MicroBooNE team also developed significantly improved simulations of expected TPC signals and noise—taking into account the aforementioned long-range induction effect and the exact drifting electron's position within a wire region—and used these new simulations to quantitatively evaluate their signal-processing algorithm. Comparing the simulations with results extracted from real data produced consistent results, which is a crucial step toward using the detector for physics studies.

"The consistency between the new simulation and the data gives us confidence that we understand our detector at the fundamental level, which is critical for upcoming physics analyses in MicroBooNE," said Brookhaven Lab physicist Chao Zhang.

Brookhaven Lab physicist Brett Viren noted, "The ability to provide more accurate simulation of both noise and signals from LArTPC wires enables us to validate reconstruction techniques and quantitatively evaluate their efficiencies. These improvements will also facilitate the use of these simulations and modern machine learning techniques—which must have training sets that closely mimic the real thing—to improve LArTPC detector accuracy."

The team has developed software for both the signal-processing algorithm and the improved signal and noise simulations in a "Wire-Cell Toolkit." This software package can run on conventional central-processing-unit (CPU) computing architectures and could also be configured for the highly parallel architectures of high-performance computing (HPC) systems as well.

"All of these achievements in signal processing, simulation, and data-simulation comparison bring us closer to realizing the full potential of LArTPC detector technology," said Brookhaven's Qian. "We now look forward to the exciting results that will come from MicroBooNE.

"In addition, the advances at MicroBooNE build the foundation for detection and signal-processing techniques that will be used with larger LArTPC detectors—including those being developed for DUNE, which is scheduled to come online in the mid-2020s."

For DUNE, Fermilab's Long-Baseline Neutrino Facility will shoot a beam of neutrinos through Earth from Illinois to an old gold mine deep underground in South Dakota. Up to four detectors in the cavern will build on bus-size MicroBoone's ability to track particles with high precision by having colossal tanks each with 100 times the volume able to pin down particles' positions to within a couple of millimeters.

"LArTPC detectors are the only technology that can achieve this precision at this large scale. That's what makes them truly revolutionary," Qian said. [40]

Scientists in Germany seek to find mass of neutrino

Researchers in Germany have started collecting data with a 60 million euro ($71 million) machine designed to help determine the mass of the universe's lightest particle.

Physicists, engineers and technicians at the Karlsruhe Institute of Technology hope the 200-metric ton (220-ton) device will narrow down or even pinpoint the actual mass of neutrinos. Those are sometimes called "ghost particles" because they're so difficult to detect.

Scientists with the Karlsruhe Tritium Neutrino experiment, or KATRIN, said Monday they'll be taking measurements "well into the next decade" and hope to produce "high-impact results."

Researchers say determining the mass of neutrinos is one of the most important open questions in particle physics and will help scientists better understand the history of the universe.

Some 200 people from 20 institutions in seven countries are working on the project. [39]

Blast from the past—First measurement of mono-energetic neutrinos

By analyzing data collected over eight years ago, scientists at the U.S. Department of Energy's (DOE) Argonne National Laboratory and Fermi National Accelerator Laboratory have made a potentially groundbreaking discovery.

In 2002, scientists began the Booster Neutrino Experiment, known as MiniBooNE, at Fermilab to learn more about how neutrinos—very light, neutral fundamental particles—interact with matter. Scientists recently reexamined data from the experiment taken between 2009 and 2011, and they found the first direct evidence of mono-energetic neutrinos, or neutrinos with definite energy, that are energetic enough to produce a muon.

Neutrinos are extremely light and are only influenced by the weak subatomic force, so they rarely interact with matter. In fact, they could travel through light-years of lead before interacting with it. The particles are very difficult to detect, but not difficult to create. Because of the neutrino's elusiveness, scientists have to work with beams composed of large numbers of the particles. They shoot the beams at nuclei in a detector, hoping for neutrinos to collide with the target material.

"One complication of using these large beams is that the energies of the neutrinos are widely varied and somewhat unpredictable," said Argonne physicist Joe Grange, one of the scientists that helped discover mono-energetic neutrinos. "This makes it difficult to fully interpret the data."

The new discovery could help experimentalists solve this problem. The scientists realized that mono-energetic neutrinos were being released from a nearby neutrino beamline at Fermilab, and they decided to look at the MiniBooNE data to see if any of these neutrinos were detected during that experiment.

Sure enough, analysis of the MiniBooNE data showed evidence of thousands of neutrino-nucleus collisions where the neutrinos all started out with the same energy, 236 mega-electron-volts (MeV). During the MiniBooNE experiment, particles called kaons created in a proton absorber of another experiment decayed into particles called muons and muon neutrinos. The muon neutrinos then traveled to the MiniBooNE detector. Because the kaons were at rest when they decayed, and because they decayed into only two particles, the neutrinos all had the same amount of starting energy before colliding with the nuclei in the MiniBooNE detector.

The decay of a kaon is a well-known reaction. "With this discovery, we can improve our understanding of how neutrinos interact with matter and also plan for future experiments that could leverage this interaction for the search for new physics processes," said Grange. Channeling this decay as a source of neutrinos for experiments would eliminate the uncertainty of the neutrino energies, making analyses simpler and potentially more illuminating.

In addition to inspiring future experimental setups, the data are also helping scientists to learn about the behavior of nuclei when bombarded with neutrinos and can help them refine models of the interactions. When a muon neutrino collides with a nucleus in a detector, a muon having one of a range of different energies can pop out. It is this spectrum of possible energies of the new muons that the scientists observed directly in this study, and it speaks to the way the neutrino transfers energy to the nucleus upon contact.

"A lot of work has been done shooting electrons at nuclei and seeing how they behave electromagnetically," said Grange. "But less work has been done to see how neutrinos interact weakly because of how difficult neutrinos are to work with."

The experimental aspect of this discovery could also help scientists search for the theorized sterile neutrino, a neutrino that only interacts through the gravitational force and not the weak force. A mid-1990s experiment at DOE's Los Alamos National Laboratory yielded neutrino data that were incompatible with data from a separate experiment at the European laboratory CERN, and that discrepancy might be explained by the existence of this "ghost" particle.

The original goal of the MiniBooNE experiment was to confirm or refute the existence of sterile neutrinos. Although the experiment may end up inconclusive, the new discovery from the depths of its data could help future experimentalists to detect their existence. Scientists are already working towards experiments that will use neutrinos from this specific kaon decay to search for sterile neutrinos.

"It's a nice story about how it was almost five years before we realized there was something important in the data," said Grange. "The moral of the story is to keep all the data and continue thinking about what other information is in there that you haven't yet extracted."

The results of the study were published in a paper titled "First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions" in *Physical Review Letters*. [38]

NOvA experiment sees strong evidence for antineutrino oscillation

For more than three years, scientists on the NOvA collaboration have been observing particles called neutrinos as they oscillate from one type to another over a distance of 500 miles. Now, in a new result unveiled today at the Neutrino 2018 conference in Heidelberg, Germany, the collaboration has announced its first results using antineutrinos, and has seen strong evidence of muon antineutrinos oscillating into electron antineutrinos over long distances, a phenomenon that has never been unambiguously observed.

NOvA, based at the U.S. Department of Energy's Fermi National Accelerator Laboratory, is the world's longest-baseline neutrino experiment. Its purpose is to discover more about neutrinos, ghostly yet abundant particles that travel through matter mostly without leaving a trace. The experiment's long-term goal is to look for similarities and differences in how neutrinos and antineutrinos change from one type—in this case, muon—into one of the other two types, electron or tau. Precisely measuring this change in both neutrinos and antineutrinos, and then comparing them, will help scientists unlock the secrets that these particles hold about how the universe operates.

NOvA uses two large particle detectors—a smaller one at Fermilab in Illinois and a much larger one 500 miles away in northern Minnesota—to study a beam of particles generated by Fermilab's accelerator complex and sent through Earth, with no tunnel required.

The new result is drawn from NOvA's first run with antineutrinos, the antimatter counterpart to neutrinos. NOvA began studying antineutrinos in February 2017. Fermilab's accelerators create a beam of muon neutrinos (or muon antineutrinos), and NOvA's far detector is specifically designed to see those particles changing into electron neutrinos (or electron antineutrinos) on their journey.

If antineutrinos did not oscillate from muon type to electron type, scientists would have expected to record just five electron antineutrino candidates in the NOvA far detector during this first run. But when they analyzed the data, they found 18, providing strong evidence that antineutrinos undergo this oscillation.

"Antineutrinos are more difficult to make than neutrinos, and they are less likely to interact in our detector," said Fermilab's Peter Shanahan, co-spokesperson of the NOvA collaboration. "This first data set is a fraction of our goal, but the number of oscillation events we see is far greater than we would expect if antineutrinos didn't oscillate from muon type to electron. It demonstrates the impact that Fermilab's high-power particle beam has on our ability to study neutrinos and antineutrinos."

Although antineutrinos are known to oscillate, the change into electron antineutrinos over long distances has not yet been definitively observed. The T2K experiment, located in Japan, announced that it had observed hints of this phenomenon in 2017. The NOvA and T2K collaborations are working toward a combined analysis of their data in the coming years.

"With this first result using antineutrinos, NOvA has moved into the next phase of its scientific program," said Associate Director for High Energy Physics at the Department of Energy Office of Science Jim Siegrist. "I'm pleased to see this important experiment continuing to tell us more about these fascinating particles."

NOvA's new antineutrino result accompanies an improvement to its methods of analysis, leading to a more precise measurement of its neutrino data. From 2014 to 2017, NOvA saw 58 candidates for interactions from muon neutrinos changing into electron neutrinos, and scientists are using this data to move closer to unraveling some of the knottiest mysteries of these elusive particles.

The key to NOvA's science program is comparing the rate at which electron neutrinos appear in the far detector with the rate that electron antineutrinos appear. A precise measurement of those differences will allow NOvA to achieve one of its main science goals: to determine which of the three types of neutrinos is the heaviest and which the lightest.

Neutrinos have been shown to have mass, but scientists have not been able to directly measure that mass. However, with enough data, they can determine the relative masses of the three, a puzzle called the mass ordering. NOvA is working toward a definitive answer to this question. Scientists on the experiment will continue studying antineutrinos through 2019 and, over the following years, will eventually collect equal amounts of data from neutrinos and antineutrinos.

"This first data set from antineutrinos is a just a start to what promises to be an exciting run," said NOvA co-spokesperson Tricia Vahle of William & Mary. "It's early days, but NOvA is already giving us new insights into the many mysteries of neutrinos and antineutrinos." [37]

PROSPECTing for antineutrinos

The Precision Reactor Oscillation and Spectrum Experiment (PROSPECT) has completed the installation of a novel antineutrino detector that will probe the possible existence of a new form of matter.

PROSPECT, located at the High Flux Isotope Reactor (HFIR) at the Department of Energy's Oak Ridge National Laboratory (ORNL), has begun taking data to study electron antineutrinos that are emitted from nuclear decays in the reactor to search for so-called sterile neutrinos and to learn about the underlying nuclear reactions that power fission reactors.

Antineutrinos are elusive, elementary particles produced in nuclear beta decay. The antineutrino is an antimatter particle, the counterpart to the neutrino.

"Neutrinos are among the most abundant particles in the universe," said Yale University physicist Karsten Heeger, principal investigator and co-spokesperson for PROSPECT. "The discovery of neutrino oscillation has opened a window to physics beyond the Standard Model of Physics. The study of antineutrinos with PROSPECT allows us to search for a previously unobserved particle, the so-called sterile neutrino, while probing the nuclear processes inside a reactor."

Over the past few years several neutrino experiments at nuclear reactors have detected fewer antineutrinos than scientists had predicted, and the energy of the neutrinos did not match expectations. This, in combination with earlier anomalous results, led to the hypothesis that a fraction of electron antineutrinos may transform into sterile neutrinos that would have remained undetected in previous experiments.

This hypothesized transformation would take place through a quantum mechanical process called neutrino oscillation. The first observation of neutrino oscillation amongst known types of neutrinos from the sun and the atmosphere led to the 2015 Nobel Prize in physics.

The installation of PROSPECT follows four years of intensive research and development by a collaboration of more than 60 participants from 10 universities and four national laboratories.

Credit: PROSPECT collaboration/Mara Lavitt

"The development of PROSPECT is based on years of research in the detection of reactor antineutrinos with surface-based detectors, an extremely challenging task because of high backgrounds," said PROSPECT co-spokesperson Pieter Mumm, a scientist at the National Institute of Standards and Technology (NIST).

The experiment uses a novel antineutrino detector system based on a segmented liquid scintillator detector technology. The combination of segmentation and a unique, lithium-doped liquid scintillator formulation allows PROSPECT to identify particle types and interaction points. These design features, along with extensive, tailored shielding, will enable PROSPECT to make a precise measurement of neutrinos in the high-background environment of a nuclear reactor.

PROSPECT's detector technology also may have applications in the monitoring of nuclear reactors for non-proliferation purposes and the measurement of neutrons from nuclear processes.

"The successful operation of PROSPECT will allow us to gain insight into one of the fundamental puzzles in neutrino physics and develop a better understanding of reactor fuel, while also providing a new tool for nuclear safeguards," said co-spokesperson Nathaniel Bowden, a scientist at Lawrence Livermore National Laboratory and an expert in nuclear non-proliferation technology.

After two years of construction and final assembly at the Yale Wright Laboratory, the PROSPECT detector was transported to HFIR in early 2018.

"The development and construction of PROSPECT has been a significant team effort, making use of the complementary expertise at U.S. national laboratories and universities," said Alfredo Galindo-Uribarri, leader of the Neutrino and Advanced Detectors group in ORNL's Physics Division.

PROSPECT is the latest in a series of fundamental science experiments located at HFIR. "We are excited to work with PROSPECT scientists to support their research," said Chris Bryan, who manages experiments at HFIR for ORNL's Research Reactors Division. [36]

The secret to measuring an antineutrino's energy

The MINERvA collaboration analyzed data from the interactions of an antineutrino—the antimatter partner of a neutrino—with a nucleus. They were surprised to find evidence that antineutrinos interacted with pairs of particles inside the nucleus. They had expected antineutrinos to interact with just single protons or neutrons. To see this evidence, the team compared their antineutrino data to a model of these interactions. The model was based on a previous analysis of neutrino interactions at MINERvA published two years ago.

Scientists are using neutrino measurements to determine why our universe is made of matter rather than antimatter—that is, why matter outstripped antimatter in the beginning of our universe. The answer relates to a phenomenon known as CP violation. Neutrinos—omnipresent, hard-to-catch particles—could hold the answer. Searches for CP violation depend on comparing neutrino and antineutrino samples and looking for small differences. Large, unknown differences between neutrino and antineutrino reaction rates in a detector (which is made only of matter) would hide the presence or absence of CP signatures. MINERvA's new analysis reveals much about how well models do and where they fall short. The team is converging on better models that describe both neutrino and antineutrino data.

It is no secret that neutrinos change flavor, or oscillate, as they travel from one place to another. The amount they change depends on how much time they have to change. This time is directly related to the distance the neutrino traveled and the energy of the neutrino itself. Measuring the distance is easy. The hard part is measuring the neutrino energy.

Experiments do this by measuring the energies of particles that are produced by the neutrino when it interacts in the detectors. But what happens if one of the produced particles, for example, a neutron, leaves barely any of its energy in the detector?

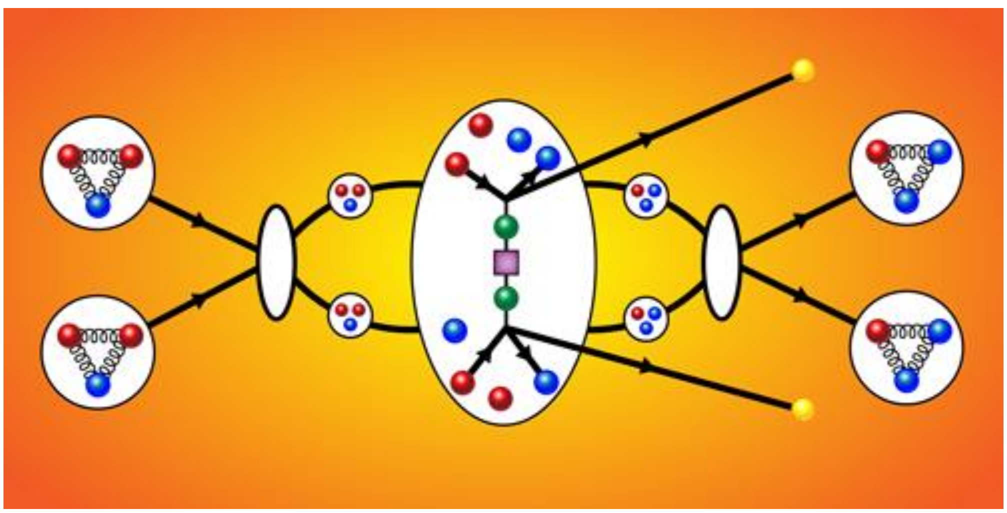
Oscillation experiments have to predict how much energy is lost and then correct for that loss. These predictions depend on accurate models of how neutrinos interact. Those models have to be right not only for neutrinos but also for antineutrinos, which are particularly good at making neutrons.

The MINERvA collaboration analyzed data from interactions of antineutrinos that produced positively charged muons. Scientists looked at both the momentum and the energy that was transferred to the nucleus in those interactions. By focusing on the kinematic region where only a neutron should be knocked out, they looked at the worst-case situation: Most of the energy goes missing. In this way, scientists directly measured the effects of an imperfect model for missing energy.

To appreciate why this new analysis of antineutrino interactions is exciting, we need to look back at a measurement from two years ago. That time, MINERvA measured neutrino interactions that produce negatively charged muons—interactions which are more likely to produce a proton than a neutron. A proton's energy is much easier to measure than a neutron's in a detector such as MINERvA. For neutrino interactions on a proton-neutron pair (rather than on only one of those two particles), scientists observed a much larger number of events than the state-of-the-art models predicted. Neutrino cross-section enthusiasts are never surprised when models don't describe data. So here is the surprise: When they used the neutrino results to change the antineutrino model to predict the antineutrino data described above, it worked. [35]

A Missing Piece in the Neutrinoless Beta-Decay Puzzle

The inclusion of short-range interactions in models of neutrinoless double-beta decay could impact the interpretation of experimental searches for the elusive decay.



J. de Vries/Nikhef; adapted by APS/**Alan Stonebraker**

The observation of a nuclear process called neutrinoless double-beta decay might help researchers figure out what gives neutrinos their mass and why there’s far more matter than antimatter in the Universe. While this hypothetical decay has never been observed, experiments have placed constraints on the maximum rate at which it could occur. Now Vincenzo Cirigliano of Los Alamos National Laboratory, New Mexico, and colleagues show that previous calculations of neutrinoless double-beta decay might have neglected a contribution that is critical for interpreting experimental data.

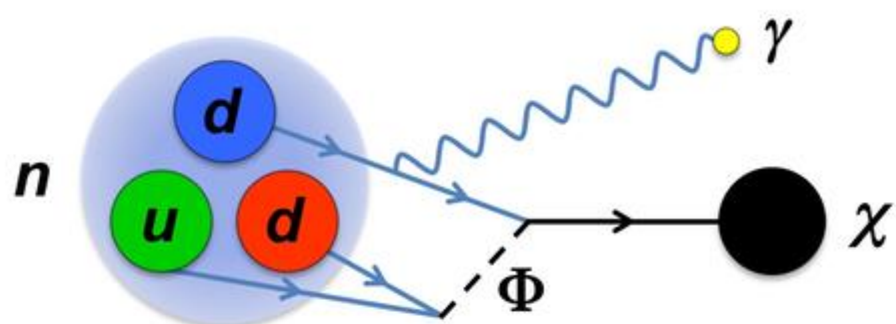
In ordinary double-beta decay, two neutrons become two protons, emitting two electrons and two electron antineutrinos. But some models indicate that neutrinos may be their own antiparticles. In that case, the two antineutrinos could cancel each other, and some decays wouldn't emit any neutrinos. Experiments searching for this neutrinoless decay in a variety of isotopes have limited the decay's half-life to be larger than 10^{25}1025 years. These half-life limits, in turn, can be used to derive information on neutrino masses. That derivation, however, depends on the calculated amplitudes of the transitions between the nuclear states involved in the decay.

Cirigliano and collaborators show that reliable amplitude calculations must include a contribution due to interactions acting on short ranges (less than 1 femtometer). Previous studies had only included longer-range contributions acting on scales up to a few femtometers. The short-range contribution generates a transition amplitude that might be as large as the one calculated based on the long-range component only. The short- and long-range components could add up to make the neutrinoless decay more likely, or they could partly cancel out to make it less likely. More work is needed to determine the sign and magnitude of the short-range component. The authors' preliminary estimates, however, indicate that it could significantly affect the neutrino mass properties derived from double-beta-decay experiments.

This research is published in *Physical Review Letters*. [34]

Synopsis: Neutron Decay May Hint at Dark Matter

The occasional decay of neutrons into dark matter particles could solve a long-standing discrepancy in neutron decay experiments.



B. Fornal and B. Grinstein/University of California, San Diego

Neutrons decay within about 14.5 min, but their exact lifetime is still debated, as two types of neutron decay experiments give conflicting results. The source for this discrepancy could be some unidentified systematic error. But another possibility is that neutrons decay into invisible particles that constitute the missing dark matter. This new hypothesis has sparked significant interest, with one group of experimenters already putting the idea to the test. The results of that effort constrain one version of the theory, but other scenarios remain viable.

Outside the nucleus, a neutron decays into a proton, an electron, and a neutrino. Studies of this decay process come in two varieties, which go by the names “bottle” and “beam.” In a bottle experiment, researchers place a set of ultracold neutrons in a container and count how many remain after a certain time has passed. In a beam experiment, researchers observe a stream of neutrons and count the number of protons created from decays. The beam neutron lifetime is roughly 9 s longer than the bottle value.

Bartosz Fornal and Benjamín Grinstein from the University of California, San Diego, propose a solution to this discrepancy that assumes neutrons decay 1% of the time into dark matter particles. Because beam experiments would not detect these decays, their inferred neutron lifetime would be longer than the actual value. Fornal and Grinstein investigate several scenarios with neutrons decaying into different combinations of dark matter and visible particles. In one of these scenarios, neutron dark decays are accompanied by a gamma ray. Inspired by this possibility, Christopher Morris from Los Alamos National Laboratory, New Mexico, and colleagues monitored the gamma-ray emission from a bottle of ultracold neutrons. They didn’t find any signal, appearing to rule out this proposed decay channel in the photon energy range of 782 to 1664 keV. But other decay scenarios—that produce lower energy gammas or no gammas at all—are still possible and might be tested by looking for anomalies in nuclear decays.

This research is published in *Physical Review Letters* and posted on the *arXiv*. [33]

Construction begins on one of the world's most sensitive dark matter experiments

The U.S. Department of Energy has approved funding and start of construction for the SuperCDMS SNOLAB experiment, which will begin operations in the early 2020s to hunt for hypothetical dark matter particles called weakly interacting massive particles, or WIMPs. The experiment will be at least 50 times more sensitive than its predecessor, exploring WIMP properties that can't be probed by other experiments and giving researchers a powerful new tool to understand one of the biggest mysteries of modern physics.

The DOE's SLAC National Accelerator Laboratory is managing the construction project for the international SuperCDMS collaboration of 111 members from 26 institutions, which is preparing to do research with the experiment.

"Understanding dark matter is one of the hottest research topics - at SLAC and around the world," said JoAnne Hewett, head of SLAC's Fundamental Physics Directorate and the lab's chief research officer. "We're excited to lead the project and work with our partners to build this next-generation dark matter experiment."

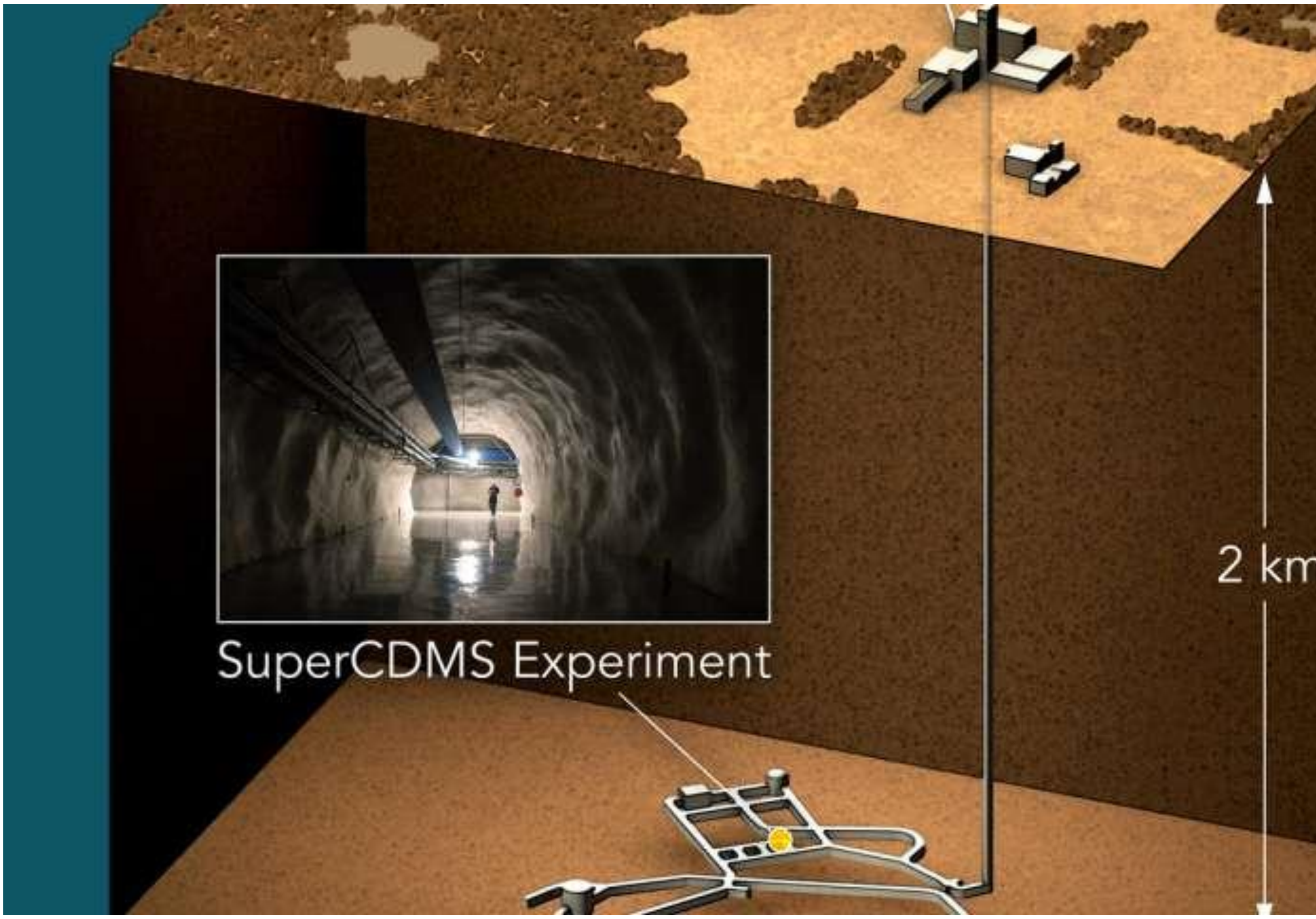
With the DOE approvals, known as Critical Decisions 2 and 3, the researchers can now build the experiment. The DOE Office of Science will contribute $19 million to the effort, joining forces with the National Science Foundation ($12 million) and the Canada Foundation for Innovation ($3 million).

"Our experiment will be the world's most sensitive for relatively light WIMPs - in a mass range from a fraction of the proton mass to about 10 proton masses," said Richard Partridge, head of the

SuperCDMS group at the Kavli Institute for Particle Astrophysics and Cosmology (KIPAC), a joint institute of SLAC and Stanford University. "This unparalleled sensitivity will create exciting opportunities to explore new territory in dark matter research."

An Ultracold Search 6,800 Feet Underground

Scientists know that visible matter in the universe accounts for only 15 percent of all matter. The rest is a mysterious substance, called dark matter. Due to its gravitational pull on regular matter, dark matter is a key driver for the evolution of the universe, affecting the formation of galaxies like our Milky Way. It therefore is fundamental to our very own existence.



The SuperCDMS dark matter experiment will be located at the Canadian laboratory SNOLAB, 2 kilometers (6,800 feet) underground inside a nickel mine near the city of Sudbury. It's the deepest underground laboratory in North America. There it ...more

But scientists have yet to find out what dark matter is made of. They believe it could be composed of dark matter particles, and WIMPs are top contenders. If these particles exist, they would barely interact with their environment and fly right through regular matter untouched. However, every so often, they could collide with an atom of our visible world, and dark matter researchers are looking for these rare interactions.

In the SuperCDMS SNOLAB experiment, the search will be done using silicon and germanium crystals, in which the collisions would trigger tiny vibrations. However, to measure the atomic jiggles, the crystals need to be cooled to less than minus 459.6 degrees Fahrenheit - a fraction of a degree above absolute zero temperature. These ultracold conditions give the experiment its name: Cryogenic Dark Matter Search, or CDMS. The prefix "Super" indicates an increased sensitivity compared to previous versions of the experiment.

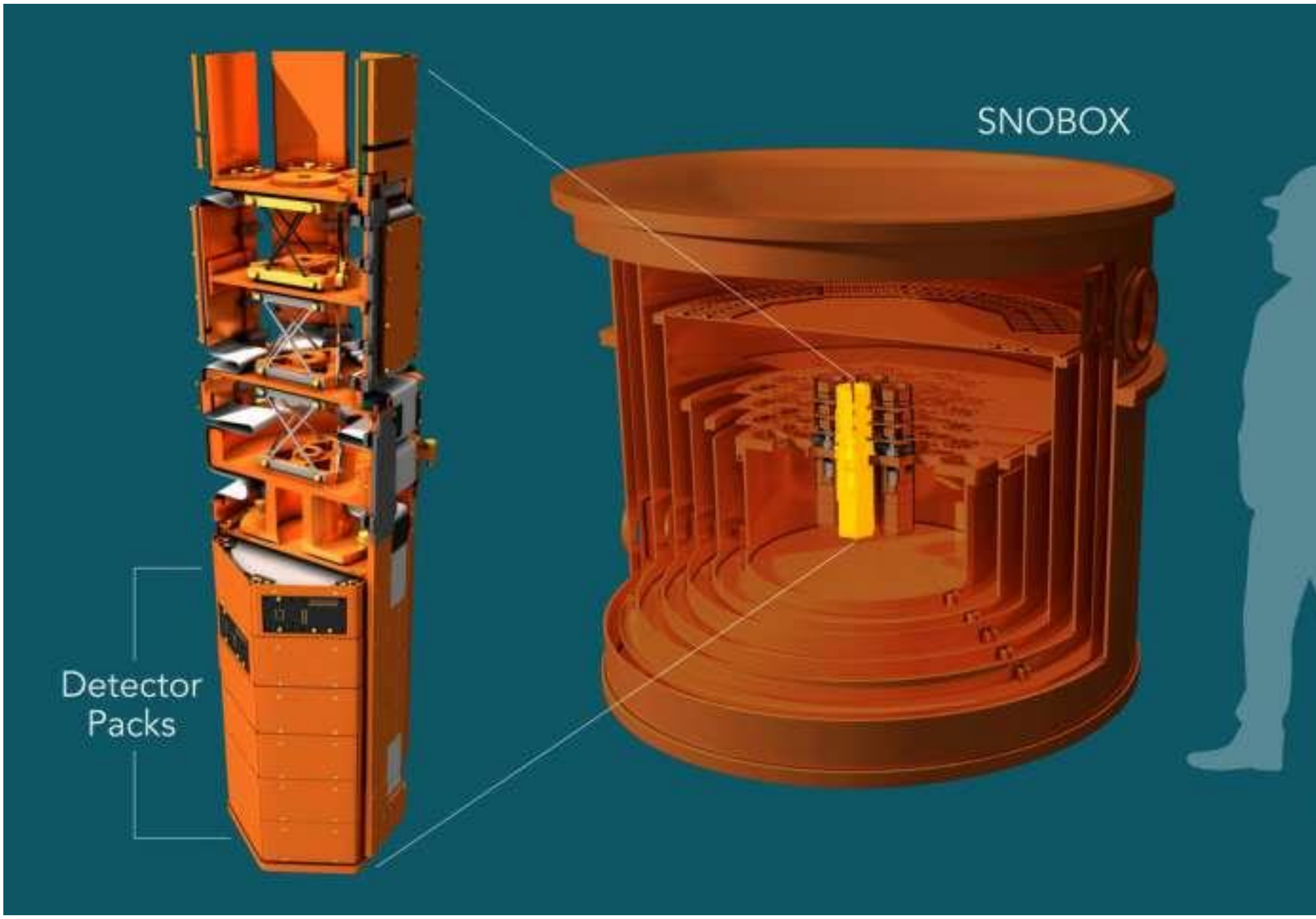
The collisions would also produce pairs of electrons and electron deficiencies that move through the crystals, triggering additional atomic vibrations that amplify the signal from the dark matter collision. The experiment will be able to measure these "fingerprints" left by dark matter with sophisticated superconducting electronics.

The experiment will be assembled and operated at the Canadian laboratory SNOLAB - 6,800 feet underground inside a nickel mine near the city of Sudbury. It's the deepest underground laboratory in North America. There it will be protected from high-energy particles, called cosmic radiation, which can create unwanted background signals.

"SNOLAB is excited to welcome the SuperCDMS SNOLAB collaboration to the underground lab," said Kerry Loken, SNOLAB project manager. "We look forward to a great partnership and to supporting this world-leading science."

Over the past months, a detector prototype has been successfully tested at SLAC. "These tests were an important demonstration that we're able to build the actual detector with high enough energy resolution, as well as detector electronics with low enough noise to accomplish our research goals," said KIPAC's Paul Brink, who oversees the detector fabrication at Stanford.

Together with seven other collaborating institutions, SLAC will provide the experiment's centerpiece of four detector towers, each containing six crystals in the shape of oversized hockey pucks. The first tower could be sent to SNOLAB by the end of 2018.



The centerpiece of the SuperCDMS SNOLAB experiment will be four detector towers (left), each containing six detector packs. The towers will be mounted inside the SNOBOX (right), a vessel in which the detector packs will be cooled to almost ...more

"The detector towers are the most technologically challenging part of the experiment, pushing the frontiers of our understanding of low-temperature devices and superconducting readout," said Bernard Sadoulet, a collaborator from the University of California, Berkeley.

A Strong Collaboration for Extraordinary Science

In addition to SLAC, two other national labs are involved in the project. Fermi National Accelerator Laboratory is working on the experiment's intricate shielding and cryogenics infrastructure, and Pacific Northwest National Laboratory is helping understand background signals in the experiment, a major challenge for the detection of faint WIMP signals.

A number of U.S. and Canadian universities also play key roles in the experiment, working on tasks ranging from detector fabrication and testing to data analysis and simulation. The largest international contribution comes from Canada and includes the research infrastructure at SNOLAB.

"We're fortunate to have a close-knit network of strong collaboration partners, which is crucial for our success," said KIPAC's Blas Cabrera, who directed the project through the CD-2/3 approval milestone. "The same is true for the outstanding support we're receiving from the funding agencies in the U.S. and Canada."

Fermilab's Dan Bauer, spokesperson of the SuperCDMS collaboration, said, "Together we're now ready to build an experiment that will search for dark matter particles that interact with normal matter in an entirely new region."

SuperCDMS SNOLAB will be the latest in a series of increasingly sensitive dark matter experiments. The most recent version, located at the Soudan Mine in Minnesota, completed operations in 2015.

"The project has incorporated lessons learned from previous CDMS experiments to significantly improve the experimental infrastructure and detector designs for the experiment," said SLAC's Ken Fouts, project manager for SuperCDMS SNOLAB. "The combination of design improvements, the deep location and the infrastructure support provided by SNOLAB will allow the experiment to reach its full potential in the search for low-mass dark matter." [32]

Start of most sensitive search yet for dark matter axion

Thanks to low-noise superconducting quantum amplifiers invented at the University of California, Berkeley, physicists are now embarking on the most sensitive search yet for axions, one of today's top candidates for dark matter.

The Axion Dark Matter Experiment (ADMX) reported results today showing that it is the world's first and only experiment to have achieved the necessary sensitivity to "hear" the telltale signs of dark matter axions.

The milestone is the result of more than 30 years of research and development, with the latest piece of the puzzle coming in the form of a quantum device that allows ADMX to listen for axions more closely than any experiment ever built.

John Clarke, a professor of physics in the graduate school at UC Berkeley and a pioneer in the development of sensitive magnetic detectors called SQUIDs (superconducting quantum interference devices), developed the amplifier two decades ago. ADMX scientists, with Clarke's input, have now incorporated it into the ADMX detector at the University of Washington, Seattle, and are ready to roll.

"ADMX is a complicated and quite expensive piece of machinery, so it took a while to build a suitable detector so that they could put the SQUID amplifier on it and demonstrate that it worked as advertised. Which it did," Clarke said.

The ADMX team published their results online today in the journal *Physical Review Letters*.

"This result signals the start of the true hunt for axions," said Andrew Sonnenschein at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, the operations manager for ADMX. "If dark matter axions exist within the frequency band we will be probing for the next few years, then it's only a matter of time before we find them."

A cutaway rendering of the ADMX detector, which can detect axions producing photons within its cold, dark interior. Credit: ADMX collaboration

Dark matter: MACHOs, WIMPs or axions?

Dark matter is the missing 84 percent of matter in the universe, and physicists have looked extensively for many possible candidates, most prominently massive compact halo objects, or MACHOs, and weakly interacting massive particles, or WIMPs. Despite decades of searching for MACHOs and WIMPs, scientists have struck out; they can see the effects of dark matter in the universe, in how galaxies and stars within galaxies move, but they can't see dark matter itself.

Axions are becoming the favored alternative, in part because their existence would also solve problems with the standard model of particle physics today, including the fact that the neutron should have an electric dipole moment, but doesn't.

Like other dark-matter candidates, axions are everywhere but difficult to detect. Because they interact with ordinary matter so rarely, they stream through space, even passing through the Earth, without "touching" ordinary matter. ADMX employs a strong magnetic field and a tuned, reflective box to encourage axions to convert to microwave-frequency photons, and uses the quantum amplifier to "listen" for them. All this is done at the lowest possible temperature to reduce background noise.

Clarke learned of a key stumbling block for ADMX in 1994, when meeting with physicist Leslie Rosenberg, now a professor at the University of Washington and chief scientist for ADMX, and Karl van Bibber, now chair of UC Berkeley's Department of Nuclear Engineering. Because the axion signal would be very faint, any detector would have to be very cold and "quiet." Noise from heat, or thermal radiation, is easy to eliminate by cooling the detector down to 0.1 Kelvin, or roughly 460 degrees below zero Fahrenheit. But eliminating the noise from standard semiconductor transistor amplifiers proved difficult.

They asked Clarke, would SQUID amplifiers solve this problem?

Listening for dark matter: How ADMX employs cold cavities and SQUID amplifiers to find the elusive axion. Credit: University of Washington, Seattle

Supercold amplifiers lower noise to absolute limit

Though he had built SQUID amplifiers that worked up to 100 MHz frequencies, none worked at the gigahertz frequencies needed, so he set to work to build one. By 1998, he and his collaborators had solved the problem, thanks in large part to initial funding from the National Science Foundation and subsequent funding from the Department of Energy (DOE) through Lawrence Berkeley National Laboratory. The amplifiers on ADMX were funded by DOE through the University of Washington.

Clarke and his group showed that, cooled to temperatures of tens of milliKelvin above absolute zero, the Microstrip SQUID Amplifier (MSA) could achieve a noise that was quantum limited, that is, limited only by Heisenberg's Uncertainty Principle.

"You can't do better than that," Clarke said.

This much quieter technology, combined with the refrigeration unit, reduced the noise by a factor of about 30 at 600 MHz so that a signal from the axion, if there is one, should come through loud and clear. The MSA currently in operation on ADMX was fabricated by Gene Hilton at the National Institute of Standards and Technology in Boulder, Colorado, and tested, calibrated and packaged by Sean O'Kelley, a graduate student in Clarke's research group at UC Berkeley.

The ADMX team plans to slowly tune through millions of frequencies in hopes of hearing a clear tone from photons produced by axion decay.

"This result plants a flag," said Rosenberg. "It tells the world that we have the sensitivity, and have a very good shot at finding the axion. No new technology is needed. We don't need a miracle anymore, we just need the time."

Clarke noted too that the high-frequency, low-noise quantum SQUID amplifiers he invented for ADMX have since been employed in another hot area of physics, to read out the superconducting quantum bits, or qubits, for quantum computers of the future. [31]

Search for superlight dark matter particles heats up

The hunt for wispy particles called axions, which might make up the dark matter whose gravity keeps galaxies from falling apart, is heating up. The Axion Dark Matter Experiment (ADMX) at the

University of Washington in Seattle has finally reached the sensitivity needed to detect axions if they make up dark matter, physicists report today in *Physical Review Letters*. However, researchers don't know exactly how much axions should weigh, and it may take them years to scan the range of possible masses.

An axion is a hypothetical particle that was invented 41 years ago to solve a problem in the theory of the strong nuclear force, which binds particles called quarks to make protons and neutrons. The axion could pull double duty, however, and supply the dark matter, which cosmological studies show makes up 85% of all matter. So far, dark matter has revealed itself only through its gravity, so one of the biggest mysteries in physics is what the particles that make up dark matter are.

If dark matter consists of axions floating around, then physicists ought to be able to detect them with essentially a strong magnetic field and an incredibly sensitive radio. The magnetic field will convert the axions into photons, and because the axions are very light, those photons will have very low radio frequencies and should provide an ultra-faint radio hum at a distinct frequency. In their new result, ADMX researchers rule out axions in the range from 2.66 microelectron volts (MeV) to 2.82 MeV—about 20 trillionths the mass of the electron. If dark matter consists purely of axions, then the particles must have a mass between about 1 MeV and 100 MeV, theorists think. So ADMX researchers will now sweep the frequency of their elaborate radio antenna upward as far as they can, to about 40 MeV. Stay tuned. [30]

Study suggests the elusive neutrino could make up a significant part of dark matter

Physicists trying to understand the fundamental structure of nature rely on consistent theoretical frameworks that can explain what we see and simultaneously make predictions that we can test. On the smallest scale of elementary particles, the standard model of particle physics provides the basis of our understanding.

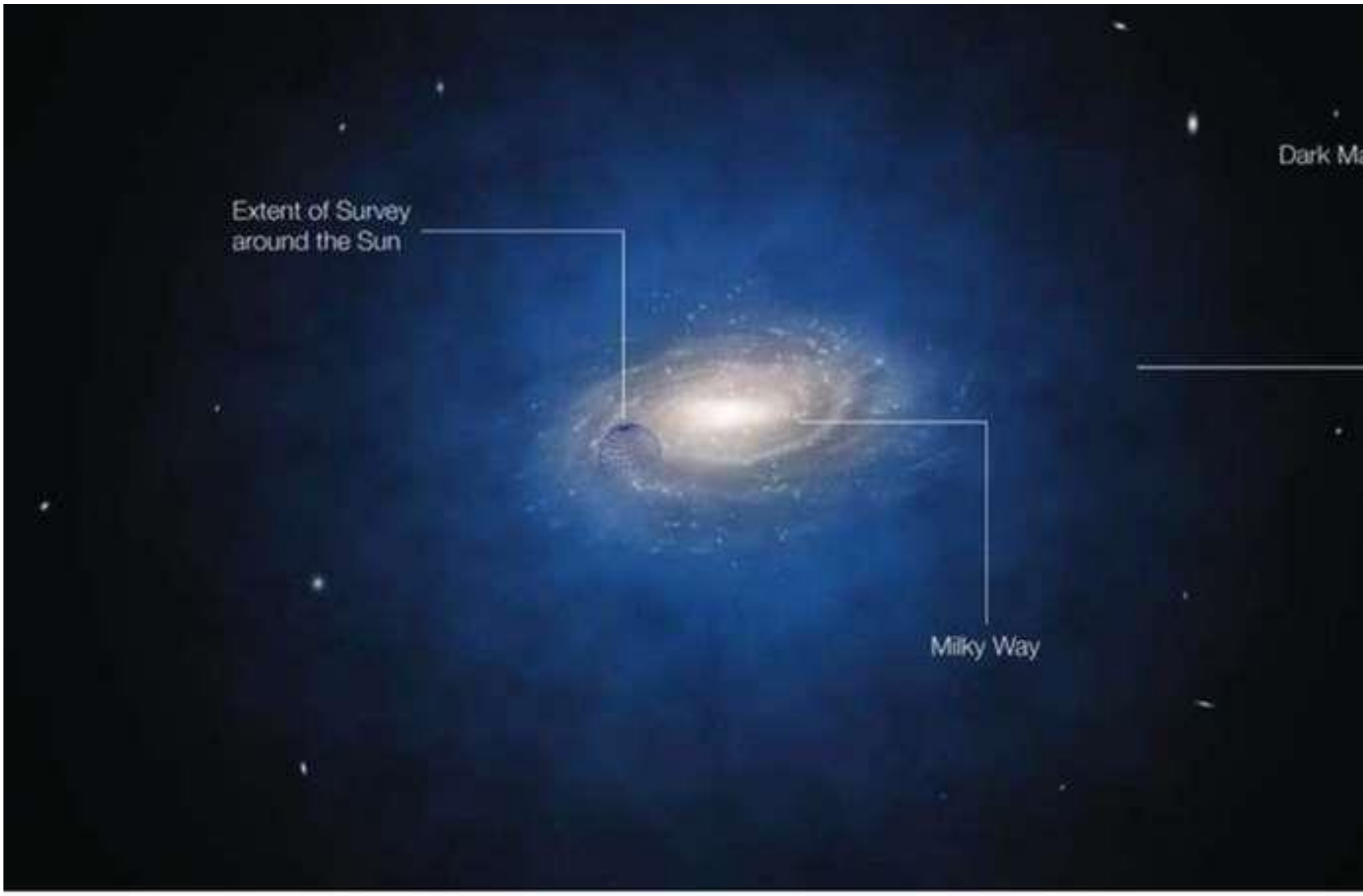
On the scale of the cosmos, much of our understanding is based on "standard model of cosmology". Informed by Einstein's theory of general relativity, it posits that the most of the mass and energy in the universe is made up of mysterious, invisible substances known as dark matter (making up 80% of the matter in the universe) and dark energy.

Over the past few decades, this model has been remarkably successful at explaining a wide range of observations of our universe. Yet we still don't know what makes up dark matter – we only know it exists because of the gravitational pull it has on galaxy clusters and other structures. A number of particles have been proposed as candidates, but we can't say for sure which one or several particles make up dark matter.

Now our new study – which hints that extremely light particles called neutrinos are likely to make up some of the dark matter – challenges our current understanding of its composition.

Hot versus cold

The standard model holds that dark matter is "cold". That means it consists of relatively heavy particles that initially had sluggish motions. As a consequence, it is very easy for neighbouring particles to get together to form objects bound by gravity. The model therefore predicts that the universe should be filled with small dark matter "haloes", some of which will merge and form progressively more massive systems – making the cosmos "lumpy".



Artist's impression of dark matter surrounding the Milky Way. Credit: ESO/L. Calçada

Credit: ESO/L. Calçada, CC BY-SA

However, it is not impossible that at least some dark matter is "hot". This would comprise relatively light particles that have quite high velocities – meaning the particles could easily escape from dense regions such as galaxies. This would slow the accumulation of new matter and lead to a universe where the formation of structure is suppressed (less lumpy).

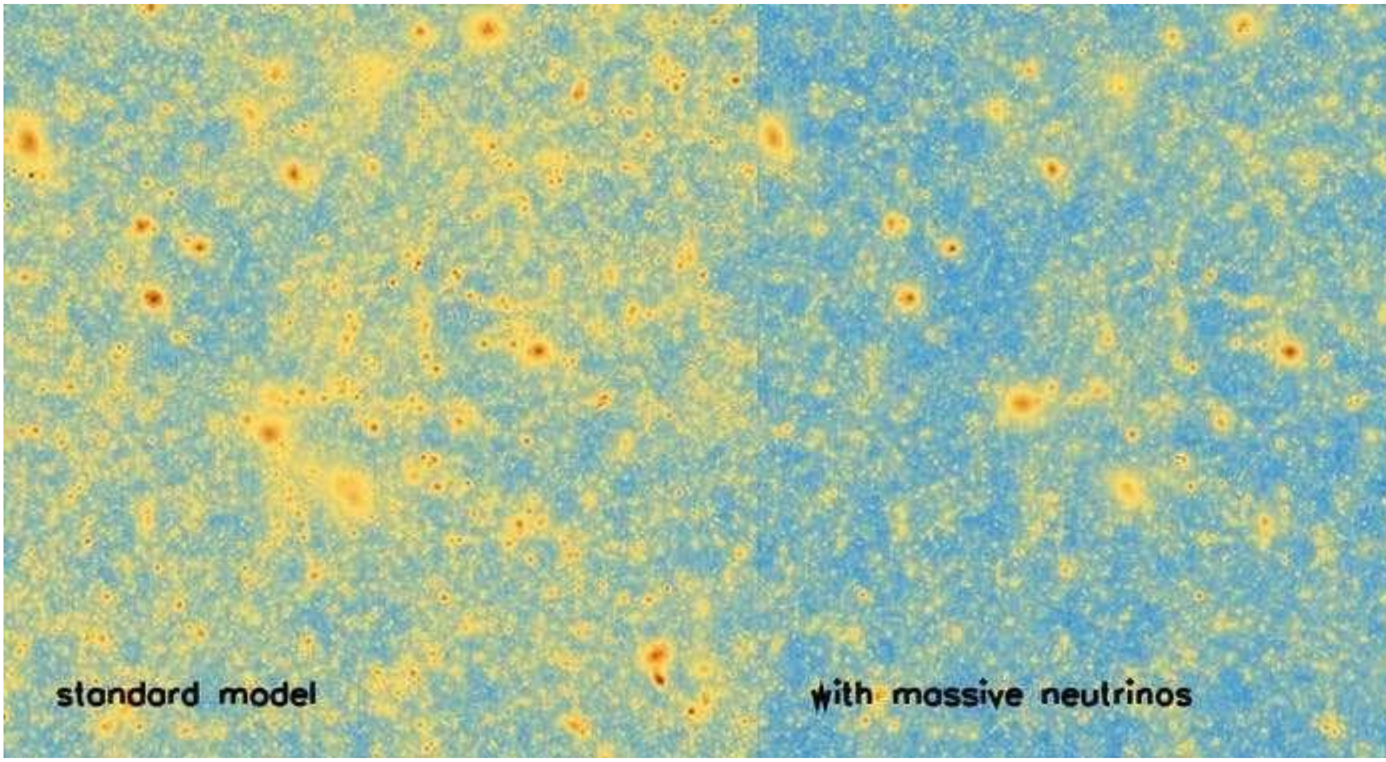
Neutrinos, which whizz around at extremely high velocities, are a good candidate for hot dark matter. In particular, they do not emit or absorb light – making them appear "dark". It was long assumed that neutrinos, which come in three different species, don't have mass. But experiments have demonstrated that they can change (oscillate) from one species to another. Importantly, scientists have shown that this changing requires them to have mass – making them a legitimate candidate for hot dark matter.

Over the past few decades, however, both particle physics experiments and various astrophysical lines of argument have ruled out neutrinos as making up most of the dark matter in the universe. What's more, the standard model assumes that neutrinos (and hot dark matter in general) have so little mass that their contribution to dark matter can be ignored completely (in most cases assumed to be 0%). And, until very recently, this model has reproduced a wide variety of cosmological observations quite well.

Changing picture

In the past few years, the quantity and quality of cosmological observations has shot up enormously. One of the most prominent examples of this has been the emergence of "gravitational lensing observations". General relativity tells us that matter curves spacetime so that light from distant galaxies can be deflected by massive objects that lie between us and the galaxies. Astronomers can measure such deflection to estimate the growth of structure (the "lumpiness") in the universe over cosmic time.

These new data sets have presented cosmologists with a number of ways to test in detail the predictions of the standard model. A picture that is beginning to emerge from these comparisons is that the mass distribution in the universe appears to be less lumpy than it ought to be if the dark matter is entirely cold.



However, making comparisons between the standard model and the new data sets may not be as straightforward as first thought. In particular, researchers have shown that the apparent lumpiness of the universe is not just affected by dark matter, but also by complex processes that affect normal matter (protons and neutrons). Previous comparisons assumed that normal matter, which "feels" both gravity and pressure forces, is distributed like dark matter, which only feels gravity.

Now our new study has produced the largest suite of cosmological computer simulations of normal and dark matter to date (called BAHAMAS). We have also made careful comparisons with a wide range of recent observations. We conclude that the discrepancy between the new observational data sets and the standard cold dark matter model is even larger than previously claimed.

We looked at the effects of neutrinos and their motions in great detail. As expected, when neutrinos were included in the model, the structure formation in the cosmos was washed out, making the universe less lumpy. Our results suggest that neutrinos make up between 3% and 5% of the total dark matter mass. This is sufficient to consistently reproduce a wide variety of observations – including the new gravitational lensing measurements. If a larger fraction of the dark matter is "hot", the growth of structure in the universe is suppressed too much.

The research may also help us solve the mystery of what the mass of an individual neutrino is. From various experiments, particle physicists have calculated that the the sum of the three neutrino species should be at least 0.06 electron Volts (a unit of energy, similar to joules). You can convert this into an estimate of the total neutrino contribution to dark matter, and it works out to be 0.5%. Given that we have found it is actually six to ten times larger than this, we can deduce that the neutrino mass should be about 0.3-0.5 eV instead.

This is tantalisingly close to values that can actually be measured by upcoming particle physics experiments. If these measurements corroborate the masses we found in our simulations, this would be very reassuring – giving us a consistent picture of the role of neutrinos as dark matter from the largest cosmological scales to the tiniest particle physics realm. [29]

Beyond the WIMP: Unique crystals could expand the search for dark matter

A new particle detector design proposed at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) could greatly broaden the search for dark matter—which makes up 85 percent of the total mass of the universe yet we don't know what it's made of—into an unexplored realm.

While several large physics experiments have been targeting theorized dark matter particles called WIMPs, or weakly interacting massive particles, the new detector design could scan for dark matter signals at energies thousands of times lower than those measurable by more conventional WIMP detectors.

The ultrasensitive detector technology incorporates crystals of gallium arsenide that also include the elements silicon and boron. This combination of elements causes the crystals to scintillate, or light up, in particle interactions that knock away electrons.

This scintillation property of gallium arsenide has been largely unexplored, said Stephen Derenzo, a senior physicist in the Molecular Biophysics and Integrated Bioimaging Division at Berkeley Lab and lead author of a study published March 20 in the *Journal of Applied Physics* that details the material's properties.

"It's hard to imagine a better material for searching in this particular mass range," Derenzo said, which is measured in MeV, or millions of electron volts. "It ticks all of the boxes. We are always worried about a 'Gotcha!' or showstopper. But I have tried to think of some way this detector material can fail and I can't."

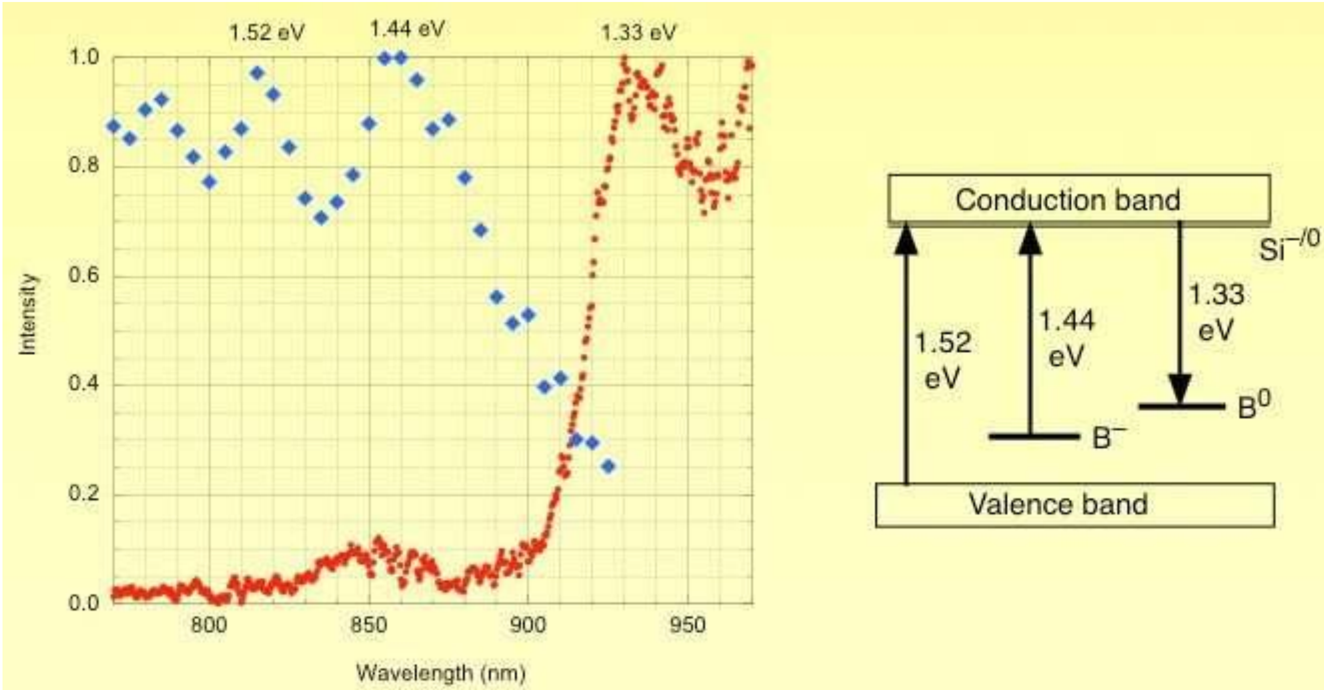
The breakthrough came from Edith Bourret, a senior staff scientist in Berkeley Lab's Materials Sciences Division who decades earlier had researched gallium arsenide's potential use in circuitry. She gave him a sample of gallium arsenide from this previous work that featured added concentrations, or "dopants," of silicon and boron.

Derenzo had previously measured some lackluster performance in a sample of commercial-grade gallium arsenide. But the sample that Bourret handed him exhibited a scintillation luminosity that was five times brighter than in the commercial material, owing to added concentrations, or "dopants," of silicon and boron that imbued the material with new and enhanced properties. This enhanced scintillation meant it was far more sensitive to electronic excitations.

"If she hadn't handed me this sample from more than 20 years ago, I don't think I would have pursued it," Derenzo said. "When this material is doped with silicon and boron, this turns out to be very important and, accidentally, a very good choice of dopants."

Derenzo noted that he has had a longstanding interest in scintillators that are also semiconductors, as this class of materials can produce ultrafast scintillation useful for medical imaging applications such as PET (positron emission tomography) and CT (computed tomography) scans, for example, as well as for high-energy physics experiments and radiation detection.

The doped gallium arsenide crystals he studied appear well-suited for high-sensitivity particle detectors because extremely pure crystals can be grown commercially in large sizes, the crystals exhibit a high luminosity in response to electrons booted away from atoms in the crystals' atomic structure, and they don't appear to be hindered by typical unwanted effects such as signal afterglow and dark current signals.



Left: Excitation curve (blue diamonds) and emission curve (red circles) showing that almost all of the emission spectrum of the GaAs scintillator is outside the absorption band. Right: Simplified diagram of excitation and emission ...more

Some of the larger WIMP-hunting detectors - such as that of the Berkeley Lab-led LUX-ZEPLIN project now under construction in South Dakota, and its predecessor, the LUX experiment - incorporate a liquid scintillation detector. A large tank of liquid xenon is surrounded by sensors to measure any light and electrical signals expected from a dark matter particle's interaction with the nucleus of a xenon atom. That type of interaction is known as a nuclear recoil.

In contrast, the crystal-based gallium arsenide detector is designed to be sensitive to the slighter energies associated with electron recoils—electrons ejected from atoms by their interaction with dark matter particles. As with LUX and LUX-ZEPLIN, the gallium arsenide detector would need to be placed deep underground to shield it from the typical bath of particles raining down on Earth.

It would also need to be coupled to light sensors that could detect the very few infrared photons (particles of light) expected from a low-mass dark matter particle interaction, and the detector would need to be chilled to cryogenic temperatures. The silicon and boron dopants could also possibly be optimized to improve the overall sensitivity and performance of the detectors.

Because dark matter's makeup is still a mystery—it could be composed of one or many particles of different masses, for example, or may not be composed of particles at all—Derenzo noted that gallium arsenide detectors provide just one window into dark matter particles' possible hiding places.

While WIMPs were originally thought to inhabit a mass range measured in billions of electron volts, or GeV, the gallium arsenide detector technology is well-suited to detecting particles in the mass range measured in millions of electron volts, or MeV.

Berkeley Lab physicists are also proposing other types of detectors to expand the dark matter search, including a setup that uses an exotic state of chilled helium known as superfluid helium to directly detect so-called "light dark matter" particles in the mass range of thousands of electron volts (keV).

"Superfluid helium is scientifically complementary to gallium arsenide since helium is more sensitive to dark matter interactions with atomic nuclei, while gallium arsenide is sensitive to dark matter interacting with electrons," said Dan McKinsey, a faculty senior scientist at Berkeley Lab and physics professor at UC Berkeley who is a part of the LZ Collaboration and is conducting R&D on dark matter detection using superfluid helium.

"We don't know whether dark matter interacts more strongly with nuclei or electrons—this depends on the specific nature of the dark matter, which is so far unknown."

Another effort would employ gallium arsenide crystals in a different approach to the light dark matter search based on vibrations in the atomic structure of the crystals, known as optical phonons. This setup could target "light dark photons," which are theorized low-mass particles that would serve as the carrier of a force between dark matter particles - analogous to the conventional photon that carries the electromagnetic force.

Still another next-gen experiment, known as the Super Cryogenic Dark Matter Search experiment, or SuperCDMS SNOLAB, will use silicon and germanium crystals to hunt for low-mass WIMPs.

"These would be complementary experiments," Derenzo said of the many approaches. "We need to look at all of the possible mass ranges. You don't want to be fooled. You can't exclude a mass range if you don't look there." [28]

Scientists investigating mysterious dark matter

University of Houston scientists are helping to develop a technology that could hold the key to unraveling one of the great mysteries of science: what constitutes dark matter? Scientists believe dark matter makes up 85 percent of the matter in the universe, but nobody actually knows what dark matter is.

"If we are the experiment that finds dark matter, we can change the fundamental understanding of the universe as we know it," said UH assistant professor Andrew Renshaw. "We can really start to understand the fundamental properties of the universe - how we got from the big bang to where we are, and what the future holds."

Renshaw and professor Ed Hungerford are leading a team of physicists from the College of Natural Sciences and Mathematics in the DarkSide program, an international research collaboration seeking to detect dark matter in the form of weakly interacting massive particles (WIMPs). In principle, when WIMP particles collide with ordinary nuclei, extremely small, low-energy nuclear recoil would result. In very simple terms, the scientists are trying to build technology that can detect WIMPS by detecting this very tiny, but observable recoil.

The UH team is using the DarkSide program's first physics detector, DarkSide-50 (DS-50), located underground at the Gran Sasso National Laboratory in Central Italy. The team and their collaborators have improved the sensitivity of the DS-50 detector in recent years by switching from atmospheric argon to low-radioactivity liquid argon, which was extracted from underground gas wells in Colorado. But a next-generation detector in development will take it even further.

DarkSide-50 time projection chamber cryostat filled with liquid argon at Gran Sasso National Laboratory in Italy. Credit: DarkSide Collaboration

DarkSide-20k (DS-20k) is currently being constructed using similar components from the present DarkSide experiment. Whereas DS-50 holds about 9.5 gallons (50 kilograms) of low-radioactivity liquid argon, this new detector, DS-20k, will employ new readout technology and will be some 400 times larger, holding 3,800 gallons (20,000 kilograms) of liquid argon. The new experiment is expected to start acquiring data at the Gran Sasso National Laboratory in 2021.

This detector, said Hungerford, will push the search for WIMP dark matter to new levels of sensitivity, hopefully finding the elusive WIMP. Or, he said, it could demonstrate that dark matter is not a particle, since this technology has now proven capable of searching for types of dark matter other than WIMPs.

"Previously, if you wanted to look for a specific kind of dark matter, you really had to look for a specific kind of detector. Now with this liquid argon technology, it's really opening the door to using a single technology to search for a handful of different kinds of dark matter," added Renshaw, who recently presented DarkSide findings at the UCLA Dark Matter Conference.

While Hungerford and Renshaw continue their research in Houston, three other members of the UH team are manning the day-to-day operations in Italy. Research associate Nicola Canci manages the DS-50 detector and monitors its performance.

"The cryogenic system keeping the argon in liquid phase needs to be monitored, and some operations are needed to allow for the good performances of the detector. Electronics are monitored. Signals coming from the detector are improved, if needed, and the quality of data is routinely checked," Canci said. [27]

Physicists contribute to dark matter detector success

In researchers' quest for evidence of dark matter, physicist Andrea Pocar of the University of Massachusetts Amherst and his students have played an important role in designing and building a key part of the argon-based DarkSide-50 detector located underground in Italy's Gran Sasso National Laboratory.

This week, scientists from around the world who gathered at the University of California, Los Angeles, at the Dark Matter 2018 Symposium learned of new results in the search for evidence of the elusive material in Weakly Interacting Massive Particles (WIMPs) by the DarkSide-50 detector. WIMPs have been candidate dark matter particles for decades, but none have been found to date.

Pocar says the DarkSide detector has demonstrated the great potential of liquid argon technology in the search for so-called "heavy WIMPs," those with mass of about 100 to 10,000 times the mass of a proton. Further, he adds, the double-phase argon technique used by the DarkSide-50 detector has unexpected power in the search for "low-mass WIMPs," with only 1-10 times the mass of a proton.

He adds, "The component we made at UMass Amherst, with very dedicated undergraduates involved from the beginning, is working very well. It's exciting this week to see the first report of our success coming out at the symposium." His graduate student Alissa Monte, who has studied surface and radon-related backgrounds using DarkSide-50, will present a poster at the UCLA meeting.

Pocar says, "There is a vibrant community of researchers around the world conducting competing experiments in this 'low mass' WIMP area. Over the past two years we collected data for a measurement we didn't expect to be able to make. At this point we are in a game we didn't think we could be in. We are reporting the high sensitivity we have achieved with the instrument, which is performing better than expected." Sensitivity refers to the instrument's ability to distinguish between dark matter and background radiation.

Dark matter, Pocar explains, represents about 25 percent of the energy content of the universe and while it has mass that can be inferred from gravitational effects, physicists have great difficulty detecting and identifying it because it hardly interacts, if at all, with "regular" matter through other forces. "Dark matter doesn't seem to want to interact much at all with the matter we know about," the physicist notes.

The DarkSide-50 detector uses 50 kg (about 110 lbs.) of liquid argon in a vat, with a small pocket of argon gas at the top, Pocar explains, as a target to detect WIMPs. The researchers hope for a WIMP to hit the nucleus of an argon atom in the tank, which then can be detected by the ionization produced by the nuclear recoil in the surrounding argon medium. Some of the ionization signal, proportional to the energy deposited inside the detector, is collected by applying an electric field to the target, he explains.

A flash of light is also produced in the argon with ionization, Pocar says. For high-enough energy events, the light pulse is bright enough to be used to tell the difference in "signature" between a nuclear recoil like that induced by a WIMP, and electron recoils induced by background or environmental radioactivity.

Pocar's lab designed, made and installed one of the electrodes that apply the electric field. He says, "For low-mass WIMPs, the amount of energy transmitted to the nucleus of argon by a WIMP is incredibly tiny. It's like hitting a billiard ball with a slow ping-pong ball. But a key thing for us is that now with two years of data, we have an exquisite understanding of our detector and we understand all non-WIMP events very well. Once you understand your detector, you can apply all that understanding in search mode, and plan for follow-up experiments."

Cristiano Galbiati, spokesperson for the DarkSide project, said at this week's symposium, "This is the best way to start the adventure of the future experiment DarkSide-20k. The results of DarkSide-50 provide great confidence on our technological choices and on the ability to carry out a compelling discovery program for dark matter. If a detector technology will ever identify convincingly dark matter induced events, this will be it." [26]

The search for dark matter—axions have ever-fewer places to hide

If they exist, axions, among the candidates for dark matter particles, could interact with the matter comprising the universe, but at a much weaker extent than previously theorized. New, rigorous constraints on the properties of axions have been proposed by an international team of scientists.

The latest analysis of measurements of the electrical properties of ultracold neutrons, published in the scientific journal *Physical Review X*, has led to surprising conclusions. On the basis of data collected in the Electric Dipole Moment of Neutron (nEDM) experiment, an international group of physicists demonstrated that axions, hypothetical particles that may comprise cold dark matter, would have to comply with much stricter limitations than previously believed with regard to their mass and manners of interacting with ordinary matter. The results are the first laboratory data imposing limits on the potential interactions of axions with nucleons (i.e. protons or neutrons) and gluons (the particles bonding quarks in nucleons).

"Measurements of the electric dipole moment of neutrons have been conducted by our international group for a good dozen or so years. For most of this time, none of us suspected that any traces associated with potential particles of dark matter might be hidden in the collected data. Only recently, theoreticians have suggested such a possibility and we eagerly took the opportunity to verify the hypotheses about the properties of axions," says Dr. Adam Kozela (IFJ PAN), one of the participants in the experiment.

Dark matter was first proposed to explain the movements of stars within galaxies and galaxies within galactic clusters. The pioneer of statistical research on star movements was the Polish astronomer Marian Kowalski. In 1859, he noticed that the movements of nearby stars could not be explained solely by the movement of the sun. This was the first observational evidence suggesting the rotation of the Milky Way. Kowalski is thus the man who "shook the foundations" of the galaxy. In 1933, the Swiss astronomer Fritz Zwicky went one step further. He analyzed the movements of structures in the Coma galaxy cluster using several methods. He then noticed that they moved as if there were a much larger amount of matter in their surroundings than that observed by astronomers.

Astronomers believe there should be almost 5.5 times as much dark matter in the universe as ordinary matter, as background microwave radiation measurements suggest. But the nature of dark matter is still unknown. Theoreticians have constructed many models predicting the existence of particles that are more or less exotic, which may account for dark matter. Among the candidates are axions. These extremely light particles would interact with ordinary matter almost exclusively via gravity. Current models predict that in certain situations, a photon could change into an axion, and after some time, transform back into a photon. This hypothetical phenomenon is the basis of the famous "lighting through a wall" experiments. These involve directing an intense beam of laser light onto a thick obstacle, and observing those photons that change into axions that penetrate the wall. After passing through, some of the axions could become photons again, with features exactly like those originally directed at the barrier.

Experiments related to measuring the electric dipole moment of neutrons have nothing to do with photons. In experiments conducted for over 10 years, scientists measured changes in the frequency of nuclear magnetic resonance (NMR) of neutrons and mercury atoms in a vacuum chamber in the presence of electric, magnetic and gravitational fields. These measurements enabled the researchers to draw conclusions about the precession of neutrons and mercury atoms, and consequently on their dipole moments.

Theoretical works have appeared in recent years that envisage the possibility of axions interacting with gluons and nucleons. Depending on the mass of the axions, these interactions could result in smaller or larger disturbances with the character of oscillations of dipole electrical moments of nucleons, or even whole atoms. The predictions meant that experiments conducted as part of the nEDM cooperation could contain valuable information about the existence and properties of potential particles of dark matter.

"In the data from the experiments at PSI, our colleagues conducting the analysis looked for frequency changes with periods in the order of minutes, and in the results from ILL—in the order of days. The latter would appear if there was an axion wind, that is, if the axions in the near Earth space were moving in a specific direction. Since the Earth is spinning, at different times of the day our measuring equipment would change its orientation relative to the axion wind, and this should result in cyclical, daily changes in the oscillations recorded by us," explains Dr. Kozela.

The results of the search turned out to be negative. No trace of the existence of axions with masses between 10^{-24} and 10^{-17} electron volts were found (for comparison: the mass of an electron is more than half a million electron volts). In addition, the scientists managed to tighten the constraints imposed by theory on the interaction of axions with nucleons by 40 times. In the case of potential interactions with gluons, the restrictions have increased more than 1000-fold. So if axions do exist, in the current theoretical models, they have fewer places to hide. [25]

MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs: New candidate for dark matter

The intensive, worldwide search for dark matter, the missing mass in the universe, has so far failed to find an abundance of dark, massive stars or scads of strange new weakly interacting particles, but a new candidate is slowly gaining followers and observational support.

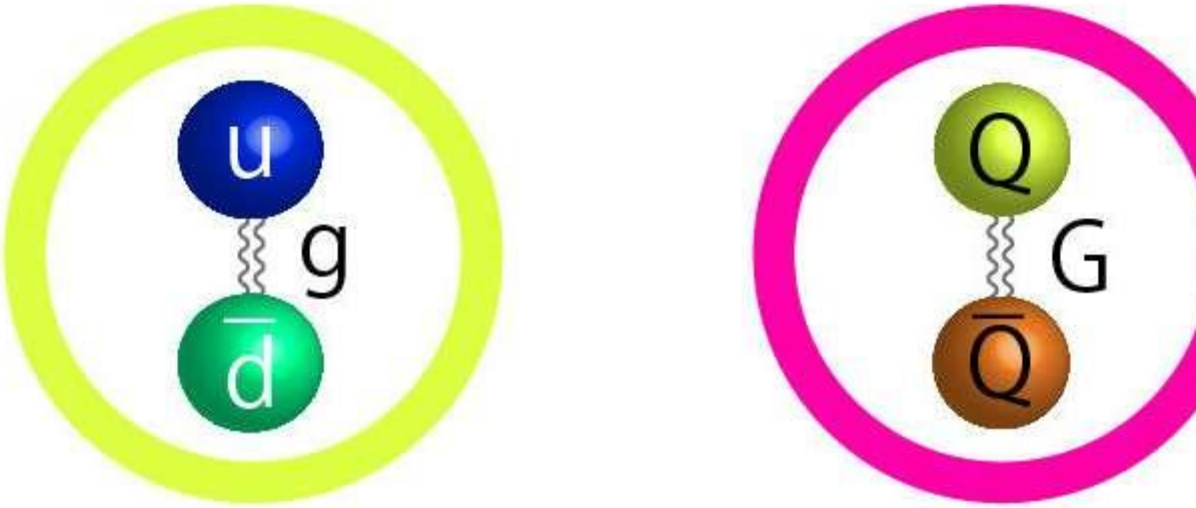
Called SIMPs - strongly interacting massive particles - they were proposed three years ago by University of California, Berkeley theoretical physicist Hitoshi Murayama, a professor of physics and director of the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) in Japan, and former UC Berkeley postdoc Yonit Hochberg, now at Hebrew University in Israel.

Murayama says that recent observations of a nearby galactic pile-up could be evidence for the existence of SIMPs, and he anticipates that future particle physics experiments will discover one of them.

Murayama discussed his latest theoretical ideas about SIMPs and how the colliding galaxies support the theory in an invited talk Dec. 4 at the 29th Texas Symposium on Relativistic Astrophysics in Cape Town, South Africa.

Astronomers have calculated that dark matter, while invisible, makes up about 85 percent of the mass of the universe. The solidest evidence for its existence is the motion of stars inside galaxies: Without an unseen blob of dark matter, galaxies would fly apart. In some galaxies, the visible stars are so rare that dark matter makes up 99.9 percent of the mass of the galaxy.

Theorists first thought that this invisible matter was just normal matter too dim to see: failed stars called brown dwarfs, burned-out stars or black holes. Yet so-called massive compact halo objects - MACHOs - eluded discovery, and earlier this year a survey of the Andromeda galaxy by the Subaru Telescope basically ruled out any significant undiscovered population of black holes. The researchers searched for black holes left over from the very early universe, so-called primordial black holes, by looking for sudden brightenings produced when they pass in front of background stars and act like a weak lens. They found exactly one - too few to contribute significantly to the mass of the galaxy.



The fundamental structure of the proposed SIMP (strongly interacting massive particle) is similar to that of a pion (left). Pions are composed of an up quark and a down antiquark, with a gluon (g) holding them together. A SIMP would be composed of a quark and an antiquark held together by a gluon (G). Credit: Kavli IPMU graphic

"That study pretty much eliminated the possibility of MACHOs; I would say it is pretty much gone," Murayama said.

WIMPs—weakly interacting massive particles—have fared no better, despite being the focus of researchers' attention for several decades. They should be relatively large - about 100 times heavier than the proton - and interact so rarely with one another that they are termed "weakly" interacting. They were thought to interact more frequently with normal matter through gravity, helping to attract normal matter into clumps that grow into galaxies and eventually spawn stars.

SIMPs interact with themselves, but not others

SIMPs, like WIMPs and MACHOs, theoretically would have been produced in large quantities early in the history of the universe and since have cooled to the average cosmic temperature. But unlike WIMPs, SIMPs are theorized to interact strongly with themselves via gravity but very weakly with normal matter. One possibility proposed by Murayama is that a SIMP is a new combination of quarks, which are the fundamental components of particles like the proton and neutron, called baryons. Whereas protons and neutrons are composed of three quarks, a SIMP would be more like a pion in containing only two: a quark and an antiquark.

The SIMP would be smaller than a WIMP, with a size or cross section like that of an atomic nucleus, which implies there are more of them than there would be WIMPs. Larger numbers would mean that, despite their weak interaction with normal matter - primarily by scattering off of it, as opposed to merging with or decaying into normal matter - they would still leave a fingerprint on normal matter, Murayama said.

He sees such a fingerprint in four colliding galaxies within the Abell 3827 cluster, where, surprisingly, the dark matter appears to lag behind the visible matter. This could be explained, he said, by interactions between the dark matter in each galaxy that slows down the merger of dark matter but not that of normal matter, basically stars.

Conventional WIMP theories predict a highly peaked distribution, or cusp, of dark matter in a small area in the center of every galaxy. SIMP theory predicts a spread of dark matter in the center, which is more typical of dwarf galaxies. ...more

"One way to understand why the dark matter is lagging behind the luminous matter is that the dark matter particles actually have finite size, they scatter against each other, so when they want to move toward the rest of the system they get pushed back," Murayama said. "This would explain the observation. That is the kind of thing predicted by my theory of dark matter being a bound state of new kind of quarks."

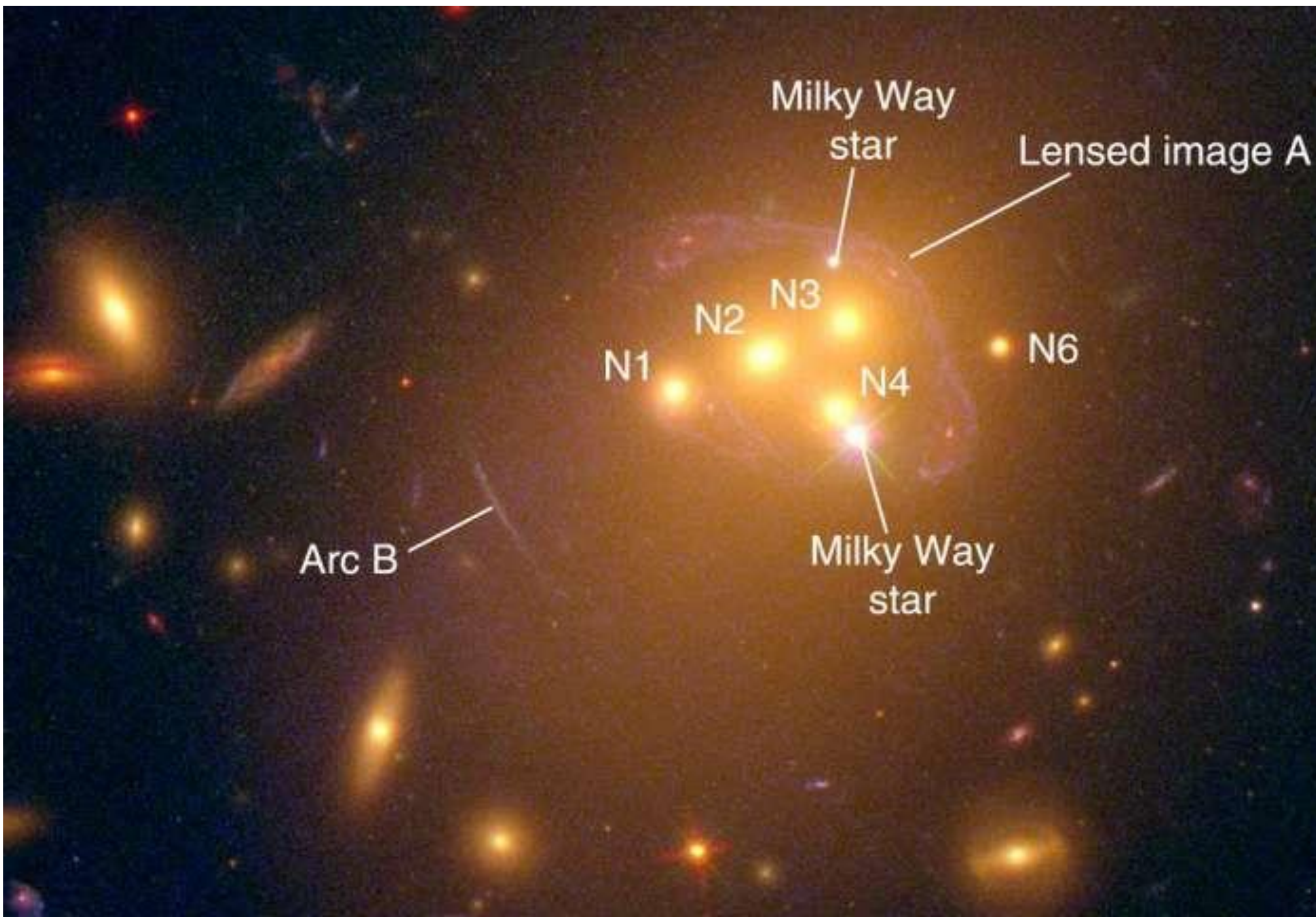
SIMPs also overcome a major failing of WIMP theory: the ability to explain the distribution of dark matter in small galaxies.

"There has been this longstanding puzzle: If you look at dwarf galaxies, which are very small with rather few stars, they are really dominated by dark matter. And if you go through numerical simulations of how dark matter clumps together, they always predict that there is a huge concentration towards the center. A cusp," Murayama said. "But observations seem to suggest that concentration is flatter: a core instead of a cusp. The core/cusp problem has been considered one of the major issues with dark matter that doesn't interact other than by gravity. But if dark matter has a finite size, like a SIMP, the particles can go 'clink' and disperse themselves, and that would actually flatten out the mass profile toward the center. That is another piece of 'evidence' for this kind of theoretical idea."

Ongoing searches for WIMPs and axions

Ground-based experiments to look for SIMPs are being planned, mostly at accelerators like the Large Hadron Collider at CERN in Geneva, where physicists are always looking for unknown particles that fit new predictions. Another experiment at the planned International Linear Collider in Japan could also be used to look for SIMPs.

As Murayama and his colleagues refine the theory of SIMPs and look for ways to find them, the search for WIMPs continues. The Large Underground Xenon (LUX) dark matter experiment in an underground mine in South Dakota has set stringent limits on what a WIMP can look like, and an upgraded experiment called LZ will push those limits further. Daniel McKinsey, a UC Berkeley professor of physics, is one of the co-spokespersons for this experiment, working closely with Lawrence Berkeley National Laboratory, where Murayama is a faculty senior scientist.



This Hubble Space Telescope image of the galaxy cluster Abell 3827 shows the ongoing collision of four bright galaxies and one faint central galaxy, as well as foreground stars in our Milky Way galaxy and galaxies behind the cluster (Arc B …more

Physicists are also seeking other dark matter candidates that are not WIMPs. UC Berkeley faculty are involved in two experiments looking for a hypothetical particle called an axion, which may fit the requirements for dark matter. The Cosmic Axion Spin-Precession Experiment (CASPEr), led by Dmitry Budker, a professor emeritus of physics who is now at the University of Mainz in Germany, and theoretician Surjeet Rajendran, a UC Berkeley professor of physics, is planning to look for perturbations in nuclear spin caused by an axion field. Karl van Bibber, a professor of nuclear engineering, plays a key role in the Axion Dark Matter eXperiment - High Frequency (ADMX-HF), which seeks to detect axions inside a microwave cavity within a strong magnetic field as they convert to photons.

"Of course we shouldn't abandon looking for WIMPs," Murayama said, "but the experimental limits are getting really, really important. Once you get to the level of measurement, where we will be in the near future, even neutrinos end up being the background to the experiment, which is unimaginable."

Neutrinos interact so rarely with normal matter that an estimated 100 trillion fly through our bodies every second without our noticing, something that makes them extremely difficult to detect.

"The community consensus is kind of, we don't know how far we need to go, but at least we need to get down to this level," he added. "But because there are definitely no signs of WIMPs appearing, people are starting to think more broadly these days. Let's stop and think about it again."

Physicists Create Theory on Self-Interacting Dark Matter

Just like identical twins, at first glance, two galaxies can often appear to be very similar, identical even. However, upon closer scrutiny, we see that simply isn't the case. In terms of galaxies, these differences include inner regions that rotate at completely different speeds. So, although they may look the same on the outside, inside is a whole different story. One recent study, led by Hai-Bo Yu of the University of California, Riverside set out to provide us with an explanation for this diversity among galaxies.

Dark matter is the invisible casing that holds galaxies together. The distribution of it is inferred from the motion of gas particles and stars within the galaxy. In Yu's research, the physicists report how the diverse curves and rotation speeds of these galaxies can be explained if dark matter particles do in fact collide with one another near the galaxy's center, in a process called dark matter selfinteraction. "In the prevailing dark matter theory, called Cold Dark Matter or CDM, dark matter particles are assumed to be collisionless, aside from gravity," confirmed Yu. "We invoke a different theory, the self-interacting dark matter model or SIDM, to show that dark matter self-interactions thermalize the inner halo, which ties ordinary dark matter and dark matter distributions together so that they behave like a collective unit." In doing this, the self-interacting dark matter halo then becomes much more flexible and easier to accommodate the diverse rotation curves.

These dark matter collisions occur in the inner halo and when the particles collide they thermalize. In galaxies of low-luminosity, the thermalization reduces the density by pushing out the inner dark matter particles. In high-luminous galaxies, such as our very own Milky Way, the thermalization process increases the dark matter density by pulling the particles into the luminous matter. "Our work demonstrates that dark matter may have strong self-interactions, a radical deviation from the prevailing theory," says Yu.

Around 85 percent of the Universe is dark matter, yet there is still so much we don't know about it. However, what we do know is that it has an unmistakable gravitational imprint on both cosmological and astronomical observations. A lot of Yu's work over the last decade has been on pioneering a new kind of research that will finally conclude what happens when dark matter interacts with itself. He has hypothesized that it would almost certainly affect the dark matter distribution in each halo.

Flip Tanedo is an assistant professor if theoretical particle physics at UC Riverside who's not involved in the study. Here's what he had to say about it: "The compatibility of this hypothesis with observations is a major advance in the field. The SIDM paradigm is a bridge between fundamental particle physics and observational astronomy. The consistency with observations is a big hint that this proposal has a chance of being correct and lays the foundation for future observational, experimental, numerical, and theoretical work. In this way, it is paving the way to new interdisciplinary research." He also added that "Hai-Bo is the architect of modern self-interacting dark matter and how it merges multiple fields: theoretical high-energy physics, experimental highenergy physics, observational, astronomy, numerical simulations of astrophysics, and early universe cosmology and galaxy formation." [23]

The hunt for light dark matter

Technology proposed 30 years ago to search for dark matter is finally seeing the light.

Scientists are using innovative sensors, called skipper CCDs (short for charge-coupled devices) in a new type of dark matter detection project. Scientists will use the project, known as SENSEI, to find the lightest dark matter particles anyone has ever looked for.

Dark matter—so named because it doesn't absorb, reflect or emit light—constitutes 27 percent of the universe, but the jury is still out on what it's made of. The primary theoretical suspect for the main component of dark matter is a particle scientists have descriptively named the weakly interactive massive particle, or WIMP.

But since none of these heavy particles, which are expected to have a mass 100 times that of a proton, have shown up in experiments, it might be time for researchers to think small.

"There is a growing interest in looking for different kinds of dark matter that are additives to the standard WIMP model," said Fermilab scientist Javier Tiffenberg, a leader of the SENSEI collaboration. "Lightweight, or low-mass, dark matter is a very compelling possibility, and for the first time, the technology is there to explore these candidates."

Low-mass dark matter would leave a tiny, difficult-to-see signature when it collides with material inside a detector. Catching these elusive particles requires a dark-matter-detecting master: SENSEI.

Sensing the unseen

In traditional dark matter experiments, scientists look for a transfer of energy that would occur if dark matter particles collided with an ordinary nucleus, but SENSEI is different. It looks for direct interactions of dark matter particles colliding with electrons.

"That is a big difference—you get a lot more energy transferred in this case because an electron is so light compared to a nucleus," Tiffenberg said.

If dark matter has low mass—much smaller than the WIMP model suggests—then it would be many times lighter than an atomic nucleus. So if it were to collide with a nucleus, the resulting energy transfer would be far too small tell us anything. It would be like throwing a ping pong ball at a boulder: the heavy object isn't going anywhere, and there would be no sign the two had come into contact.

An electron is nowhere near as heavy as an atomic nucleus. In fact, a single proton has about 1,836 times more mass than an electron. So the collision of a low-mass dark matter particle with an electron has a much better chance of leaving a mark—more bowling ball than the nucleus's boulder.

Even so, the electron is still a bowling ball compared to the low-mass dark matter particle. An energy transfer between the two would leave only a blip of energy, one either too small for most detectors to pick up or easily overshadowed by noise in the data. There is a small exchange of energy, but, if the detector isn't sensitive enough, it could appear as though nothing happens.

"The bowling ball will move a very tiny amount," said Fermilab scientist Juan Estrada, a SENSEI collaborator. "You need a very precise detector to see this interaction of lightweight particles with something that is much heavier."

That's where SENSEI's sensitive skipper CCDs come in: They will pick up on that tiny transfer of energy.

CCDs have been used for other dark matter detection experiments, such as the Dark Matter in CCDs (or DAMIC) experiment operating at SNOLAB in Canada. These CCDs were a spinoff from sensors developed for use in the Dark Energy Camera in Chile and other dark energy search projects.

CCDs are typically made of silicon divided into pixels. When a dark matter particle passes through the CCD, it collides with silicon's electrons, knocking them free, leaving a net electric charge in each pixel the particle passes through. The electrons then flow through adjacent pixels and are ultimately read as a current in a device that measures the number of electrons freed from each

CCD pixel. That measurement tells scientists about the mass and energy of the particle—in this case the dark matter particle—that got the chain reaction going. A massive particle, like a WIMP, would free a gusher of electrons, but a low-mass particle might free only one or two.

Typical CCDs can measure the charge left behind only once, which makes it difficult to decide if a tiny energy signal from one or two electrons is real or an error.

Skipper CCDs are a new generation of the technology that helps eliminate the "iffiness" of a measurement that has a one- or two-electron margin of error. That allows for much higher precision thanks to a unique design.

"In the past, detectors could measure the amount of charge of the energy deposited in each pixel only once," Tiffenberg said. "The big step forward for the skipper CCD is that we are able to measure this charge as many times as we want."

The charge left behind in the skipper CCD by dark matter knocking electrons free can be sampled multiple times and then averaged, a method that yields a more precise measurement of the charge deposited in each pixel than the measure-one-and-done technique. That's the rule of statistics: With more data, you get closer to a property's true value.

SENSEI scientists take advantage of the skipper CCD architecture, measuring the number of electrons in a single pixel a whopping 4,000 times and then averaging them. That minimizes the measurement's error—or noise—and clarifies the signal.

"This is a simple idea, but it took us 30 years to get it to work," Estrada said.

From idea, to reality, to beyond

A small SENSEI prototype is currently running at Fermilab in a detector hall 385 feet below ground, and it has demonstrated that this detector design will work in the hunt for dark matter.

After a few decades existing as only an idea, skipper CCD technology and SENSEI were brought to life by Laboratory Directed Research and Development (LDRD) funds at Fermilab and Lawrence Berkeley National Laboratory (Berkeley Lab). The Fermilab LDRDs were awarded only recently—less than two years ago—but close collaboration between the two laboratories has already yielded SENSEI's promising design, partially thanks to Berkeley lab's previous work in skipper CCD design.

Fermilab LDRD funds allow researchers to test the sensors and develop detectors based on the science, and the Berkeley Lab LDRD funds support the sensor design, which was originally proposed by Berkeley Lab scientist Steve Holland.

"It is the combination of the two LDRDs that really make SENSEI possible," Estrada said.

LDRD programs are intended to provide funding for development of novel, cutting-edge ideas for scientific discovery, and SENSEI technology certainly fits the bill—even beyond its search for dark matter.

Future SENSEI research will also receive a boost thanks to a recent grant from the Heising-Simons Foundation.

"SENSEI is very cool, but what's really impressive is that the skipper CCD will allow the SENSEI science and a lot of other applications," Estrada said. "Astronomical studies are limited by the sensitivity of their experimental measurements, and having sensors without noise is the equivalent of making your telescope bigger—more sensitive."

SENSEI technology may also be critical in the hunt for a fourth type of neutrino, called the sterile neutrino, which seems to be even more shy than its three notoriously elusive neutrino family members.

A larger SENSEI detector equipped with more skipper CCDs will be deployed within the year. It's possible it might not detect anything, sending researchers back to the drawing board in the hunt for dark matter. Or SENSEI might finally make contact with dark matter—and that would be SENSEItional. [22]

Looking at dark matter

The age of discovery is not over. Once, scurvy-riddled Europeans sailed into the unknown to claim foreign, fantastic parts of the world. Now, physicists sit in labs and ask, "Is this all there is?"

No, they aren't suffering a collective existential crisis. They're looking for dark matter—the stuff that theoretically makes up a quarter of our universe. And West Aussie researchers are at the forefront of this search, as part of an Australian-wide project to detect a particle called the axion.

What's the (dark) matter?

If dark matter exists, you are probably sitting in a soup of it right now.

Scientists predict it makes up 26.8% of the universe, which is pretty significant when you consider that everything else we can observe—from hydrogen atoms to black holes—makes up only 5%. (The other 69% is something scientists call dark energy. Don't worry about it.)

There's just one problem. It doesn't interact with electromagnetism—the force between positively and negatively charged particles. It's responsible for practically everything we can observe in day-today life—with the exception of gravity.

Electromagnetic forces present between atoms and molecules in the ground is the reason Earth's gravity doesn't keep pulling us all the way down to its (molten hot) core. The light being emitted from your computer, allowing you to read this story, is generated by interactions of electrically charged particles in your monitor, otherwise known as electricity.

Ordinary matter looks like ordinary matter because of the electromagnetic forces between atoms and molecules. But dark matter doesn't interact with electromagnetism. That means we can't see, smell, taste or touch it. So if dark matter is essentially undetectable, why do we think it exists? And what on Earth are we looking for?

In the dark

Let's start with a basic assumption—gravity exists. Along with electromagnetism, gravity is one of the four basic forces that physicists use to explain almost everything. Gravity says that heavy things attract all other heavy things, so Earth's gravitational pull is the reason we aren't all floating aimlessly in space.

If we peer into all that space, we can see that our Milky Way galaxy is spiral shaped. Smack bang in the galactic centre is a big, bar-shaped bulge from which spiralling arms snake around in a flat circle. Earth sits somewhere in the middle of one of those arms and completes one lap of the galaxy every 225 to 250 million years.

If we think about the entire universe as a giant amusement park, we can imagine our Milky Way to be a carousel. Unlike normal carousels that have plastic ponies fixed in place by poles, the stars, moons and planets that make up our galaxy are disconnected and free to spin around at different speeds.

So if everything is disjointed and spinning, what's keeping us orbiting neatly in our little spiral? Well if we continue with the theme park analogy, we can liken this phenomenon to a swing chair ride.

When swinging in a chair around a tower, a metal chain provides a constant force into the centre of the ride that keeps you spinning round and around that central pole.

The same sort of thing occurs in space, except instead of a chain, we've got gravity. Gravity is provided by the mass of stuff—specifically, the mass of our galactic centre, which scientists believe to be a supermassive black hole. It has so much mass in so little space that it exerts a gravitational force so high it sucks in light.

When you move away from the centre and into the flat galactic halo, we see a lot less stuff. Less stuff means less mass, which means less gravity. We could therefore expect the stuff in the spiral arms to be spinning slower than the stuff closer to the middle.

What astrophysicists actually see is that things on the outer edge of the galaxy are spinning at the same rate as things near the centre of the galaxy—and that's pretty damn fast. If this was the case in our theme park, we would have slipped into a nightmare scenario.

The spinning chair ride would be whirling around so fast that the chain would no longer provide enough force to keep you moving in a circle. The chain would break, and you would be flung to a death worthy of a B-grade horror movie.

Scientists predict the galaxy should rotate like the image on the right. Our galaxy is actually rotating much faster—as on the left. Why then haven't we been flung into space? Probably because of dark matter. Credit: ESO/L. CALÇADA

The fact that Earth has not been slingshotted far and wide suggests that we are surrounded by a lot more mass, which provides a whole bunch of gravity and keeps our galaxy in shape. And most physicists think that mass might just be dark matter.

Dark candidates

Just for a second, forget everything you just read. We're going to stop staring at stars and instead investigate much smaller things—particles. Particle physics is home to this problem called the strong charge parity (CP) problem. It's a very big unexplainable problem in the otherwise successful theory of quantum chromodynamics. Don't worry about it.

Using mathematical equations, particle physicists in the 70s suggested we could solve this strong CP problem with the introduction of a theoretical particle called the axion. And if we do more maths and write a description of what the axion particle should look like, we would find that it has two very exciting qualities—a) it has mass and b) it does not interact with electromagnetism very much at all.

Which sounds suspiciously like the qualities of dark matter. The axion is what physicists call a 'promising candidate' for dark matter. It's like killing two birds with one theoretical, invisible stone.

And if axions are dark matter, we should be surrounded by them right now. If we could only build the right equipment, we could perhaps detect the mysterious mass that's holding our galaxy together. As it happens, some clever scientists at UWA are doing just that.

Dark matter turns light

Physicists at a UWA node of the ARC Centre of Excellence for Engineered Quantum Systems (EQuS) are employing a piece of equipment called a haloscope—so called because it searches for axions in the galactic halo (which you're sitting in right now).

A haloscope is basically an empty copper can (a 'resonant cavity') placed in a very cold, very strong magnetic field. If axions are dark matter and exist all around us, one might enter the resonant cavity, react with the magnetic field and transform into a particle of light—a photon.

Whilst we wouldn't be able to see these photons, scientists are pretty good at measuring them. They're able to measure how much energy it has (its frequency) as it sits inside the resonant cavity. And that frequency corresponds to the mass of the axion that it came from.

The problem is, resonant cavities (those empty copper cans) are created to detect photons with specific frequencies. We don't know how heavy axions are, so we don't know what frequency photon they will produce, which means building the right resonator involves a bit of guesswork.

The search for the axion is more of a process of elimination. What have they been able to exclude so far? Well, mostly due to technical limitations, scientists have previously been looking for axions with a low mass. New theoretical models predict that the axion is a bit heavier. How heavy? We don't know. But Aussie researchers have just been awarded 7 years of funding to try and find out.

Scoping the halo

The Oscillating Resonant Group AxioN (ORGAN) experiment is a nationwide collaboration between members of EQuS and is hosted at UWA. Part of the physicists' work over the next 7 years will be to design resonant cavities that are capable of detecting heavier axions.

They ran an initial experiment over Christmas 2016, the ORGAN Pathfinder, to confirm that their haloscopes were up to the task ahead and that the physicists were capable of analysing their results. This experiment yielded no results—but that doesn't mean that axions don't exist. It only means that they don't exist with the specific mass that they searched for in December 2016 and to a certain level of sensitivity.

The intrepid explorers at UWA will set sail into the next stages of the ORGAN experiment in 2018. And perhaps soon, we'll know exactly what the matter is. [21]

A silent search for dark matter

Results from its first run indicate that XENON1T is the most sensitive dark matter detector on Earth. The sensitivity of the detector—an underground sentinel awaiting a collision that would confirm a hypothesis—stems from both its size and its "silence." Shielded by rock and water, and purified with a sophisticated system, the detector demonstrated a new record low radioactivity level, many orders of magnitude below surrounding material on Earth.

"We are seeing very good quality data from this detector, which tells us that it is running perfectly," said Ethan Brown, a XENON1T Collaboration member, and assistant professor of physics, applied physics, and astronomy at Rensselaer Polytechnic Institute.

Dark matter is theorized as one of the basic constituents of the universe, five times more abundant than ordinary matter. But because it cannot be seen and seldom interacts with ordinary matter, its existence has never been confirmed. Several astronomical measurements have corroborated the existence of dark matter, leading to a worldwide effort to directly observe dark matter particle interactions with ordinary matter. Up to the present, the interactions have proven so feeble that they have escaped direct detection, forcing scientists to build ever-more-sensitive detectors.

Since 2006, the XENON Collaboration has operated three successively more sensitive liquid xenon detectors in the Gran Sasso Underground Laboratory (LNGS) in Italy, and XENON1T is its most powerful venture to date and the largest detector of its type ever built. Particle interactions in liquid xenon create tiny flashes of light, and the detector is intended to capture the flash from the rare occasion in which a dark matter particle collides with a xenon nucleus.

But other interactions are far more common. To shield the detector as much as possible from natural radioactivity in the cavern, the detector (a so-called Liquid Xenon Time Projection Chamber) sits within a cryostat submersed in a tank of water. A mountain above the underground laboratory further shields the detector from cosmic rays. Even with shielding from the outside world, contaminants seep into the xenon from the materials used in the detector. Among his contributions, Brown is responsible for a purification system that continually scrubs the xenon in the detector.

"If the xenon is dirty, we won't see the signal from a collision with dark matter," Brown said. "Keeping the xenon clean is one of the major challenges of this experiment, and my work involves developing new techniques and new technologies to keep pace with that challenge."

Brown also aids in calibrating the detector to ensure that interactions which are recorded can be properly identified. In rare cases, for example, the signal from a gamma ray may approach the expected signal of a dark matter particle, and proper calibration helps to rule out similar false positive signals.

In the paper "First Dark Matter Search Results from the XENON1T Experiment" posted on arXiv.org and submitted for publication, the collaboration presented results of a 34-day run of XENON1T from November 2016 to January 2017. While the results did not detect dark matter particles—known as "weakly interacting massive particles" or "WIMPs" - the combination of record low radioactivity levels with the size of the detector implies an excellent discovery potential in the years to come.

"A new phase in the race to detect dark matter with ultralow background massive detectors on Earth has just began with XENON1T," said Elena Aprile, a professor at Columbia University and project spokesperson. "We are proud to be at the forefront of the race with this amazing detector, the first of its kind." [20]

3 knowns and 3 unknowns about dark matter

What's known:

1. We can observe its effects.

While we can't see dark matter, we can observe and measure its gravitational effects. Galaxies have been observed to spin much faster than expected based on their visible matter, and galaxies move faster in clusters than expected, too, so scientists can calculate the "missing mass" responsible for this motion.

2. It is abundant.

It makes up about 85 percent of the total mass of the universe, and about 27 percent of the universe's total mass and energy.

3. We know more about what dark matter is not.

Increasingly sensitive detectors are lowering the possible rate at which dark mark matter particles can interact with normal matter.

What's unknown

1. Is it made up of one particle or many particles?

Could dark matter be composed of an entire family of particles, such as a theorized "hidden valley" or "dark sector?"

2. Are there "dark forces" acting on dark matter?

Are there forces beyond gravity and other known forces that act on dark matter but not on ordinary matter, and can dark matter interact with itself?

3. Is there dark antimatter?

Could dark matter have an antimatter counterpart, as does normal matter, and is there a similar imbalance that favored dark matter over "dark antimatter" as with normal matter-antimatter? [20]

New theory on the origin of dark matter

Only a small part of the universe consists of visible matter. By far the largest part is invisible and consists of dark matter and dark energy. Very little is known about dark energy, but there are many theories and experiments on the existence of dark matter designed to find these as yet unknown particles. Scientists at Johannes Gutenberg University Mainz (JGU) in Germany have now come up with a new theory on how dark matter may have been formed shortly after the origin of the universe. This new model proposes an alternative to the WIMP paradigm that is the subject of various experiments in current research.

Dark matter is present throughout the universe, forming galaxies and the largest known structures in the cosmos. It makes up around 23 percent of our universe, whereas the particles visible to us that make up the stars, planets, and even life on Earth represent only about four percent of it. The current assumption is that dark matter is a cosmological relic that has essentially remained stable since its creation. "We have called this assumption into question, showing that at the beginning of the universe dark matter may have been unstable," explained Dr. Michael Baker from the Theoretical High Energy Physics (THEP) group at the JGU Institute of Physics. This instability also indicates the existence of a new mechanism that explains the observed quantity of dark matter in the cosmos.

The stability of dark matter is usually explained by a symmetry principle. However, in their paper, Dr. Michael Baker and Prof. Joachim Kopp demonstrate that the universe may have gone through a phase during which this symmetry was broken. This would mean that it is possible for the hypothetical dark matter particle to decay. During the electroweak phase transition, the symmetry that stabilizes dark matter would have been re-established, enabling it to continue to exist in the universe to the present day.

With their new theory, Baker and Kopp have introduced a new principle into the debate about the nature of dark matter that offers an alternative to the widely accepted WIMP theory. Up to now, WIMPs, or weakly interacting massive particles, have been regarded as the most likely components of dark matter, and experiments involving heavily shielded underground detectors have been carried out to look for them. "The absence of any convincing signals caused us to start looking for alternatives to the WIMP paradigm," said Kopp.

The two physicists claim that the new mechanism they propose may be connected with the apparent imbalance between matter and antimatter in the cosmos and could leave an imprint which would be detected in future experiments on gravitational waves. In their paper published in the scientific journal Physical Review Letters, Baker and Kopp also indicate the prospects of finding proof of their new principle at CERN's LHC particle accelerator and other experimental facilities. [19]

Dark Energy Survey reveals most accurate measurement of dark matter structure in the universe

Imagine planting a single seed and, with great precision, being able to predict the exact height of the tree that grows from it. Now imagine traveling to the future and snapping photographic proof that you were right.

If you think of the seed as the early universe, and the tree as the universe the way it looks now, you have an idea of what the Dark Energy Survey (DES) collaboration has just done. In a presentation today at the American Physical Society Division of Particles and Fields meeting at the U.S. Department of Energy's (DOE) Fermi National Accelerator Laboratory, DES scientists will unveil the most accurate measurement ever made of the present large-scale structure of the universe.

These measurements of the amount and "clumpiness" (or distribution) of dark matter in the present-day cosmos were made with a precision that, for the first time, rivals that of inferences from the early universe by the European Space Agency's orbiting Planck observatory. The new DES result (the tree, in the above metaphor) is close to "forecasts" made from the Planck measurements of the distant past (the seed), allowing scientists to understand more about the ways the universe has evolved over 14 billion years.

"This result is beyond exciting," said Scott Dodelson of Fermilab, one of the lead scientists on this result. "For the first time, we're able to see the current structure of the universe with the same clarity that we can see its infancy, and we can follow the threads from one to the other, confirming many predictions along the way."

Most notably, this result supports the theory that 26 percent of the universe is in the form of mysterious dark matter and that space is filled with an also-unseen dark energy, which is causing the accelerating expansion of the universe and makes up 70 percent.

Paradoxically, it is easier to measure the large-scale clumpiness of the universe in the distant past than it is to measure it today. In the first 400,000 years following the Big Bang, the universe was filled with a glowing gas, the light from which survives to this day. Planck's map of this cosmic microwave background radiation gives us a snapshot of the universe at that very early time. Since then, the gravity of dark matter has pulled mass together and made the universe clumpier over time. But dark energy has been fighting back, pushing matter apart. Using the Planck map as a start, cosmologists can calculate precisely how this battle plays out over 14 billion years.

"The DES measurements, when compared with the Planck map, support the simplest version of the dark matter/dark energy theory," said Joe Zuntz, of the University of Edinburgh, who worked on the analysis. "The moment we realized that our measurement matched the Planck result within 7 percent was thrilling for the entire collaboration."

The primary instrument for DES is the 570-megapixel Dark Energy Camera, one of the most powerful in existence, able to capture digital images of light from galaxies eight billion light-years from Earth. The camera was built and tested at Fermilab, the lead laboratory on the Dark Energy Survey, and is mounted on the National Science Foundation's 4-meter Blanco telescope, part of the Cerro Tololo Inter-American Observatory in Chile, a division of the National Optical Astronomy Observatory. The DES data are processed at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign.

Scientists on DES are using the camera to map an eighth of the sky in unprecedented detail over five years. The fifth year of observation will begin in August. The new results released today draw from data collected only during the survey's first year, which covers 1/30th of the sky.

"It is amazing that the team has managed to achieve such precision from only the first year of their survey," said National Science Foundation Program Director Nigel Sharp. "Now that their analysis techniques are developed and tested, we look forward with eager anticipation to breakthrough results as the survey continues."

DES scientists used two methods to measure dark matter. First, they created maps of galaxy positions as tracers, and second, they precisely measured the shapes of 26 million galaxies to directly map the patterns of dark matter over billions of light-years, using a technique called gravitational lensing.

To make these ultraprecise measurements, the DES team developed new ways to detect the tiny lensing distortions of galaxy images, an effect not even visible to the eye, enabling revolutionary advances in understanding these cosmic signals. In the process, they created the largest guide to spotting dark matter in the cosmos ever drawn (see image). The new dark matter map is 10 times the size of the one DES released in 2015 and will eventually be three times larger than it is now.

"It's an enormous team effort and the culmination of years of focused work," said Erin Sheldon, a physicist at the DOE's Brookhaven National Laboratory, who co-developed the new method for detecting lensing distortions.

These results and others from the first year of the Dark Energy Survey will be released today online and announced during a talk by Daniel Gruen, NASA Einstein fellow at the Kavli Institute for Particle Astrophysics and Cosmology at DOE's SLAC National Accelerator Laboratory, at 5 p.m. Central time. The talk is part of the APS Division of Particles and Fields meeting at Fermilab and will be streamed live.

The results will also be presented by Kavli fellow Elisabeth Krause of the Kavli Insitute for Particle Astrophysics and Cosmology at SLAC at the TeV Particle Astrophysics Conference in Columbus, Ohio, on Aug. 9; and by Michael Troxel, postdoctoral fellow at the Center for Cosmology and AstroParticle Physics at Ohio State University, at the International Symposium on Lepton Photon Interactions at High Energies in Guanzhou, China, on Aug. 10. All three of these speakers are coordinators of DES science working groups and made key contributions to the analysis.

"The Dark Energy Survey has already delivered some remarkable discoveries and measurements, and they have barely scratched the surface of their data," said Fermilab Director Nigel Lockyer. "Today's world-leading results point forward to the great strides DES will make toward understanding dark energy in the coming years." [18]

Mapping dark matter

About eighty-five percent of the matter in the universe is in the form of dark matter, whose nature remains a mystery. The rest of the matter in the universe is of the kind found in atoms. Astronomers studying the evolution of galaxies in the universe find that dark matter exhibits gravity and, because it is so abundant, it dominates the formation of large-scale structures in the universe like clusters of galaxies. Dark matter is hard to observe directly, needless to say, and it shows no evidence of interacting with itself or other matter other than via gravity, but fortunately it can be traced by modeling sensitive observations of the distributions of galaxies across a range of scales.

Galaxies generally reside at the centers of vast clumps of dark matter called haloes because they surround the clusters of galaxies. Gravitational lensing of more distant galaxies by dark matter haloes offers a particularly unique and powerful probe of the detailed distribution of dark matter. So-called strong gravitational lensing creates highly distorted, magnified and occasionally multiple images of a single source; so-called weak lensing results in modestly yet systematically deformed shapes of background galaxies that can also provide robust constraints on the distribution of dark matter within the clusters.

CfA astronomers Annalisa Pillepich and Lars Hernquist and their colleagues compared gravitationally distorted Hubble images of the galaxy cluster Abell 2744 and two other clusters with the results of computer simulations of dark matter haloes. They found, in agreement with key predictions in the conventional dark matter picture, that the detailed galaxy substructures depend on the dark matter halo distribution, and that the total mass and the light trace each other. They also found a few discrepancies: the radial distribution of the dark matter is different from that predicted by the simulations, and the effects of tidal stripping and friction in galaxies are smaller than expected, but they suggest these issues might be resolved with more precise simulations. Overall, however, the standard model of dark matter does an excellent and reassuring job of describing galaxy clustering. [17]

Dark matter is likely 'cold,' not 'fuzzy,' scientists report after new simulations

Dark matter is the aptly named unseen material that makes up the bulk of matter in our universe. But what dark matter is made of is a matter of debate.

Scientists have never directly detected dark matter. But over decades, they have proposed a variety of theories about what type of material—from new particles to primordial black holes—could comprise dark matter and explain its many effects on normal matter. In a paper published July 20 in the journal Physical Review Letters, an international team of cosmologists uses data from the intergalactic medium—the vast, largely empty space between galaxies—to narrow down what dark matter could be.

The team's findings cast doubt on a relatively new theory called "fuzzy dark matter," and instead lend credence to a different model called "cold dark matter." Their results could inform ongoing efforts to detect dark matter directly, especially if researchers have a clear idea of what sorts of properties they should be seeking.

"For decades, theoretical physicists have tried to understand the properties of the particles and forces that must make up dark matter," said lead author Vid Iršic, a postdoctoral researcher in the Department of Astronomy at the University of Washington. "What we have done is place constraints on what dark matter could be—and 'fuzzy dark matter,' if it were to make up all of dark matter, is not consistent with our data."

Scientists had drawn up both the "fuzzy" and "cold" dark-matter theories to explain the effects that dark matter appears to have on galaxies and the intergalactic medium between them.

Cold dark matter is the older of these two theories, dating back to the 1980s, and is currently the standard model for dark matter. It posits that dark matter is made up of a relatively massive, slowmoving type of particle with "weakly interacting" properties. It helps explain the unique, large-scale structure of the universe, such as why galaxies tend to cluster in larger groups.

But the cold dark matter theory also has some drawbacks and inconsistencies. For example, it predicts that our own Milky Way Galaxy should have hundreds of satellite galaxies nearby. Instead, we have only a few dozen small, close neighbors.

The newer fuzzy dark matter theory addressed the deficiencies of the cold dark matter model. According to this theory, dark matter consists of an ultralight particle, rather than a heavy one, and also has a unique feature related to quantum mechanics. For many of the fundamental particles in our universe, their large-scale movements—traveling distances of meters, miles and beyond—can be explained using the principles of "classic" Newtonian physics. Explaining small-scale movements, such as at the subatomic level, requires the complex and often contradictory principles of quantum mechanics. But for the ultralight particle predicted in the fuzzy dark matter theory, movements at incredibly large scales—such as from one end of a galaxy to the other—also require quantum mechanics.

With these two theories of dark matter in mind, Iršic and his colleagues set out to model the hypothetical properties of dark matter based on relatively new observations of the intergalactic medium, or IGM. The IGM consists largely of dark matter—whatever that may be—along with hydrogen gas and a small amount of helium. The hydrogen within IGM absorbs light emitted from distant, bright objects, and astronomers have studied this absorption for decades using Earth-based instruments.

The team looked at how the IGM interacted with light emitted by quasars, which are distant, massive, starlike objects. One set of data came from a survey of 100 quasars by the European Southern Observatory in Chile. The team also included observations of 25 quasars by the Las Campanas Observatory in Chile and the W.M. Keck Observatory in Hawaii.

Using a supercomputer at the University of Cambridge, Iršic and co-authors simulated the IGM—and calculated what type of dark matter particle would be consistent with the quasar data. They discovered that a typical particle predicted by the fuzzy dark matter theory is simply too light to account for the hydrogen absorption patterns in the IGM. A heavier particle—similar to predictions of the traditional cold dark matter theory—is more consistent with their simulations.

"The mass of this particle has to be larger than what people had originally expected, based on the fuzzy dark matter solutions for issues surrounding our galaxy and others," said Iršic.

An ultralight "fuzzy" particle could still exist. But it cannot explain why galactic clusters form, or other questions like the paucity of satellite galaxies around the Milky Way, said Iršic. A heavier "cold" particle remains consistent with the astronomical observations and simulations of the IGM, he added.

The team's results do not address all of the longstanding drawbacks of the cold dark matter model. But Iršic believes that further mining of data from the IGM can help resolve the type—or types—of particles that make up dark matter. In addition, some scientists believe that there are no problems with the cold dark matter theory. Instead, scientists may simply not understand the complex forces at work in the IGM, Iršic added.

"Either way, the IGM remains a rich ground for understanding dark matter," said Iršic.

Co-authors on the paper are Matteo Viel of the International School for Advanced Studies in Italy, the Astronomical Observatory of Trieste and the National Institute for Nuclear Physics in Italy; Martin Haehnelt of the University of Cambridge; James Bolton of the University of Nottingham; and George Becker of the University of California, Riverside. The work was funded by the National Science Foundation, the National Institute for Nuclear Physics in Italy, the European Research Council, the National Institute for Astrophysics in Italy, the Royal Society in the United Kingdom and the Kavli Foundation. [16]

This New Explanation For Dark Matter Could Be The Best One Yet

It makes up about 85 percent of the total mass of the Universe, and yet, physicists still have no idea what dark matter actually is.

But a new hypothesis might have gotten us closer to figuring out its identity, because physicists now suspect that dark matter has been changing forms this whole time - from ghostly particles in the Universe's biggest structures, to a strange, superfluid state at smaller scales. And we might soon have the tools to confirm it.

Dark matter is a hypothetical substance that was proposed almost a century ago to account for the clear imbalance between the amount of matter in the Universe, and the amount of gravity that holds our galaxies together.

We can't directly detect dark matter, but we can see its effects on everything around us - the way galaxies rotate and the way light bends as it travels through the Universe suggests there's far more at play than we're able to pick up.

And now two physicists propose that dark matter has been changing the rules this whole time, and that could explain why it's been so elusive.

"It's a neat idea," particle physicist Tim Tait from the University of California, Irvine, who wasn't involved in the study, told Quanta Magazine.

"You get to have two different kinds of dark matter described by one thing."

The traditional view of dark matter is that it's made up of weakly interacting particles such as axions, which are influenced by the force of gravity in ways that we can observe at large scales.

This 'cold' form of dark matter can be used to predict how massive clusters of galaxies will behave, and fits into what we know about the 'cosmic web' of the Universe - scientists suggest that all galaxies are connected within a vast intergalactic web made up of invisible filaments of dark matter.

But when we scale down to individual galaxies and the way their stars rotate in relation to the galactic centre, something just doesn't add up.

"Most of the mass [in the Universe], which is dark matter, is segregated from where most of the ordinary matter lies," University of Pennsylvania physicist Justin Khoury explains in a press statement.

"On a cosmic web scale, this does well in fitting with the observations. On a galaxy cluster scale, it also does pretty well. However, when on the scale of galaxies, it does not fit."

Khoury and his colleague Lasha Berezhiani, now at Princeton University, suggest that the reason we can't reconcile dark matter's behaviour on both large and small scales in the Universe is because it can shift forms.

We've got the 'cold' dark matter particles for the massive galaxy clusters, but on a singular galactic scale, they suggest that dark matter takes on a superfluid state.

Superfluids are a form of cold, densely packed matter that has zero friction and viscosity, and can sometimes become a Bose-Einstein condensate, referred to as the 'fifth state of matter'.

And as strange as they sound, superfluids are starting to appear more accessible than ever before, with researchers announcing just last week that they were able to create light that acts like a liquid - a form of superfluid - at room temperature for the first time.

The more we come to understand superfluids, the more physicists are willing to entertain the idea that they could be far more common in the Universe than we thought.

"Recently, more physicists have warmed to the possibility of superfluid phases forming naturally in the extreme conditions of space," Jennifer Ouellette explains for Quanta Magazine.

"Superfluids may exist inside neutron stars, and some researchers have speculated that space-time itself may be a superfluid. So why shouldn't dark matter have a superfluid phase, too?"

The idea is that the 'halos' of dark matter that exist around individual galaxies create the conditions necessary to form a superfluid - the gravitational pull of the galaxy ensures that it's densely packed, and the coldness of space keeps the temperature suitably low.

Zoom out to a larger scale, and this gravitational pull becomes too weak to form a superfluid.

The key here is that the existence of superfluid dark matter could explain the strange behaviours of individual galaxies that gravity alone can't explain - it could be creating a second, as-yet-undefined force that acts just like gravity within the dark matter halos surrounding them.

As Ouellette explains, when you disturb an electric field, you get radio waves, and when you disturb a gravitational field, you get gravitational waves. When you disturb a superfluid? You get phonons (sound waves), and this extra force could work in addition to gravity.

"It's nice because you have an additional force on top of gravity, but it really is intrinsically linked to dark matter," Khoury told her. "It's a property of the dark matter medium that gives rise to this force."

We should be clear that this hypothesis is yet to be peer-reviewed, so this is all squarely in the realm of the hypothetical for now. But it's been published on the pre-print website arXiv.org for researchers in the field to pick over.

A big thing it has going for it is the fact that it could also explain 'modified Newtonian dynamics' (MOND) - a theory that says a modification of Newton's laws is needed to account for specific properties that have been observed within galaxies.

"In galaxies, there is superfluid movement of dark matter and MOND applies. However, in galaxy clusters, there is no superfluid movement of dark matter and MOND does not apply," the team suggests in a press statement.

We'll have to wait and see where this hypothesis goes, but the Khoury and Berezhiani say they're close to coming up with actual, testable ways that we can confirm their predictions based on superfluid dark matter.

And if their predictions bear out - we might finally be onto something when it comes to this massive cosmic mystery.

The research is available online at arXiv.org. [15]

Dark Matter Recipe Calls for One Part Superfluid

For years, dark matter has been behaving badly. The term was first invoked nearly 80 years ago by the astronomer Fritz Zwicky, who realized that some unseen gravitational force was needed to stop individual galaxies from escaping giant galaxy clusters. Later, Vera Rubin and Kent Ford used unseen dark matter to explain why galaxies themselves don't fly apart.

Yet even though we use the term "dark matter" to describe these two situations, it's not clear that the same kind of stuff is at work. The simplest and most popular model holds that dark matter is made of weakly interacting particles that move about slowly under the force of gravity. This socalled "cold" dark matter accurately describes large-scale structures like galaxy clusters. However, it doesn't do a great job at predicting the rotation curves of individual galaxies. Dark matter seems to act differently at this scale.

In the latest effort to resolve this conundrum, two physicists have proposed that dark matter is capable of changing phases at different size scales. Justin Khoury, a physicist at the University of Pennsylvania, and his former postdoc Lasha Berezhiani, who is now at Princeton University, say that in the cold, dense environment of the galactic halo, dark matter condenses into a superfluid — an exotic quantum state of matter that has zero viscosity. If dark matter forms a superfluid at the galactic scale, it could give rise to a new force that would account for the observations that don't fit the cold dark matter model. Yet at the scale of galaxy clusters, the special conditions required for a superfluid state to form don't exist; here, dark matter behaves like conventional cold dark matter.

"It's a neat idea," said Tim Tait, a particle physicist at the University of California, Irvine. "You get to have two different kinds of dark matter described by one thing." And that neat idea may soon be testable. Although other physicists have toyed with similar ideas, Khoury and Berezhiani are nearing the point where they can extract testable predictions that would allow astronomers to explore whether our galaxy is swimming in a superfluid sea.

Impossible Superfluids

Here on Earth, superfluids aren't exactly commonplace. But physicists have been cooking them up in their labs since 1938. Cool down particles to sufficiently low temperatures and their quantum nature will start to emerge. Their matter waves will spread out and overlap with one other, eventually coordinating themselves to behave as if they were one big “superatom.” They will become coherent, much like the light particles in a laser all have the same energy and vibrate as one. These days even undergraduates create so-called Bose-Einstein condensates (BECs) in the lab, many of which can be classified as superfluids.

Superfluids don’t exist in the everyday world — it’s too warm for the necessary quantum effects to hold sway. Because of that, “probably ten years ago, people would have balked at this idea and just said ‘this is impossible,’” said Tait. But recently, more physicists have warmed to the possibility of superfluid phases forming naturally in the extreme conditions of space. Superfluids may exist inside neutron stars, and some researchers have speculated that space-time itself may be a superfluid. So why shouldn’t dark matter have a superfluid phase, too?

To make a superfluid out of a collection of particles, you need to do two things: Pack the particles together at very high densities and cool them down to extremely low temperatures. In the lab, physicists (or undergraduates) confine the particles in an electromagnetic trap, then zap them with lasers to remove the kinetic energy and lower the temperature to just above absolute zero. [14]

XENON1T, the most sensitive detector on Earth searching for WIMP dark matter, releases its first result

"The best result on dark matter so far—and we just got started." This is how scientists behind XENON1T, now the most sensitive dark matter experiment world-wide, commented on their first result from a short 30-day run presented today to the scientific community.

Dark matter is one of the basic constituents of the universe, five times more abundant than ordinary matter. Several astronomical measurements have corroborated the existence of dark matter, leading to a world-wide effort to observe dark matter particle interactions with ordinary matter in extremely sensitive detectors, which would confirm its existence and shed light on its properties. However, these interactions are so feeble that they have escaped direct detection up to this point, forcing scientists to build detectors that are increasingly sensitive. The XENON Collaboration, that with the XENON100 detector led the field for years in the past, is now back on the frontline with the XENON1T experiment. The result from a first short 30-day run shows that this detector has a new record low radioactivity level, many orders of magnitude below surrounding materials on Earth. With a total mass of about 3200kg, XENON1T is the largest detector of this type ever built. The combination of significantly increased size with much lower background implies excellent dark matter discovery potential in the years to come.

The XENON Collaboration consists of 135 researchers from the U.S., Germany, Italy, Switzerland, Portugal, France, the Netherlands, Israel, Sweden and the United Arab Emirates. The latest detector of the XENON family has been in science operation at the LNGS underground laboratory since autumn 2016. The only things you see when visiting the underground experimental site now are a gigantic cylindrical metal tank filled with ultra-pure water to shield the detector at his center, and a three-story-tall, transparent building crowded with equipment to keep the detector running.

The XENON1T central detector, a so-called liquid xenon time projection chamber (LXeTPC), is not visible. It sits within a cryostat in the middle of the water tank, fully submersed in order to shield it as much as possible from natural radioactivity in the cavern. The cryostat keeps the xenon at a temperature of -95°C without freezing the surrounding water. The mountain above the laboratory further shields the detector, preventing perturbations by cosmic rays. But shielding from the outer world is not enough since all materials on Earth contain tiny traces of natural radioactivity. Thus, extreme care was taken to find, select and process the materials of the detector to achieve the lowest possible radioactive content. Laura Baudis, professor at the University of Zürich and professor Manfred Lindner from the Max-Planck-Institute for Nuclear Physics in Heidelberg, emphasize that this allowed XENON1T to achieve record "silence," which is necessary to listen for the very weak voice of dark matter.

A particle interaction in liquid xenon leads to tiny flashes of light. This is what the XENON scientists are recording and studying to infer the position and the energy of the interacting particle, and whether or not it might be dark matter. The spatial information allows the researchers to select interactions occurring in the one-ton central core of the detector.

XENON1T, the most sensitive detector on Earth searching for WIMP dark matter, releases its first result

The surrounding xenon further shields the core xenon target from all materials that already have tiny surviving radioactive contaminants. Despite the shortness of the 30-day science run, the sensitivity of XENON1T has already overcome that of any other experiment in the field, probing unexplored dark matter territory. "WIMPs did not show up in this first search with XENON1T, but we also did not expect them so soon," says Elena Aprile, Professor at Columbia University and spokesperson for the project. "The best news is that the experiment continues to accumulate excellent data, which will allow us to test quite soon the WIMP hypothesis in a region of mass and cross-section with normal atoms as never before. A new phase in the race to detect dark matter with ultra-low background massive detectors on Earth has just began with XENON1T. We are proud to be at the forefront of the race with this amazing detector, the first of its kind." [13]

Out with the WIMPs, in with the SIMPs?

Like cops tracking the wrong person, physicists seeking to identify dark matter—the mysterious stuff whose gravity appears to bind the galaxies—may have been stalking the wrong particle. In fact, a particle with some properties opposite to those of physicists' current favorite dark matter candidate—the weakly interacting massive particle, or WIMP—would do just as good a job at explaining the stuff, a quartet of theorists says. Hypothetical strongly interacting massive particles— or SIMPs—would also better account for some astrophysical observations, they argue.

SIMPs can also provide just the right amount of dark matter, assuming the theorists add a couple of wrinkles. The SIMPs must disappear primarily through collisions in which three SIMPs go in and only two SIMPs come out. These events must be more common than ones in which two SIMPs annihilate each other to produce two ordinary particles. Moreover, the theorists argue, SIMPs must interact with ordinary matter, although much more weakly than WIMPs. That's because the three-to-two collisions would heat up the SIMPs if they could not interact and share heat with ordinary matter.

Moreover, the fact that SIMPs must interact with ordinary matter guarantees that, in principle, they should be detectable in some way, Hochberg says. Whereas physicists are now searching for signs of WIMPs colliding with massive atomic nuclei, researchers would probably have to look for SIMPs smacking into lighter electrons because the bantamweight particles would not pack enough punch to send a nucleus flying.

Compared with WIMPy dark matter, SIMPy dark matter would also have another desirable property. As the universe evolved, dark matter coalesced into clumps, or halos, in which the galaxies then formed. But computer simulations suggest that dark matter that doesn't interact with itself would form myriad little clumps that are very dense in the center. And little "dwarf galaxies" aren't as abundant and the centers of galaxies aren't as dense as the simulations suggest. But strongly interacting dark matter would smooth out the distribution of dark matter and solve those problems, Hochberg says. "This isn't some independent thing that we've just forced into the model," she says. "It just naturally happens."

The new analysis "has the flavor of the WIMP miracle, which is nice," says Jonathan Feng, a theorist at UC Irvine who was not involved in the work. Feng says he's been working on similar ideas and that the ability to reconcile the differences between dark matter simulations and the observed properties of galaxies makes strongly interacting dark matter attractive conceptually.

However, he cautions, it may be possible that, feeble as they may be, the interactions between dark and ordinary matter might smooth out the dark matter distribution on their own. And Feng says he has some doubts about the claim that SIMPs must interact with ordinary matter strongly enough to be detected. So the SIMP probably won't knock WIMP off its perch as the best guess for the dark matter particle just yet, Feng says: "At the moment, it's not as well motivated as the WIMP, but it's definitely worth exploring." [12]

Dark matter composition research - WIMP

The WIMP (Weakly interactive massive particles) form a class of heavy particles, interacting slightly with matter, and constitute excellent candidates with the nonbaryonic dark matter. The neutralino postulated by the supersymetric extensions of the standard model of particle physics. The idea of supersymmetry is to associate each boson to a fermion and vice versa. Each particle is then given a super-partner, having identical properties (mass, load), but with a spin which differes by 1/2. Thus, the number of particles is doubled. For example, the photon is accompanied by a photino, the graviton by a gravitino, the electron of a selectron, etc. Following the impossibility to detect a 511 keV boson (the electron partner), the physicists had to re-examine the idea of an exact symmetry. Symmetry is 'broken' and superpartners have a very important mass. One of these superparticules called LSP (Lightest Supersymmetric Particle) is the lightest of all. In most of the supersymmetric theories (without violation of the R-parity) the LSP is a stable particle because it cannot disintegrate in a lighter element. It is of neutral color and electric charge and is then only sensitive to weak interaction (weak nuclear force). It is then an excellent candidate for the not-baryonic dark matter. [11]

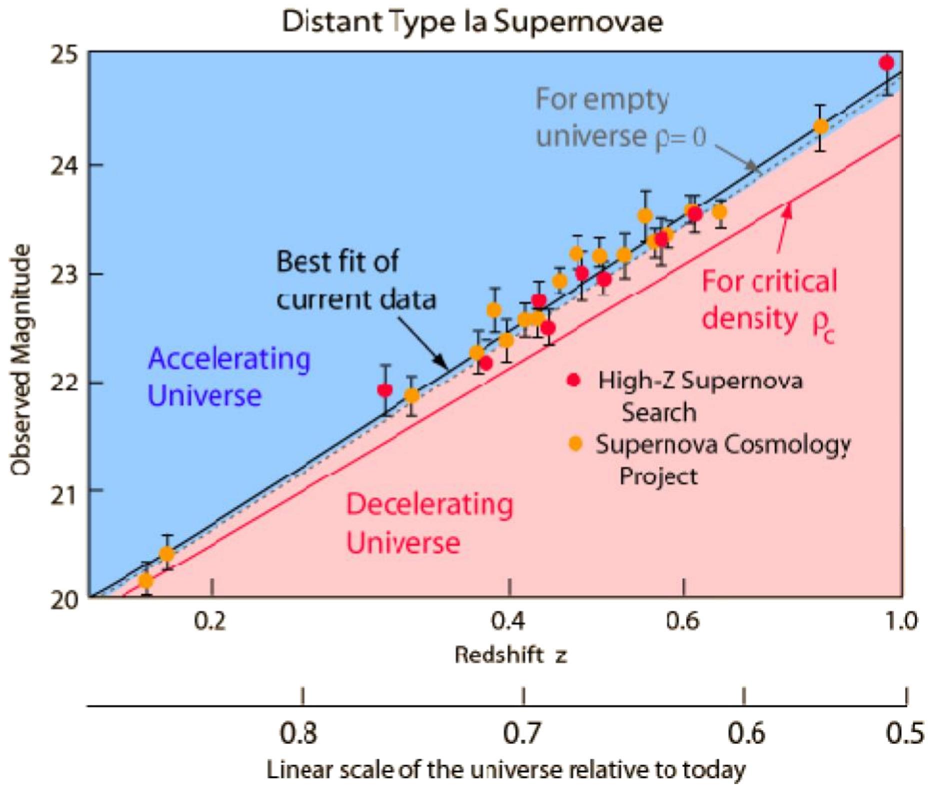
Weakly interacting massive particles

In particle physics and astrophysics, weakly interacting massive particles, or WIMPs, are among the leading hypothetical particle physics candidates for dark matter. The term “WIMP” is given to a dark matter particle that was produced by falling out of thermal equilibrium with the hot dense plasma of the early universe, although it is often used to refer to any dark matter candidate that interacts with standard particles via a force similar in strength to the weak nuclear force. Its name comes from the fact that obtaining the correct abundance of dark matter today via thermal production requires a self-annihilation cross section, which is roughly what is expected for a new particle in the 100 GeV mass range that interacts via the electroweak force. This apparent coincidence is known as the “WIMP miracle”. Because supersymmetric extensions of the standard model of particle physics readily predict a new particle with these properties, a stable supersymmetric partner has long been a prime WIMP candidate. However, recent null results from direct detection experiments including LUX and SuperCDMS, along with the failure to produce evidence of supersymmetry in the Large Hadron Collider (LHC) experiment has cast doubt on the simplest WIMP hypothesis. Experimental efforts to detect WIMPs include the search for products of WIMP annihilation, including gamma rays, neutrinos and cosmic rays in nearby galaxies and galaxy clusters; direct detection experiments designed to measure the collision of WIMPs with nuclei in the laboratory, as well as attempts to directly produce WIMPs in colliders such as the LHC. [10]

Evidence for an accelerating universe

One of the observational foundations for the big bang model of cosmology was the observed expansion of the universe. [9] Measurement of the expansion rate is a critical part of the study, and it has been found that the expansion rate is very nearly "flat". That is, the universe is very close to the critical density, above which it would slow down and collapse inward toward a future "big crunch". One of the great challenges of astronomy and astrophysics is distance measurement over the vast distances of the universe. Since the 1990s it has become apparent that type Ia supernovae offer a unique opportunity for the consistent measurement of distance out to perhaps 1000 Mpc. Measurement at these great distances provided the first data to suggest that the expansion rate of the universe is actually accelerating. That acceleration implies an energy density that acts in opposition to gravity which would cause the expansion to accelerate. This is an energy density which we have not directly detected observationally and it has been given the name "dark energy".

The type Ia supernova evidence for an accelerated universe has been discussed by Perlmutter and the diagram below follows his illustration in Physics Today.



The data summarized in the illustration above involve the measurement of the redshifts of the distant supernovae. The observed magnitudes are plotted against the redshift parameter z. Note

that there are a number of Type 1a supernovae around z=.6, which with a Hubble constant of 71 km/s/mpc is a distance of about 5 billion light years.

Equation

The cosmological constant Λ appears in Einstein's field equation [5] in the form of

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda\,g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}\,,$$

where *R* and *g* describe the structure of spacetime, *T* pertains to matter and energy affecting that structure, and *G* and *c* are conversion factors that arise from using traditional units of measurement. When Λ is zero, this reduces to the original field equation of general relativity. When *T* is zero, the field equation describes empty space (the vacuum).

The cosmological constant has the same effect as an intrinsic energy density of the vacuum, ρ_{vac} (and an associated pressure). In this context it is commonly moved onto the right-hand side of the equation, and defined with a proportionality factor of 8π: $\Lambda = 8\pi\rho_{vac}$, where unit conventions of general relativity are used (otherwise factors of *G* and *c* would also appear). It is common to quote values of energy density directly, though still using the name "cosmological constant".

A positive vacuum energy density resulting from a cosmological constant implies a negative pressure, and vice versa. If the energy density is positive, the associated negative pressure will drive an accelerated expansion of the universe, as observed. (See dark energy and cosmic inflation for details.)

Explanatory models

Models attempting to explain accelerating expansion include some form of dark energy, dark fluid or phantom energy. The most important property of dark energy is that it has negative pressure which is distributed relatively homogeneously in space. The simplest explanation for dark energy is that it is a cosmological constant or vacuum energy; this leads to the Lambda-CDM model, which is generally known as the Standard Model of Cosmology as of 2003-2013, since it is the simplest model in good agreement with a variety of recent observations.

Dark Matter and Energy

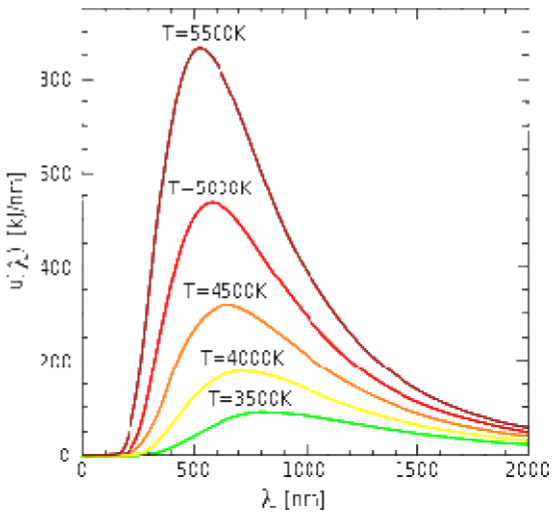
Dark matter is a type of matter hypothesized in astronomy and cosmology to account for a large part of the mass that appears to be missing from the universe. Dark matter cannot be seen directly with telescopes; evidently it neither emits nor absorbs light or other electromagnetic radiation at any significant level. It is otherwise hypothesized to simply be matter that is not reactant to light. Instead, the existence and properties of dark matter are inferred from its gravitational effects on visible matter, radiation, and the large-scale structure of the universe. According to the Planck mission team, and based on the standard model of cosmology, the total mass–energy of the known universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy. Thus, dark matter is estimated to constitute 84.5% of the total matter in the universe, while dark energy plus dark matter constitute 95.1% of the total content of the universe. [6]

Cosmic microwave background

The cosmic microwave background (CMB) is the thermal radiation assumed to be left over from the "Big Bang" of cosmology. When the universe cooled enough, protons and electrons combined to form neutral atoms. These atoms could no longer absorb the thermal radiation, and so the universe became transparent instead of being an opaque fog. [7]

Thermal radiation

Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. All matter with a temperature greater than absolute zero emits thermal radiation. When the temperature of the body is greater than absolute zero, interatomic collisions cause the kinetic energy of the atoms or molecules to change. This results in charge-acceleration and/or dipole oscillation which produces electromagnetic radiation, and the wide spectrum of radiation reflects the wide spectrum of energies and accelerations that occur even at a single temperature. [8]



Electromagnetic Field and Quantum Theory

Needless to say that the accelerating electrons of the steady stationary current are a simple demystification of the magnetic field, by creating a decreasing charge distribution along the wire, maintaining the decreasing U potential and creating the **A** vector potential experienced by the electrons moving by **v** velocity relative to the wire. This way it is easier to understand also the time dependent changes of the electric current and the electromagnetic waves as the resulting fields moving by c velocity.

It could be possible something very important law of the nature behind the self maintaining **E** accelerating force by the accelerated electrons. The accelerated electrons created electromagnetic fields are so natural that they occur as electromagnetic waves traveling with velocity c. It shows that the electric charges are the result of the electromagnetic waves diffraction.

One of the most important conclusions is that the electric charges are moving in an accelerated way and even if their velocity is constant, they have an intrinsic acceleration anyway, the so called spin, since they need at least an intrinsic acceleration to make possible they movement .

The bridge between the classical and quantum theory is based on this intrinsic acceleration of the spin, explaining also the Heisenberg Uncertainty Principle. The particle – wave duality of the electric charges and the photon makes certain that they are both sides of the same thing. Basing the

gravitational force on the accelerating Universe caused magnetic force and the Planck Distribution Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions. [4]

Lorentz transformation of the Special Relativity

In the referential frame of the accelerating electrons the charge density lowering linearly because of the linearly growing way they takes every next time period. From the referential frame of the wire there is a parabolic charge density lowering.

The difference between these two referential frames, namely the referential frame of the wire and the referential frame of the moving electrons gives the relativistic effect. Important to say that the moving electrons presenting the time coordinate, since the electrons are taking linearly increasing way every next time period, and the wire presenting the geometric coordinate. The Lorentz transformations are based on moving light sources of the Michelson - Morley experiment giving a practical method to transform time and geometric coordinates without explaining the source of this mystery.

The real mystery is that the accelerating charges are maintaining the accelerating force with their charge distribution locally. The resolution of this mystery that the charges are simply the results of the diffraction patterns, that is the charges and the electric field are two sides of the same thing. Otherwise the charges could exceed the velocity of the electromagnetic field.

The increasing mass of the electric charges the result of the increasing inductive electric force acting against the accelerating force. The decreasing mass of the decreasing acceleration is the result of the inductive electric force acting against the decreasing force. This is the relativistic mass change explanation, especially importantly explaining the mass reduction in case of velocity decrease.

The Classical Relativistic effect

The moving charges are self maintain the electromagnetic field locally, causing their movement and this is the result of their acceleration under the force of this field.
In the classical physics the charges will distributed along the electric current so that the electric potential lowering along the current, by linearly increasing the way they take every next time period because this accelerated motion.

Electromagnetic inertia and Gravitational attraction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass.

It looks clear that the growing acceleration results the relativistic growing mass - limited also with the velocity of the electromagnetic wave.

Since $E = hv$ and $E = mc^2$, $m = hv /c^2$ that is the m depends only on the v frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the m_o inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

If the mass is electromagnetic, then the gravitation is also electromagnetic effect caused by the accelerating Universe! The same charges would attract each other if they are moving parallel by the magnetic effect.

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force.

Electromagnetic inertia and mass

Electromagnetic Induction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass. [1]

Relativistic change of mass

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The frequency dependence of mass

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Electron – Proton mass rate

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force. [1]

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

Gravity from the point of view of quantum physics

The Gravitational force

The gravitational attractive force is basically a magnetic force.

The same electric charges can attract one another by the magnetic force if they are moving parallel in the same direction. Since the electrically neutral matter is composed of negative and positive charges they need 2 photons to mediate this attractive force, one per charges. The Bing Bang caused parallel moving of the matter gives this magnetic force, experienced as gravitational force.

Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

You can think about photons as virtual electron – positron pairs, obtaining the necessary virtual mass for gravity.

The mass as seen before a result of the diffraction, for example the proton – electron mass rate Mp=1840 Me. In order to move one of these diffraction maximum (electron or proton) we need to intervene into the diffraction pattern with a force appropriate to the intensity of this diffraction maximum, means its intensity or mass.

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The Graviton

In physics, the graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. If it exists, the graviton is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. The spin follows from the fact that the source of gravitation is the stress-energy tensor, a second-rank tensor (compared to electromagnetism's spin-1 photon, the source of which is the four-current, a first-rank tensor). Additionally, it can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress-energy tensor in the same way that the gravitational field does. This result suggests that, if a massless spin-2 particle is discovered, it must be the graviton, so that the only experimental verification needed for the graviton may simply be the discovery of a massless spin-2 particle. [2]

Conclusions

SIMPs would resolve certain discrepancies between simulations of the distribution of dark matter, like this one, and the observed properties of the galaxies.
In particle physics and astrophysics, weakly interacting massive particles, or WIMPs, are among the leading hypothetical particle physics candidates for dark matter.

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.
There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.
The electric currents causing self maintaining electric potential is the source of the special and general relativistic effects. The Higgs Field is the result of the electromagnetic induction. The Graviton is two photons together. [3]

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