Proton Radius Puzzle

Instead, it involves smashing electrons into protons at nearly the speed of light, then measuring how far the electrons travel when they bounce off, or scatter, from the protons. [47]

Ten years ago, just about any nuclear physicist could tell you the approximate size of the proton. But that changed in 2010, when atomic physicists unveiled a new method that promised a more precise measurement. [46]

"Spin has surprises. Everybody thought it's simple … and it turns out it's much more complicated," Aschenauer says. [45]

Approximately one year ago, a spectacular dive into Saturn ended NASA's Cassini mission—and with it a unique, 13-year research expedition to the Saturnian system. [44]

Scientists from the Niels Bohr Institute, University of Copenhagen, and their colleagues from the international ALICE collaboration recently collided xenon nuclei, in order to gain new insights into the properties of the Quark-Gluon Plasma (the QGP) – the matter that the universe consisted of up to a microsecond after the Big Bang. [43]

The energy transfer processes that occur in this collisionless space plasma are believed to be based on wave-particle interactions such as particle acceleration by plasma waves and spontaneous wave generation, which enable energy and momentum transfer. [42]

Plasma particle accelerators more powerful than existing machines could help probe some of the outstanding mysteries of our universe, as well as make leaps forward in cancer treatment and security scanning—all in a package that's around a thousandth of the size of current accelerators. [41]

The Department of Energy's SLAC National Accelerator Laboratory has started to assemble a new facility for revolutionary accelerator technologies that could make future accelerators 100 to 1,000 times smaller and boost their capabilities. [40]

The authors designed a mechanism based on the deployment of a transport barrier to confine the particles and prevent them from moving from one region of the accelerator to another.

"There is strong experimental evidence that there is indeed some new physics lurking in the lepton sector," Dev said. [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.

Contents

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.

Resolving the 'proton radius puzzle'

How do you measure the width of a proton?

A ruler won't help and neither will a microscope. Instead, it involves smashing electrons into protons at nearly the speed of light, then measuring how far the electrons travel when they bounce off, or scatter, from the protons.

This method is called electron scattering, and a new version was used at Jefferson Laboratory for the first time, providing one of the most precise measurements ever for the charge radius of a proton.

Physicists who spend their lives exploring the subatomic universe say these results bring science closer to solving the "proton radius puzzle"—or explaining why different experimental methods over the years have come up with two different measurements.

For a long time, the proton radius was measured at 0.88 femtometers (fm). Then in 2010 a different type of experiment came up with 0.84 fm, or about 4% smaller.

Why would a 4% difference on an infinitesimal scale matter?

For one, said Ashot Gasparian, a professor at North Carolina A&T State University and experiment team leader, the proton, which sits at the heart of the atom, lies at the intersection of three major branches of physics: atomic, nuclear and particle. So even a tiny difference is a big deal—some physicists even speculated the 2010 results might signal a fifth force of nature.

And, for another, more precise measurements of subatomic particles help hone the Standard Model of particle physics, a template that helps explain how the universe works.

So in 2012 Gasparian and his team worked to come up with a new type of electron scattering experiment—the first new method in half a century—to measure the proton radius. Called the PRad experiment, it was given high priority at Jefferson Lab and its powerful CEBAF accelerator.

"People were searching for answers," Gasparian said. "But to make another electron-proton scattering experiment, many skeptics didn't believe that we could do anything new."

Still, the team came up with three tools and methods.

The first was implementing a new type of windowless target system that essentially allowed scattered electrons to move fairly seamlessly into the detectors.

The second was using a calorimeter rather than a traditional magnetic spectrometer to detect and measure the energies and positions of the scattered electrons, while a newly built gas electron multiplier also detected the electrons' positions with ever-greater accuracy.

And the third was placing these detectors extremely close in angular distance from where the electron beam struck the hydrogen target.

"In electron scattering, in order to extract the radius, we have to go to as small a scattering angle as possible," said Dipangkar Dutta, team member and professor at Mississippi State University. "To get the proton radius, you need to extrapolate to zero angle, which you cannot access in an experiment. So the closer to zero you can get, the better."

The measurement the team came up with was 0.831 fm, essentially confirming the 2010 measurement. Their results dashed the hopes of physicists who had dreamed of a fifth force.

"The PRad experiment seems to shut the door on that possibility," said Dutta. "This is still to be confirmed with similar experiments, but right now it seems that way."

Their results were published recently in the journal *Nature*. The team is already working toward more experiments at Jefferson Lab to decrease the uncertainty in the proton radius even further, Gasparian said. Meanwhile, a few other nuclear physics facilities around the world are doing the same.

"If the precision is further improved," said Gasparian, "it might show that there is some small difference, and that will be very important for figuring out new physics. Also, this same technique can be applied not just for measuring the proton size, but also for other types of measurements where we would be able to look beyond Standard Model physics."

Where could such efforts lead one day out in the real world?

"That is very hard to predict," said Dutta. "Because whenever you do basic science nobody knows what the eventual application is going to be."

But there are significant precedents, he said. MRIs, or magnetic resonance imaging scanners, came from somebody trying the measure the spin of the proton in the molecular structure. Silicon transistors, which revolutionized electronics, sprang from somebody tinkering with pieces of silicon to figure out how they behave. And proton therapies to treat cancer came from somebody trying to measure how the proton deposits its energy as it passes through materials. [47]

Physicists team up to tackle proton radius problem

Ten years ago, just about any nuclear physicist could tell you the approximate size of the proton. But that changed in 2010, when atomic physicists unveiled a new method that promised a more precise measurement. The new quantity came up 4% shorter than expected, setting off a scramble within the nuclear and atomic physics communities to determine if this discrepant result was due to new physics or an indication of problems with the extractions of the quantity from experiments.

Now, four nuclear physicists, two experimentalists and two theorists, think that they've resolved the discrepancy using experimental nuclear physics data and an advanced physical model to obtain a new value for the size of the proton. The result was published in *Physical Review C* in April.

Taking A Yardstick to the Proton

One thing that all of the methods agree on is that the proton is tiny. The proton's charge radius, which measures the size of the distribution of electric charge in the nuclear particle, is a bit less than a femtometer, with a single femtometer registering at one-quadrillionth of a meter.

Stated another way, if you take a meter stick and split its length into one billion equal pieces, and then take just one of those pieces and split its length into another million pieces, the length of each one of those million pieces will be a femtometer.

Because it is so small, the charge radius of the proton can't be measured directly. Instead, nuclear and atomic physicists use sophisticated methods to determine the proton size.

"Basically, it's about the interaction of the proton with electromagnetic fields, that's part of what's called the electromagnetic structure of the proton, or the form factor of the proton," explained Christian Weiss, a staff scientist at the Department of Energy's Thomas Jefferson National Accelerator Facility in the Center for Theoretical and Computational Physics. "What you are measuring is the size of the spatial distribution of electric charge of the proton."

Two's Company, Three's a Crowd

About 30 years ago, nuclear and atomic physicists came up with two different methods to determine this electric charge radius.

Nuclear physicists conduct experiments via electron scattering, where electrons are hurled at protons, and the proton's charge radius is determined by the change in path of the electrons after they bounce off the proton.

"In some sense, the electron ever-so-gently scatters off that proton," Weiss said.

Atomic physicists also use electrons to measure the proton's radius. They observe, using spectroscopy, the energy levels of electrons as they orbit a small nucleus, such as hydrogen (with one proton) or deuterium (with a proton and a neutron).

Using these two different methods, a radius of about .88 femtometers was established as the world value.

Then, in 2010, an atomic physics research team made a shocking announcement. In a twist on the atomic physics method, the team measured the energy levels of electrons in orbit around lab-made hydrogen atoms that replaced an orbiting electron with a muon. While a muon is the same class of particle as the electron, it has 200 times the electron's mass and so orbits much closer to the proton. This proximity means that the proton's charge radius has a greater effect on its orbit.

The new, more precise method yielded a measurement of .84 femtometers, or about 4% smaller than the world value.

The new result set off a frenzy of activity around a value that most physicists thought had already been settled. Further electron-scattering experiments were planned, additional hydrogen and muonic hydrogen spectroscopy measurements were made, and atomic and nuclear theory were re-examined for clues.

Physicists Face Off

Here at Jefferson Lab, the new efforts galvanized a review of the experiments that were used to establish the world value and a review of nuclear theory for more precise ways to examine the data or predict the value from results. A team of four nuclear physicists came together to work on the science behind the Physical Review C publication.

They began by addressing one of the concerns that experimental nuclear physicists had about electron-scattering data: how the quantity for the proton radius was obtained from experimental data.

"There has been a challenge to extract the radius of the proton from these electron-scattering data, because the actual scattering experiments require some finite momentum transfer from the proton," Weiss explained. "The number that you're interested in is the response of the proton at zero momentum transfer, so that's something that's not directly accessible."

Instead, nuclear physicists analyze the data they get from experiments at the lowest momentum transfers and then use a procedure to extrapolate down to zero. There's an ongoing debate, however, about what momentum transfers are still relevant and how the extrapolation should be done.

Two members of the team are experimentalists: Douglas Higinbotham, a Jefferson Lab staff scientist, and Zhihong Ye, a senior research associate at Argonne National Lab. They resolved the experimental side of the challenge by considering the pre-analysis world data over a wide range of momentum transfers.

Instead of extrapolating from the data to get a value, they instead plotted the data over the full range of measured momentum transfers while taking into account that the proton's charge radius could be any one of many possible values.

"We just fixed the radius in our fits and repeated the analysis many, many times, for every reasonable value of the radius," said Higinbotham. "And then went to theorists and asked them to generate the theoretical curves for those radii, so that we can compare and see if there is agreement."

The other two members of the four-person team are theorists: Weiss and José Manuel Alarcón, a research professor at the Universidad Complutense de Madrid. They worked together to tighten up the theoretical methods used to analyze the problem.

"We used a particular theoretical method called effective field theory to make a model of the structure of the proton for how it responds to electromagnetic scattering at low momentum transfers," Weiss explained. "The theory condenses the relevant structure of the proton to a few numbers. And it allows you to predict the response of the proton to electron scattering at finite momentum transfers, and how that's related to the charge radius that you want to extract."

When the experimentalists and theorists then compared their work, they found that it converged on a new value for the proton's radius, as shown in the animation.

"What is absolutely beautiful and striking is when you look at whether there is a radius where the global fit and the theoretical calculation agree, there is one. It's .845 femtometers," said Higinbotham. "And it's oddly consistent with the muonic radius result and not with many of the previous electron-scattering extraction results."

A Window into New Physics

The quest to solve this discrepancy isn't one of idle curiosity—the value for this quantity has far-reaching effects. For instance, a more precise result may reveal uncharted areas of nuclear and particle physics.

"It can be a window for new physics. If we cannot reconcile different measurements for the proton radius, maybe it's because there is new physics that we don't understand or that we don't have in our theory. That's one of the reasons why this proton radius is so important," explained Alarcón.

When asked if they think this is the final determination for this quantity, all four researchers demurred.

"Science is a process of successive refinement of ideas and methods, in which our present understanding is only a stage from which we move on to more accurate theory and experiments," said Weiss.

For now, they point to several recent experimental studies that use newer technologies to measure the value to even higher precision, including the PRad experiment that took electron-scattering data in Jefferson Lab's Experimental Hall B in 2016. It's named for its goal: an ever-more precise measurement of the proton's radius.

"The PRad result will be out this year. It will be interesting to see whether the new result can confirm our scientific analysis," said Ye. [46]

How a proton gets its spin is surprisingly complicated

Like a quantum version of a whirling top, protons have angular momentum, known as spin. But the source of the subatomic particles' spin has confounded physicists. Now scientists have confirmed that some of that spin comes from a frothing sea of particles known as quarks and their antimatter partners, antiquarks, found inside the proton.

Surprisingly, a less common type of antiquark contributes more to a proton's spin than a more plentiful variety, scientists with the STAR experiment report March 14 in *Physical Review D*.

Quarks come in an assortment of types, the most common of which are called up quarks and down quarks. Protons are made up of three main quarks: two up quarks and one down quark. But protons also have a "sea," or an entourage of transient quarks and antiquarks of different types, including up, down and other varieties (*SN: 4/29/17, p. 22*).

Previous measurements suggested that the spins of the quarks within this sea contribute to a proton's overall spin. The new result — made by slamming protons together at a particle accelerator called the Relativistic Heavy Ion Collider, or RHIC — clinches that idea, says physicist Elke-Caroline Aschenauer of Brookhaven National Lab in Upton, N.Y., where the RHIC is located.

A proton's sea contains more down antiquarks than up antiquarks. But, counterintuitively, more of the proton's spin comes from up than down antiquarks, the researchers found. In fact, the down antiquarks actually spin in the opposite direction, slightly subtracting from the proton's total spin.

"Spin has surprises. Everybody thought it's simple … and it turns out it's much more complicated," Aschenauer says. [45]

First results from Cassini's final mission phase show protons of extreme energies between the planet and its dense rings

Approximately one year ago, a spectacular dive into Saturn ended NASA's Cassini mission—and with it a unique, 13-year research expedition to the Saturnian system. In the mission's last five months, the probe entered uncharted territory again: Twenty-two times, it plunged into the almost unexplored region between the planet Saturn and its innermost ring, the D ring. On Friday, 5

October 2018, the journal *Science* is releasing six articles describing first results from this mission phase.

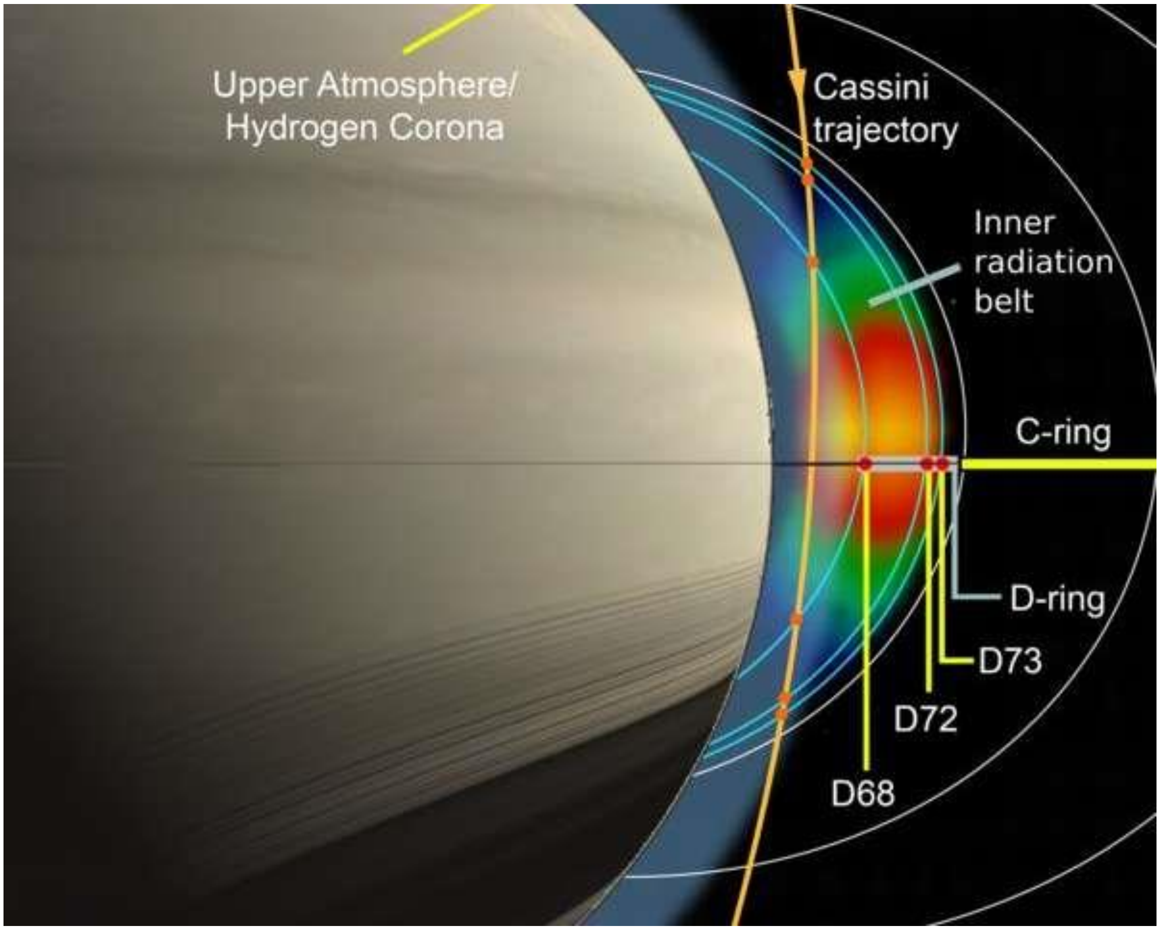
In one of these papers, a research team led by the Max Planck Institute for Solar System Research in Germany and the Applied Physics Laboratory of Johns Hopkins University in the U.S. reports on the unique proton radiation belts formed in close proximity to the planet. Due to presence of the dense A, B, and C rings, this area is almost completely decoupled from the main radiation belt and the rest of the magnetosphere, which extend farther outward.

When the space probe Cassini swung into its first orbit around Saturn and its rings on July 1, 2004, the Magnetospheric Imaging Instrument (MIMI) particle detector suite, including Low Energy Magnetospheric Measurement System (LEMMS), developed and built under the leadership of MPS, caught a brief glimpse of the region between the planet and the innermost D ring. The measurements indicated that a population of charged particles may be present, but its exact composition and properties remained obscure. In the following years, MIMI-LEMMS investigated the particles that are trapped by Saturn's strong magnetic field outside its rings, forming its main radiation belt that consists of high-energy protons and electrons. The proton radiation belt extends more than 285,000 kilometers into space and is strongly influenced by Saturn's numerous moons, which segment it into five sectors. "Only 13 years later, shortly before the end of the mission, we were given the opportunity to follow up on our very first measurements at Saturn and see if an additional radiation belt sector co-exists with the D ring and the upper atmosphere of the planet," explains Elias Roussos, scientist at the Max Planck Institute for Solar Systems lead author of the current study.

The 13-year-long test of patience has now paid off. In their current *Science* article, the scientists paint a comprehensive picture of the protons surrounding Saturn in close proximity. Two articles in the journal *Geophysical Research Letters* elaborate these findings.

Similar to the main proton belt of Saturn, the protons that populate the region close to the planet are generated by incident galactic cosmic radiation. When cosmic radiation interacts with material in Saturn's atmosphere or in its dense rings, it triggers a chain of reactions generating high-energy protons that are subsequently trapped by the planet's magnetic field.

Saturn's magnetic field is more than 10 times stronger near the planet than it is in the main radiation belts. That makes trapping so efficient that protons can remain for years in the same magnetic field line. That forces them to interact continuously with the D ring and the Saturnian atmosphere and gradually lose their full energy. But with the densities of the tenuous D ring unknown, it was unclear how fast this energy loss develops and whether a radiation belt could be maintained. Theoretical modeling indicated that one viable scenario might be MIMI measuring nothing but noise.



In its final mission phase, the Cassini probe entered the region between Saturn and the D-ring along the orange trajectory. The observed accumulation of protons extends across the D-ring. While the proton intensity is visibly reduced at …more

That fortunately did not happen – at least for protons. LEMMS measurements revealed a stable accumulation of energetic protons that extends from the atmosphere of Saturn and all across the D ring. The energy that many of these protons have is extreme: more than 10 times higher than what LEMMS was designed to measure. "We had to dig out old mechanical drawings of the instrument and construct new models of it to understand how it would measure in such an extreme environment," Roussos adds.

"Outward of the D ring, Saturn's A, B and C rings are significantly denser and dustier, forming an effective 62,000-kilometer barrier for the trapping of charged particles," Roussos continues. That meant that the outer edge of the D ring was as far as this new proton belt could extend – and LEMMS measurements confirmed that. "This creates a radiation belt that is completely isolated from the rest of the magnetosphere," says MPS scientist Dr. Norbert Krupp, Principal Investigator of the MIMI-LEMMS team and co-author of the study in *Science*.

This region is unique in the solar system. It offers the possibility to examine a radiation belt in laboratory-like conditions, as its protons are created by a very stable process, guided and controlled by Saturn's strong magnetic field. In Saturn's main radiation belt and in the radiation belts of Earth and Jupiter, these conditions are different—and much more complicated. At Earth, for example, a variable influx of high-energy particles from the sun can have a strong influence on the radiation belt structure.

Equally valuable is the new information that LEMMS adds about the D ring system, which is too faint to study by imaging alone. This ring contains a total of three narrow ringlets, all brighter than the rest of the ring and named as D68, D72 and D73. While the intensity of protons was reduced by ringlets D68 and D73, ringlet D72 lying between them does not appear to have an effect. "Even though the D72 and D68 ringlets are similarly bright, LEMMS measurements show us that they must actually be very different," says Roussos.

MIMI measurements also revealed a secondary, lower-energy proton radiation belt at an altitude below several thousand kilometers. This belt forms occasionally when fast neutral hydrogen atoms created in Saturn's magnetosphere get trapped near the planet when they impact its atmosphere and become charged. "The presence of this lower-altitude belt shows that some minimal information by Saturn's variable, distant magnetosphere can be transmitted across the planet's dense rings," Krupp adds.

In the 13 years the MIMI/LEMMS instrument spent at Saturn, it conducted one of the most comprehensive investigations of a planetary radiation belt other than that of the Earth and even helped to discover unknown rings. A summary of these and further discoveries can be found in the book *Saturn in the 21st Century*, which is published by Cambridge University Press this month. Dr. Norbert Krupp from the MPS is among its four editors. [44]

The early universe was a fluid quark-gluon plasma

Scientists from the Niels Bohr Institute, University of Copenhagen, and their colleagues from the international ALICE collaboration recently collided xenon nuclei, in order to gain new insights into the properties of the Quark-Gluon Plasma (the QGP) – the matter that the universe consisted of up to a microsecond after the Big Bang. The QGP, as the name suggests, is a special state consisting of the fundamental particles, the quarks, and the particles that bind the quarks together, the gluons. The result was obtained using the ALICE experiment at the 27 km long superconducting Large Hadron Collider (LHC) at CERN. The result is now published in *Physics Letters B*.

The particle physicists at the Niels Bohr Institute have obtained new results, working with the LHC, replacing the lead-ions, usually used for collisions, with Xenon-ions. Xenon is a "smaller" atom with fewer nucleons in its nucleus. When colliding ions, the scientists create a fireball that recreates the initial conditions of the universe at temperatures in excess of several thousand billion degrees. In contrast to the Universe, the lifetime of the droplets of QGP produced in the laboratory is ultra short, a fraction of a second (In technical terms, only about 10^{-22} seconds). Under these conditions the density of quarks and gluons is very large and a special state of matter is formed in which quarks and gluons are quasi-free (dubbed the strongly interacting QGP). The experiments reveal that the primordial matter, the instant before atoms formed, behaves like a liquid that can be described in terms of hydrodynamics.

"One of the challenges we are facing is that, in heavy ion collisions, only the information of the final state of the many particles which are detected by the experiments are directly available – but we want to know what happened in the beginning of the collision and first few moments afterwards," You Zhou, Postdoc in the research group Experimental Subatomic Physics at the Niels Bohr Institute, explains. "We have developed new and powerful tools to investigate the properties of the small droplet of QGP (early universe) that we create in the experiments." They rely on studying the spatial distribution of the many thousands of particles that emerge from the collisions when the quarks and gluons have been trapped into the particles that the Universe consists of today. This reflects not only the initial geometry of the collision, but is sensitive to the properties of the QGP. It can be viewed as a hydrodynamical flow." The transport properties of the Quark-Gluon Plasma will determine the final shape of the cloud of produced particles, after the collision, so this is our way of approaching the moment of QGP creation itself," You Zhou says.

Two main ingredients in the soup: Geometry and viscosity

The degree of anisotropic particle distribution – the fact that there are more particles in certain directions—reflects three main pieces of information: The first is, as mentioned, the initial geometry of the collision. The second is the conditions prevailing inside the colliding nucleons. The third is the shear viscosity of the Quark-Gluon Plasma itself. Shear viscosity expresses the liquid's resistance to flow, a key physical property of the matter created. "It is one of the most important parameters to define the properties of the Quark-Gluon Plasma," You Zhou explains, " because it tells us how strongly the gluons bind the quarks together ".

"With the new Xenon collisions, we have put very tight constraints on the theoretical models that describe the outcome. No matter the initial conditions, Lead or Xenon, the theory must be able to describe them simultaneously. If certain properties of the viscosity of the quark gluon plasma are claimed, the model has to describe both sets of data at the same time, says You Zhou. The possibilities of gaining more insight into the actual properties of the "primordial soup" are thus enhanced significantly with the new experiments. The team plans to collide other nuclear systems to further constrain the physics, but this will require significant development of new LHC beams.

"This is a collaborative effort within the large international ALICE Collaboration, consisting of more than 1800 researchers from 41 countries and 178 institutes." You Zhou emphasised. [43]

Wave-particle interactions allow collision-free energy transfer in space plasma

The Earth's magnetosphere contains plasma, an ionized gas composed of positive ions and negative electrons. The motion of these charged plasma particles is controlled by electromagnetic fields. The energy transfer processes that occur in this collisionless space plasma are believed to be based on wave-particle interactions such as particle acceleration by plasma waves and spontaneous wave generation,which enable energy and momentum transfer.

However, while the coexistence of waves with accelerated particles in the magnetosphere has been studied for many years, the gradual nature of the interactions between them has made observation of these processes difficult. Detection of local energy transfer between the particles and the fields is therefore required to enable quantitative assessment of their interactions.

Researchers from Nagoya University's Institute for Space-Earth Environmental Research (ISEE) are part of a research team that have performed ultrafast measurements using four Magnetospheric Multiscale (MMS) spacecraft to evaluate the energy transfer that occurred during interactions associated with electromagnetic ion cyclotron waves. "We observed that the ion distributions were not symmetrical around the magnetic field direction but were in fact in phase with the plasma wave fields," states Nagoya University's Masafumi Shoji.

The high-time-resolution measurements provided by the MMS spacecraft were combined with composition-resolved ion measurements to demonstrate the simultaneous occurrence of two energy transfers. The first energy transfer was from hot anisotropic hydrogen ions to an ion cyclotron wave via a cyclotron resonance process,while the second transfer was from the cyclotron wave to helium ions,which took place via a nonresonant interaction and saw the cold He^+ ions being accelerated to energies of up to 2 keV.

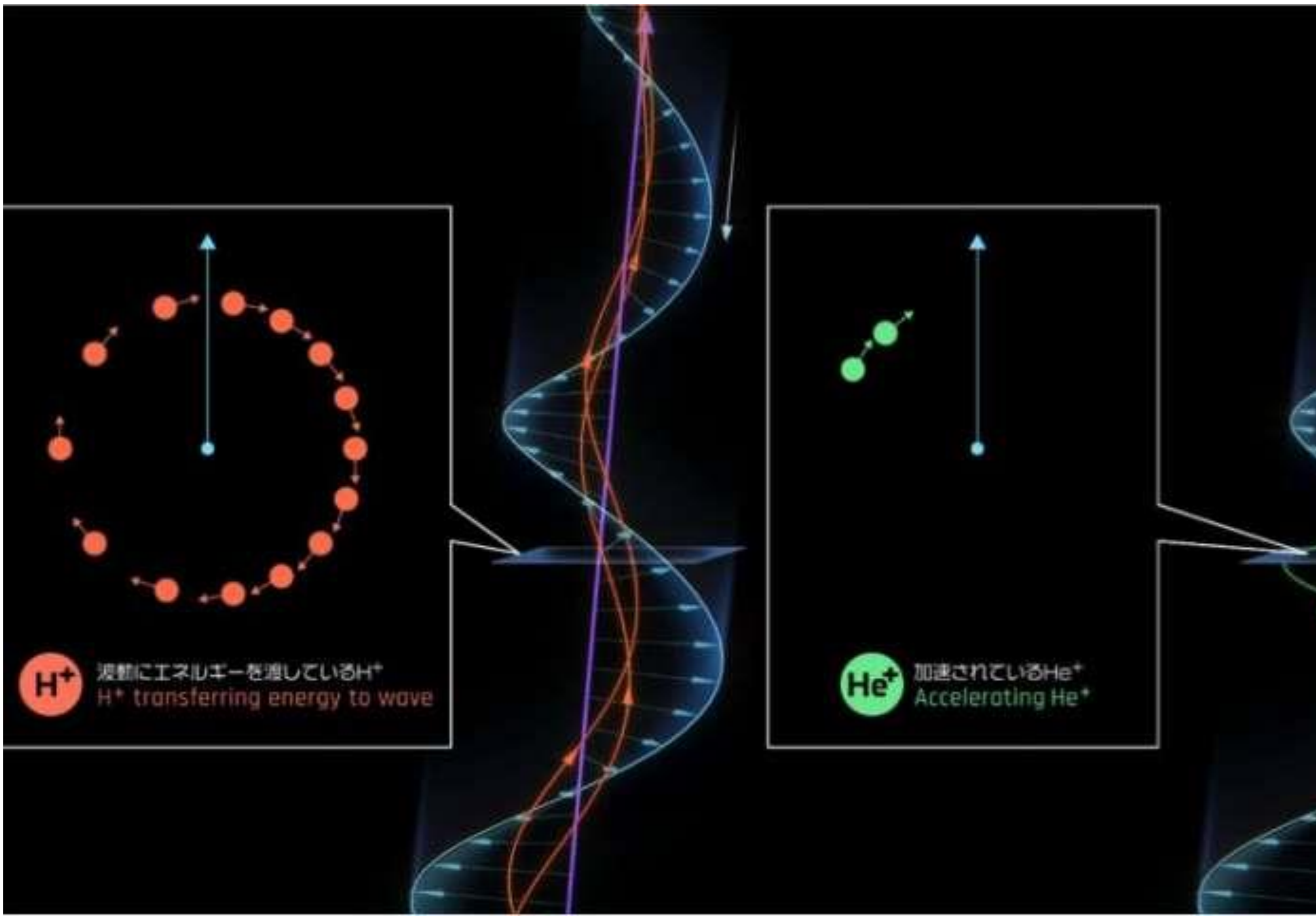


Fig. 2: The energy transfer process from the hydrogen ions to the helium ions occurs via wave-particle interactions. Credit: Nagoya University

"This represents direct quantitative evidence of the occurrence of collisionless energy transfer between two distinct particle populations via wave-particle interactions,"says Yoshizumi Miyoshi from Nagoya University's ISEE. "Measurements of this type will even provide the capability to identify the types of wave-particle interactions that are occurring." The team's findings were recently published in *Science*.

It is hoped that this research represents a major step towards a quantitative understanding of wave-particle interactions and energy transfer between particle populations in space plasma. This would have implications for our understanding of a wide variety of space plasma phenomena, including the Van Allen radiation belt, geomagnetic storms, auroral particle precipitation, and atmospheric loss from planets, such as the loss of oxygen ions from Earth's atmosphere. [42]

Plasma accelerators could overcome size limitations of Large Hadron Collider

Plasma particle accelerators more powerful than existing machines could help probe some of the outstanding mysteries of our universe, as well as make leaps forward in cancer treatment and security scanning—all in a package that's around a thousandth of the size of current accelerators. All that's left is for scientists to build one.

If you know what a particle accelerator is, you probably think first of the Large Hadron Collider (LHC) – that gargantuan ring on the Franco-Swiss border that smashes protons and ions together, exposing the secrets of the subatomic world.

Built by the European lab CERN, the LHC accelerates particles to the kinds of speeds found during the eruption of the early universe. To do so, it needs a very, very big circumference – 27 kilometres.

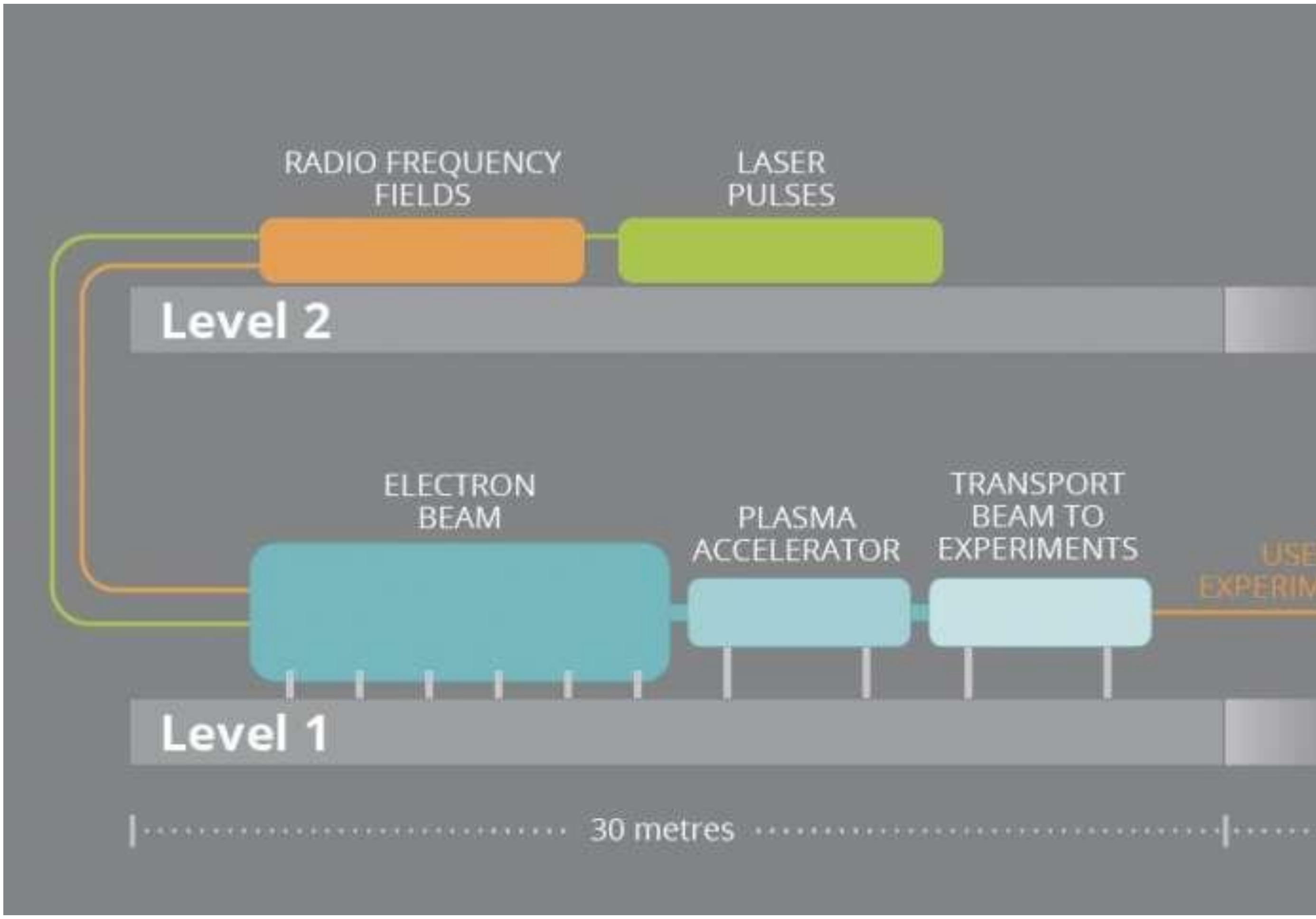
Yet the LHC is already finding limits to what it can explore. Physicists want even more powerful accelerators – but building one much bigger than the LHC is hard to contemplate.

Dr. Ralph Assmann, a leading scientist at the German particle physics lab DESY, believes a completely different approach is needed. He thinks accelerators can be powerful, yet up to 1,000 times smaller, if they are based on a strange type of matter known as a plasma – a cloud of negative electrons and positive ions.

"Plasma accelerators provide a path to energies beyond the LHC," he said. "Particle physicists must take this opportunity very seriously."

Swing

Conventional accelerators work by sending charged particles through oscillating electromagnetic fields. By switching back and forth, these fields kick the particles to an incrementally higher energy with every cycle – a bit like pushing a child on a swing.



A two-storey design limits the length of the 5 GeV EuPRAXIA plasma accelerator facility, although it could extend to 35-250m depending on what applications are added downstream. Diagram not to scale. Credit: Horizon

The trouble with this approach is that the individual kicks – which are generated by electrical components – can only be so powerful, or the field itself will break down. High energies therefore demand lots and lots of soft kicks, which is why conventional accelerators get so big.

Plasmas, however, can sustain much bigger fields. Nearly 40 years ago, physicists discovered that if a laser pulse or a particle beam is sent into a plasma, it is possible to momentarily separate the negative and positive charges, generating a field of some 100 billion volts per metre.

Any electrons stranded in the wake of this separation are propelled forwards. The effect, like a surfer riding a wave, is known as plasma wakefield acceleration.

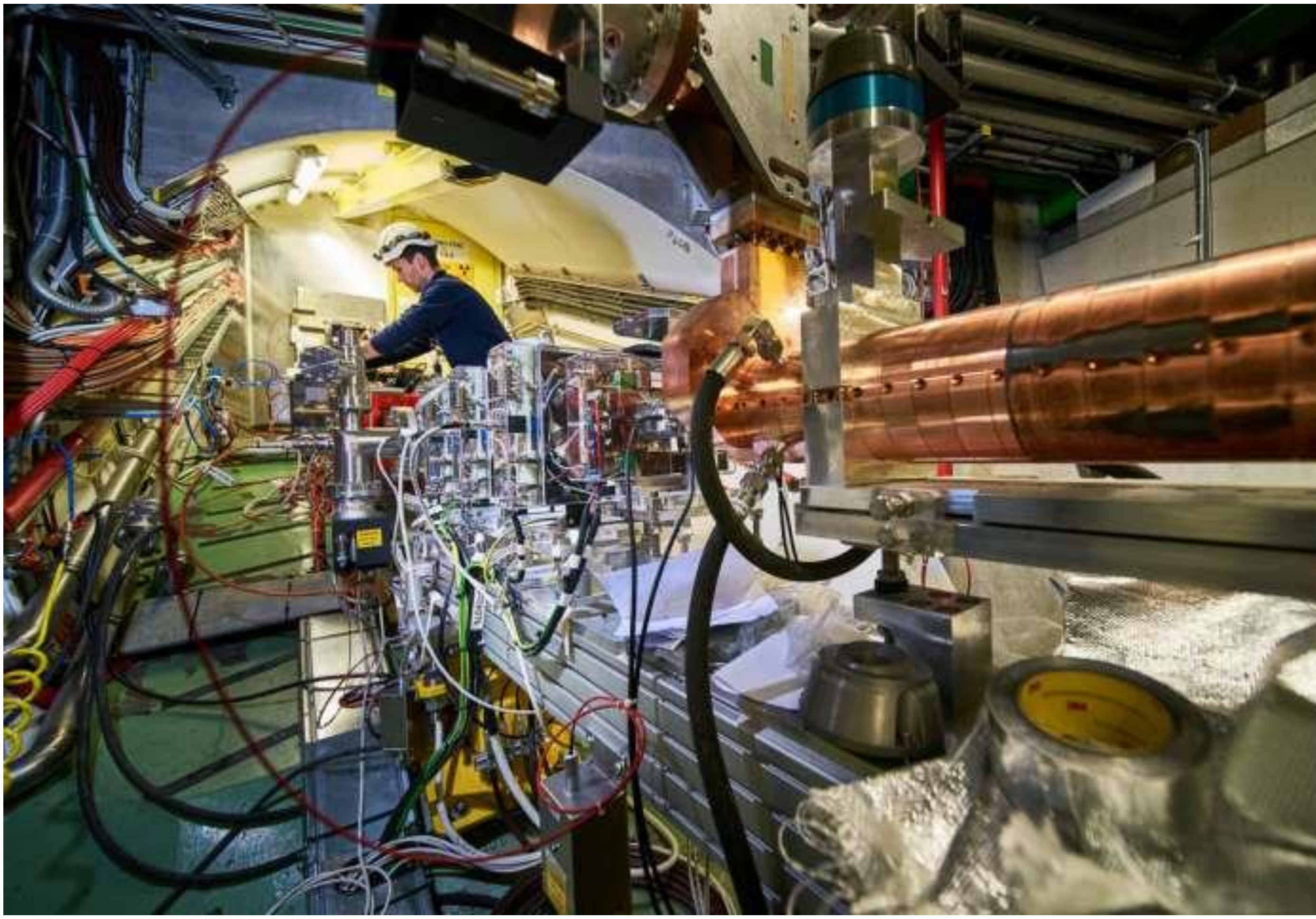
In recent years, the energies accessible with plasma wakefield accelerators have risen sharply. Scientists like Dr. Assmann want to increase these energies, but also to improve the stability and quality of the electron beams coming out of the accelerator.

Host of applications

That would make plasma accelerators suitable for particle physics but also a host of other applications, including cancer treatment, medical diagnostics, security scanners and the study of advanced materials. Conventional accelerators already help with these applications, but their size and cost means that demand currently far outstrips supply.

Dr. Assmann is coordinating a project, EuPRAXIA, to come up with a design for the world's first plasma wakefield accelerator with an energy of five giga-electronvolts (GeV) that can actually be used for research. That is less than one-thousandth the energy of the LHC but, as Dr. Assmann points out, you have to walk before you can run.

"Clearly, high-field accelerators, like plasma accelerators, (are) the logical long-term solution for advancing the energy frontier in particle physics," he said. "But it will require a realistic and sustained approach."



The AWAKE experiment uses a proton beam to create a strong plasma wakefield. Credit: CERN

With 40 labs and universities on board, EuPRAXIA will have to answer key questions, such as whether all the accelerated electrons should come from the plasma, or whether additional electrons should be fed into the machine. The design is expected to be completed towards the end of next year.

EuPRAXIA is not the only plasma accelerator project in town, however. At CERN, a powerful wakefield accelerator called AWAKE has already been built, but with a twist – it uses a proton beam to drive it.

Bigger impact

Protons are more than 1,800 times more massive than electrons, which means they have a much bigger impact when it comes to dividing the charges in a plasma. According to Dr. Edda Gschwendtner, the CERN project leader of the AWAKE experiment, that means a proton-driven plasma accelerator could accelerate electrons to high energies in just a single stage, rather than multiple stages, as is often proposed.

AWAKE takes the proton beam from one of CERN's existing accelerators, and in the last two years has successfully created strong plasma wakefields. This year, the goal is to actually accelerate electrons in that wakefield to energies exceeding 1 GeV.

In years to come, Dr. Gschwendtner wants to boost AWAKE's output to several tens of GeV. That would be enough to probe certain theoretical proposals of today's particle physics – dark photons, for instance, which some physicists believe could constitute the dark matter that predominates in the universe.

Plasma accelerators still have a long way to go before they can out-perform the likes of the LHC. But when conventional accelerators are so big and costly, Dr. Gschwendtner believes they could be the only way forward.

"New technologies must be developed," she said. "Plasma wakefield acceleration is a very promising novel accelerator technique." [41]

Work Begins on New SLAC facility for revolutionary accelerator science

The Department of Energy's SLAC National Accelerator Laboratory has started to assemble a new facility for revolutionary accelerator technologies that could make future accelerators 100 to 1,000 times smaller and boost their capabilities.

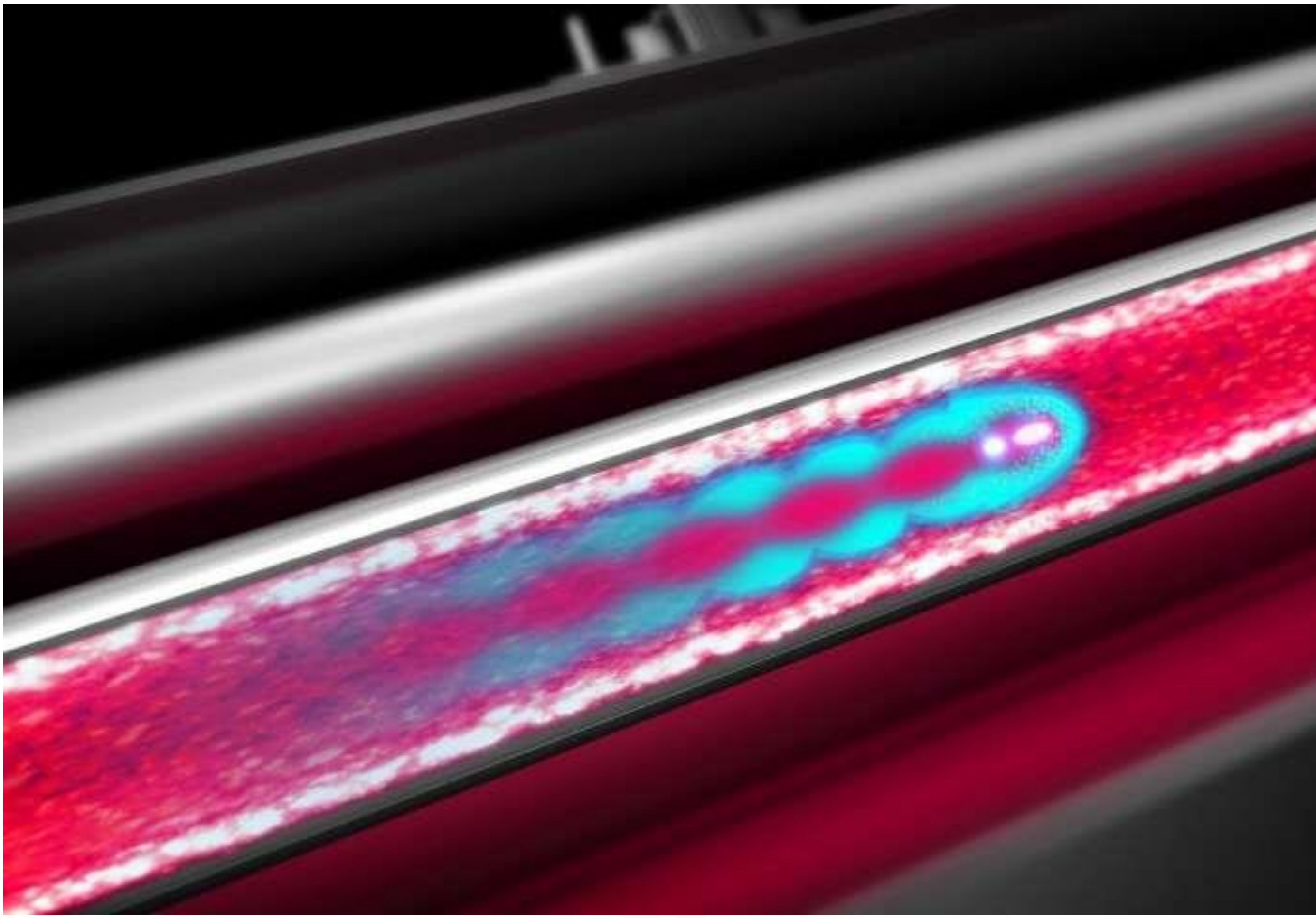
The project is an upgrade to the Facility for Advanced Accelerator Experimental Tests (FACET), a DOE Office of Science user facility that operated from 2011 to 2016. FACET-II will produce beams of highly energetic electrons like its predecessor, but with even better quality. These beams will primarily be used to develop plasma acceleration techniques, which could lead to next-generation particle colliders that enhance our understanding of nature's fundamental particles and forces and novel X-ray lasers that provide us with unparalleled views of ultrafast processes in the atomic world around us.

FACET-II will be a unique facility that will help keep the U.S. at the forefront of accelerator science, said SLAC's Vitaly Yakimenko, project director. "Its high-quality beams will enable us to develop novel acceleration methods," he said. "In particular, those studies will bring us close to turning plasma acceleration into actual scientific applications."

The DOE has now approved the $26 million project (Critical Decisions 2 and 3). The new facility, which is expected to be completed by the end of 2019, will also operate as an Office of Science user facility—a federally sponsored research facility for advanced accelerator research available on a competitive, peer-reviewed basis to scientists from around the world.

"As a strategically important national user facility, FACET-II will allow us to explore the feasibility and applications of plasma-driven accelerator technology," said James Siegrist, associate director of the High Energy Physics (HEP) program of DOE's Office of Science, which stewards advanced accelerator R&D in the U.S. for the development of applications in science and society. "We're looking forward to seeing the groundbreaking science in this area that FACET-II promises, with the potential for significant reduction of the size and cost of future accelerators, including free-electron lasers and medical accelerators."

Bruce Dunham, head of SLAC's Accelerator Directorate, said, "Our lab was built on accelerator technology and continues to push innovations in the field. We're excited to see FACET-II move forward."



Researchers will use FACET-II to develop the plasma wakefield acceleration method, in which researchers send a bunch of very energetic particles through a hot ionized gas, or plasma, creating a plasma wake for a trailing bunch to “surf” on …more

Surfing the Plasma Wake

The new facility will build on the successes of FACET, where scientists already demonstrated that the plasma technique can very efficiently boost the energy of electrons and their antimatter particles, positrons. In this method, researchers send a bunch of very energetic particles through a hot ionized gas, or plasma, creating a plasma wake for a trailing bunch to "surf" on and gain energy.

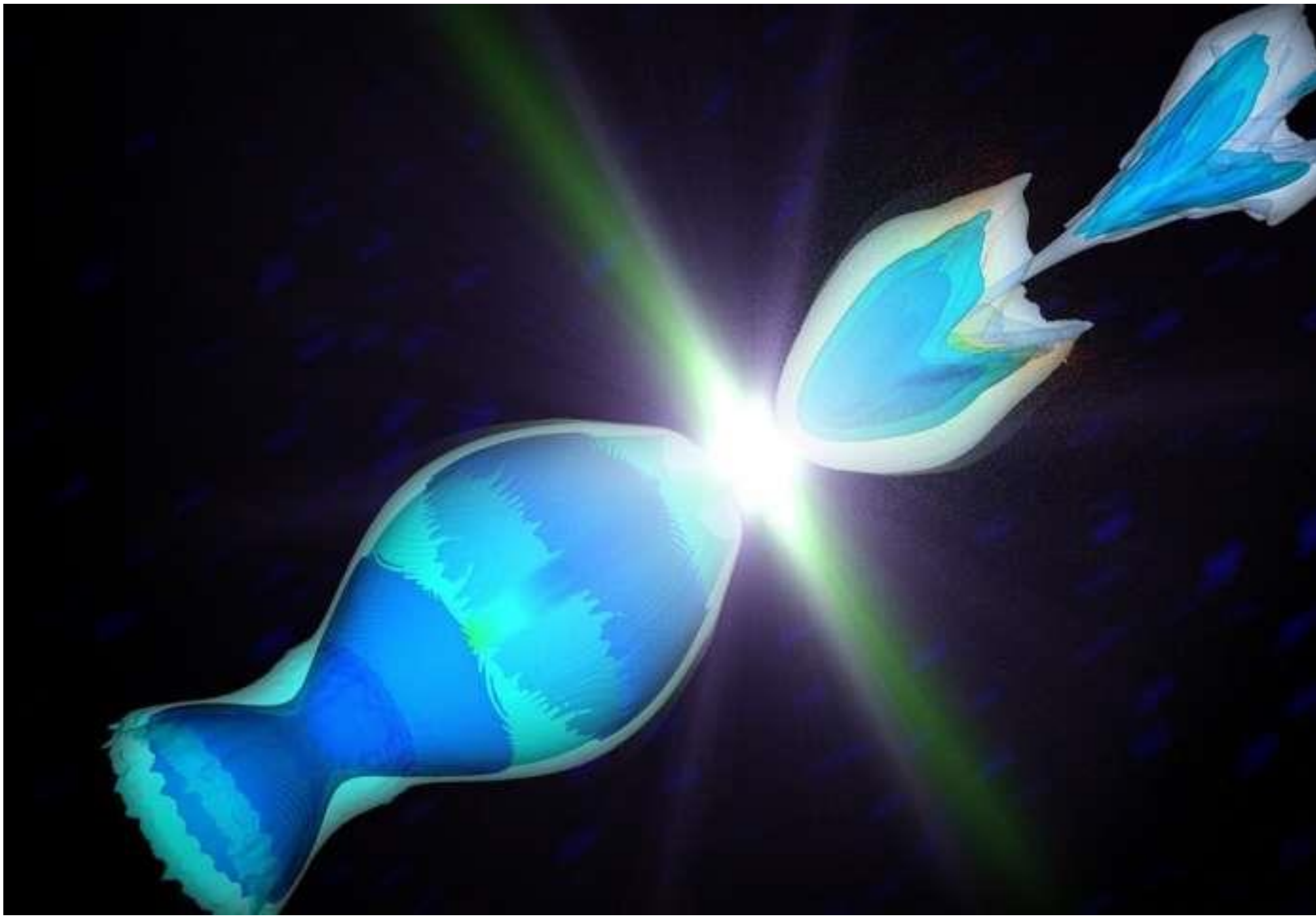
In conventional accelerators, particles draw energy from a radiofrequency field inside metal structures. However, these structures can only support a limited energy gain per distance before breaking down. Therefore, accelerators that generate very high energies become very long, and very expensive. The plasma wakefield approach promises to break new ground. Future plasma accelerators could, for example, unfold the same acceleration power as SLAC's historic 2-mile-long copper accelerator (linac) in just a few meters.

Researchers will use FACET-II for crucial developments before plasma accelerators can become a reality. "We need to show that we're able to preserve the quality of the beam as it passes through plasma," said SLAC's Mark Hogan, FACET-II project scientist. "High-quality beams are an absolute requirement for future applications in particle and X-ray laser physics."

The FACET-II facility is currently funded to operate with electrons, but its design allows adding the capability to produce and accelerate positrons later—a step that would enable the development of plasma-based electron-positron particle colliders for particle physics experiments.

Another important objective is the development of novel electron sources that could lead to next-generation light sources, such as brighter-than-ever X-ray lasers. These powerful discovery machines provide scientists with unprecedented views of the ever-changing atomic world and open up new avenues for research in chemistry, biology and materials science.

Other science goals for FACET-II include compact wakefield accelerators that use certain electrical insulators (dielectrics) instead of plasma, as well as diagnostics and computational tools that will accurately measure and simulate the physics of the new facility's powerful electron beams. Science goals are being developed with regular input from the FACET user community.



Future particle colliders will require highly efficient acceleration methods for both electrons and positrons. Plasma wakefield acceleration of both particle types, as shown in this simulation, could lead to smaller and more powerful …more

"The approval for FACET-II is an exciting milestone for the science community," said Chandrashekhar Joshi, a researcher from the University of California, Los Angeles, and longtime collaborator of SLAC's plasma acceleration team. "The facility will push the boundaries of accelerator science, discover new and unexpected physics and substantially contribute to the nation's coordinated effort in advanced accelerator R&D."

Fast Track to First Experiments

To complete the facility, crews will install an electron source and magnets to compress electron bunches, as well as new shielding, said SLAC's Carsten Hast, FACET-II technical director. "We'll also upgrade the facility's control systems and install tools to analyze the beam properties."

FACET-II will use one kilometer (one-third) of the SLAC linac—sending electrons from the source at one end to the experimental area at the other end—to generate an electron beam with an energy of 10 billion electronvolts that will drive the facility's versatile research program.

FACET-II has issued its first call for proposals for experiments that will run when the facility goes online in 2020.

"The project team has done an outstanding job in securing DOE approval for the facility," said DOE's Hannibal Joma, federal project director for FACET-II. "We'll now deliver the project on time for the user program at SLAC."

SLAC's Selina Green, project manager, said, "After two years of very hard work, it's very exciting to see the project finally come together. Thanks to the DOE's continued support we'll soon be able to open FACET-II for groundbreaking new science." [40]

Study develops a model enhancing particle beam efficiency

The use of particle accelerators is not confined to basic research in high-energy physics. Large-scale accelerators and gigantic instruments such as the Large Hadron Collider (LHC) are used for this purpose, but relatively small accelerators are used in medicine (diagnostic imaging, cancer treatment), industry (food sterilization, cargo scanning, electronic engineering), and various types of investigation (oil prospecting, archaeological surveying, analysis of artworks).

Whatever the use, controlling chaos and boosting particle flow efficiency are the goals of the scientific community in this field.

A paper describing a new contribution in this direction has recently been published in the journal *Physics of Plasmas* by Meirielen Caetano de Sousa, a postdoctoral student with a scholarship from São Paulo Research Foundation—FAPESP working at the University of São Paulo's Physics Institute (IF-USP) in Brazil, and her supervisor Iberê Luiz Caldas, Full Professor at IF-USP.

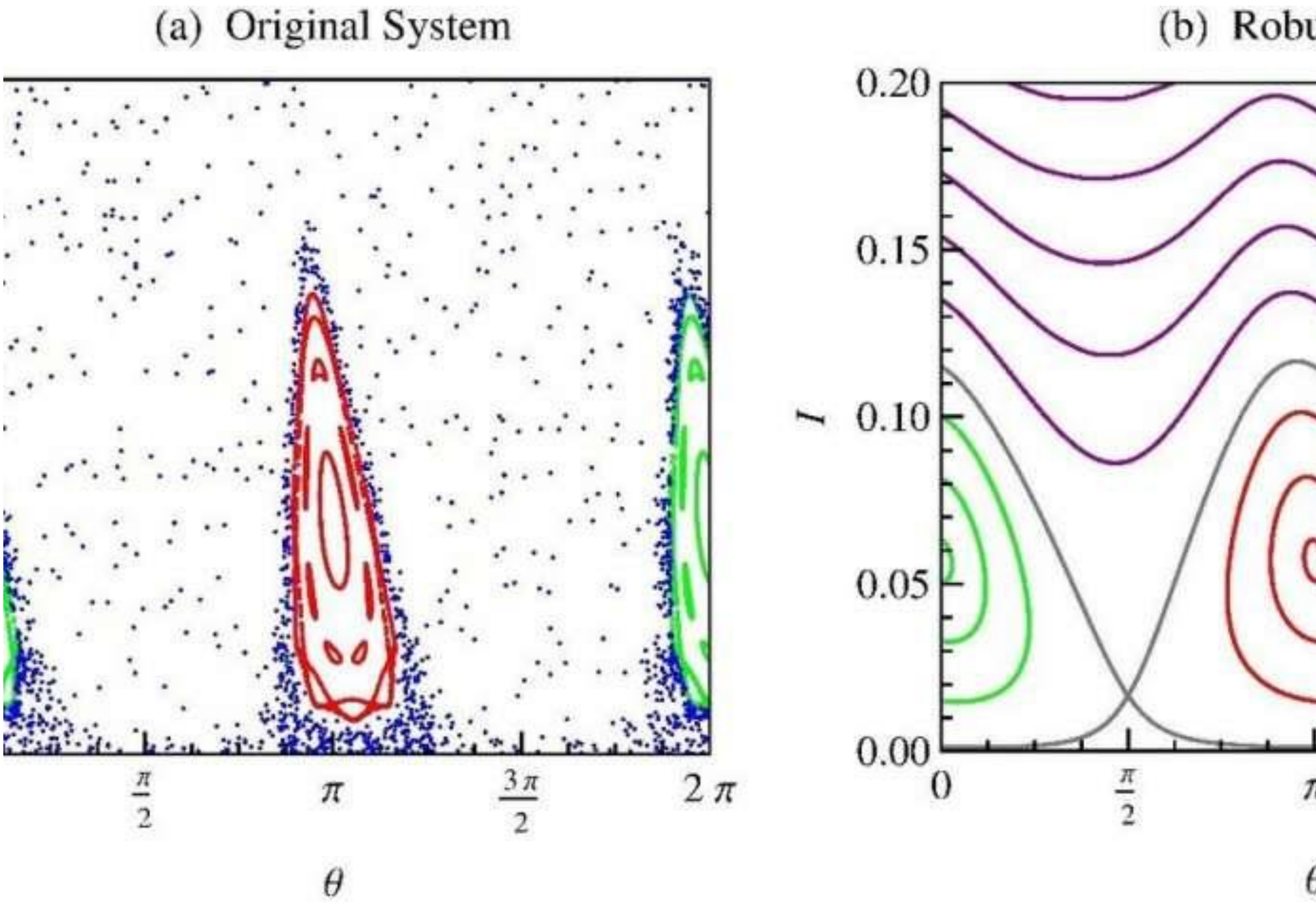
"We performed a theoretical study with modeling and numerical simulation to investigate ways of controlling chaos inside accelerators and increasing the maximum velocity of accelerated particles," Sousa said.

The authors designed a mechanism based on the deployment of a transport barrier to confine the particles and prevent them from moving from one region of the accelerator to another. This procedure has not yet been implemented in ordinary accelerators but is used in tokamaks (experimental toroidal reactors used in nuclear fusion research), where superheated plasma is prevented by particle confinement from interacting with the walls of the device.

"In tokamaks, the transport barrier is obtained by means of electrodes inserted into the plasma edge to alter the electric field. This hasn't yet been done in accelerators, where the usual solution is to add an electrostatic wave with well-defined parameters to the system," said the researcher.

"When the wave interacts with the particles, it controls chaos in the system but creates multiple barriers that don't seal the region as precisely. This is a less robust solution. In our study, we modeled a system with a single barrier along similar lines to what happens in tokamaks."

This single robust barrier would be produced by a resonant magnetic perturbation. In responding to the RMP, the plasma is confined to a single region.



The image compares particle trajectories without (left-hand) and with (right-hand) the presence of the transport barrier. The vertical axis is proportional to the energy of the particles in the accelerator. The blue dots in the left-hand …more

"We created the model and described it mathematically. The numerical simulations showed that it works. The next step is to take the proposal to experimental physicists who can test it in practice," Sousa said.

The particles are generated by an electron gun owing to the difference in potential between the anode and cathode or by applying a laser pulse to the plasma. They are accelerated by successive injections of energy from electromagnetic waves. Interaction between the waves and particles creates chaos. A solution tested experimentally in accelerators consists of adding another wave with parameters adjusted to offset the chaotic process.

"This was discussed in a previous article published in 2012 in *Physical Review E* . The method works, but as noted, it creates multiple transport barriers that are susceptible to perturbation, making particle confinement less effective. In this latest study, we modeled a solution based on a single robust barrier, which continues to exist even in the presence of high perturbations," Sousa said.

Substitution of radioisotopes

The transport barrier controls chaos, allowing maximum particle velocity to increase and reducing the requisite initial velocity. For a low-amplitude wave, the simulated final velocity rose 7 percent, and the initial velocity fell 73 percent.

For a wave of higher amplitude, the system proved chaotic without the barrier but was regularized with the barrier. The final velocity rose 3 percent, and the initial velocity fell approximately 98 percent. This shows that the transport barrier's main contribution is a reduction in the initial velocity required for the particles when they are injected into the accelerator.

"What's expected of an accelerator is that all particles arrive together at the end without going astray en route, and with more or less the same energy and velocity. If they behave chaotically, that doesn't happen, and the beam is of no use for any application," Caldas said.

"Particle emission for medical or industrial use is still based mostly on the use of radioactive materials. This causes a number of problems, such as pollution, decay of the emitter material requiring replenishment, and high cost. Accelerators avoid these problems and are a partial substitute for radioisotopes. Hence the strong interest in optimization of accelerator functioning," said the FAPESP grant supervisor. [39]

New particle accelerators will probe how charged particles assume a new identity, or change 'flavor'

Particle accelerators are powerful devices that use electromagnetic fields to propel charged particles like electrons or protons at speeds close to the speed of light, then smash them head-on. What happens in a blink of an eye during these high-speed collisions can tell us about some of the fundamental secrets of nature.

In a new paper in the June 1 issue of the journal *Physical Review Letters*, Bhupal Dev, assistant professor of physics in Arts & Sciences at Washington University in St. Louis, describes how future accelerators could crash together charged particles in a new way to shed light on their behavior.

Theorists like Dev are working to outline the big ideas that will shape the experimental approach for next-generation colliders, such as the International Linear Collider, to be built in Japan, or the Circular Electron-Positron Collider, proposed in China.

Dev, who wrote the paper with postdoctoral fellow Yongchao Zhang from Washington University and Rabi Mohapatra from the University of Maryland, is looking for a clear signal of something beyond the Standard Model of particle physics.

"There is strong experimental evidence that there is indeed some new physics lurking in the lepton sector," Dev said.

He and his collaborators believe a new collider built to crash together point-like, charged particles called leptons, which have no internal structure, is the best bet for finding this new physics.

This approach is different from the one employed at today's most famous particle accelerator—the Large Hadron Collider (LHC). Built by the European Organization for Nuclear Research, or CERN, researchers used the LHC to discover the Higgs boson, the particle that supposedly gives mass to all elementary particles.

But there are profound questions that the LHC is not ideally suited to answer.

Dev's new work on lepton colliders was initially motivated by the phenomenon of neutrino oscillations. Neutrinos are the electrically neutral counterpart of the charged leptons, and they have been observed to change from one species to another in a quantum-mechanical way. This suggests a tiny, but non-zero, mass for neutrinos.

"Ever since we directly observed neutrino oscillations, researchers have been trying to see the equivalent effect in the charged siblings of neutrinos, such as muons transforming into electrons," Dev said.

This would give a better understanding of the neutrino mass generation, which is difficult to explain by the same Higgs mechanism as for other elementary particles.

But so far, searches for such rare processes have been confined to energies much lower than those expected on the new physics scale.

In their new paper, Dev and colleagues propose how to search for the evidence of lepton "flavor violation"— the moment of transformation of charged particles into other types of charged particles—at the high energy frontier, using the new colliders. In the Standard Model, these effects are known to be negligible. Therefore, any positive signal would be a sign of new physics.

In particular, they suggest one possibility that arises due to the presence of a new type of Higgs boson that might be responsible for the tiny neutrino masses. [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?

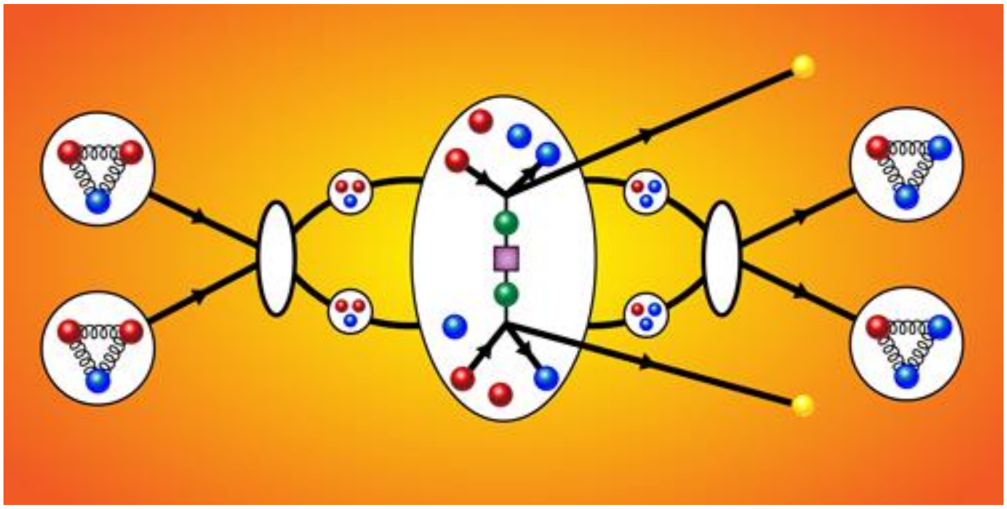
Oscillation experiments have to predict how much energy is lost and then correct for that loss. These predictions depend on accurate models of how neutrinos interact. Those models have to be right not only for neutrinos but also for antineutrinos, which are particularly good at making neutrons.

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.

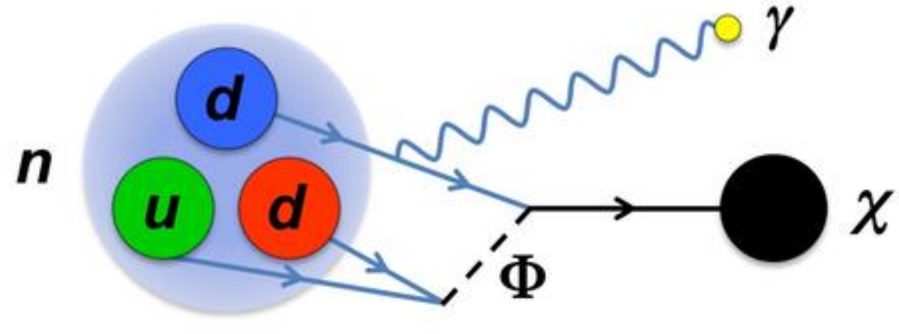
In ordinary double-beta decay, two neutrons become two protons, emitting two electrons and two electron antineutrinos. But some models indicate that neutrinos may be their own antiparticles. In that case, the two antineutrinos could cancel each other, and some decays wouldn't emit any neutrinos. Experiments 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."

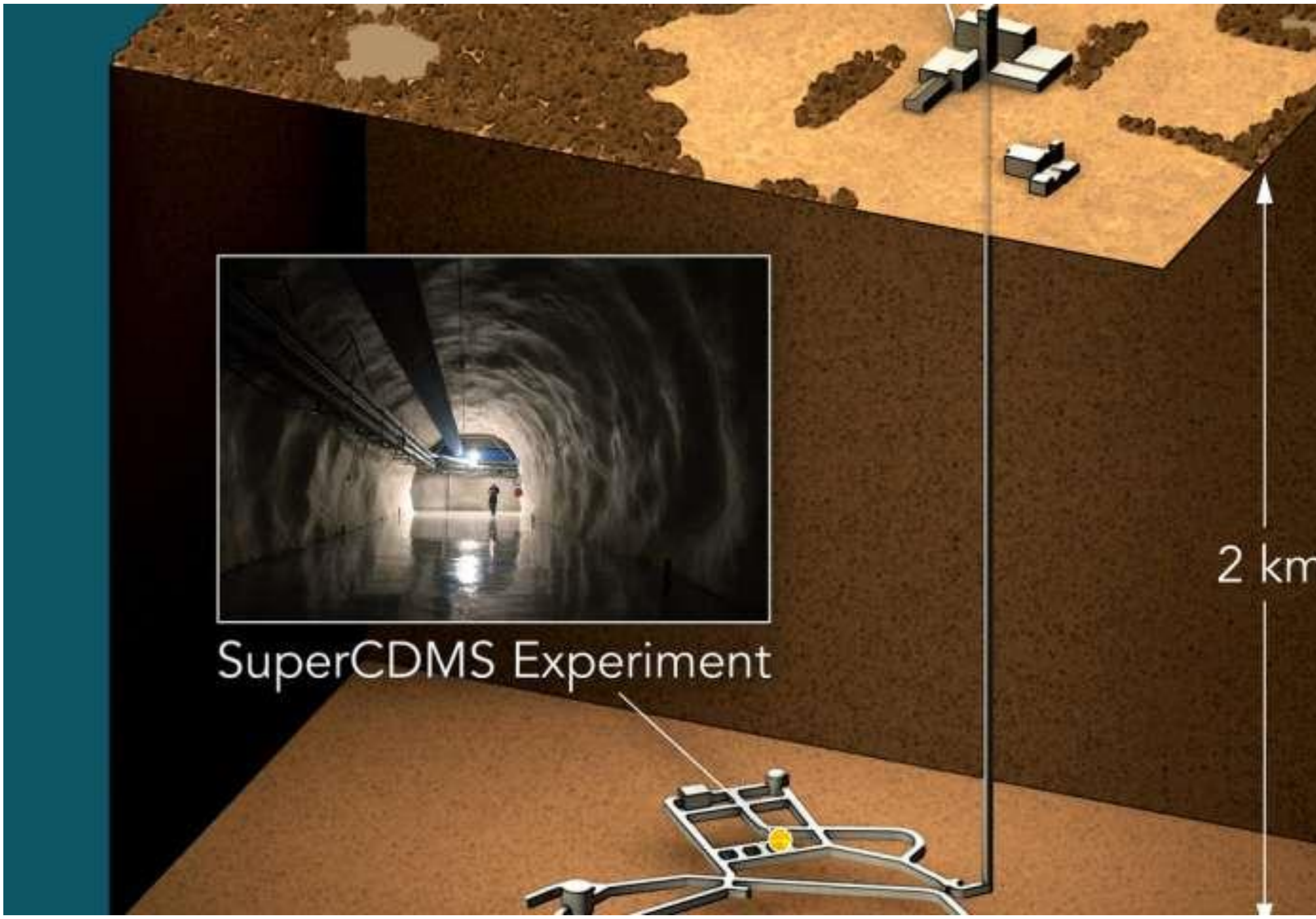
With the DOE approvals, known as Critical Decisions 2 and 3, the researchers can now build the experiment. The DOE Office of Science will contribute $19 million to the effort, joining forces with the National Science Foundation ($12 million) and the Canada Foundation for Innovation ($3 million).

"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.

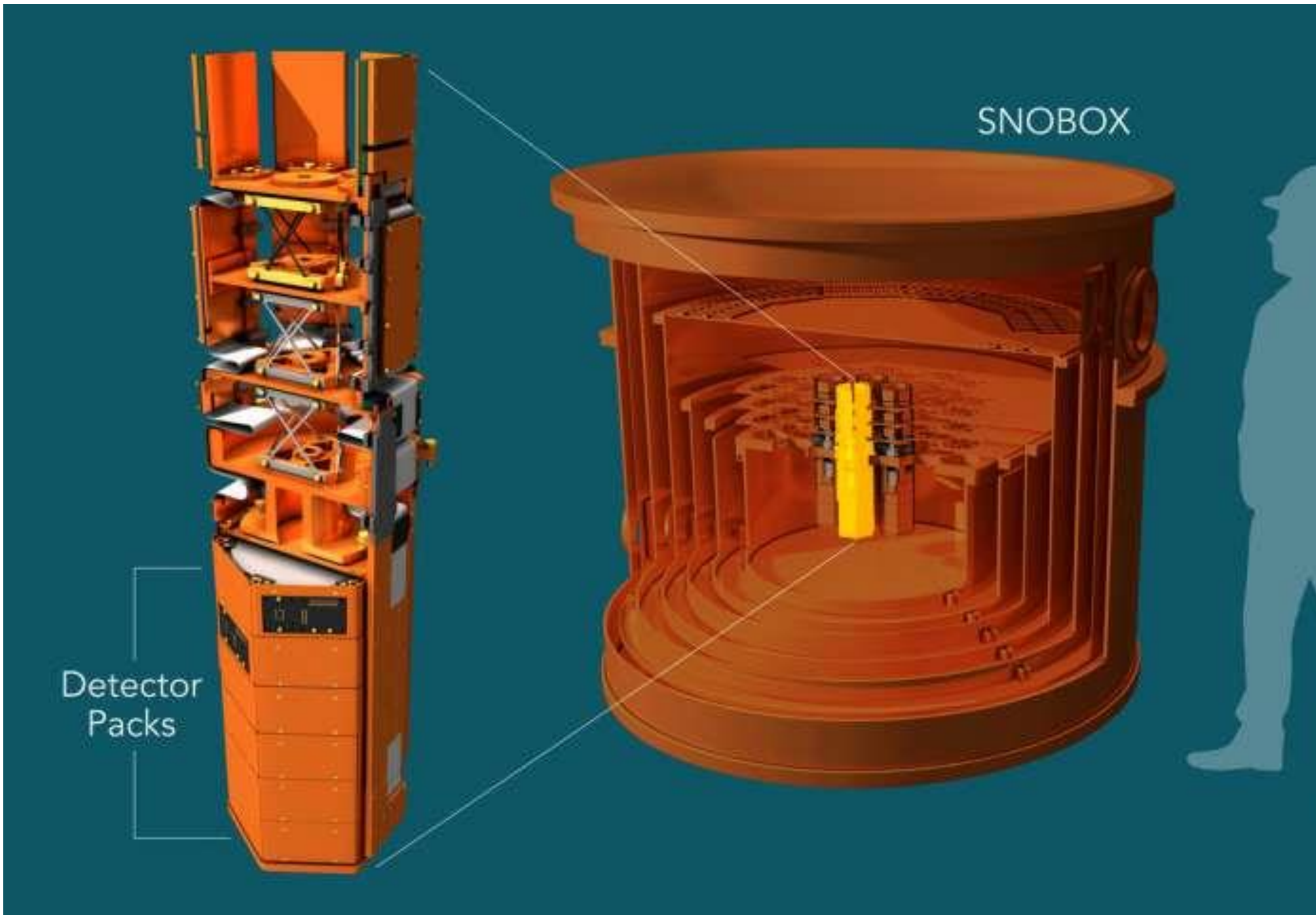
The collisions would also produce pairs of electrons and electron deficiencies that move through the crystals, triggering additional atomic vibrations that amplify the signal from the dark matter collision. The experiment will be able to measure these "fingerprints" left by dark matter with sophisticated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

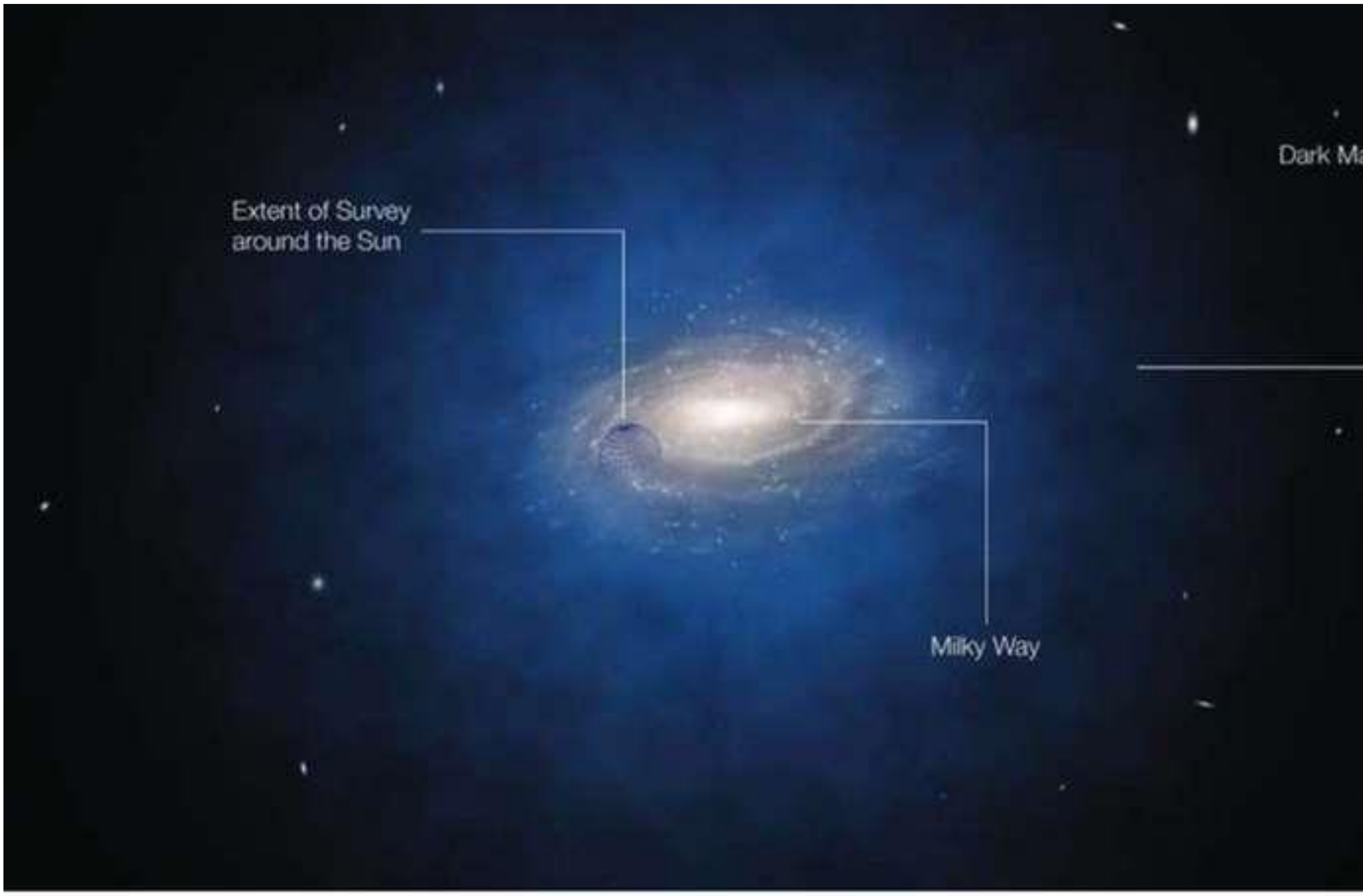
On the scale of the cosmos, much of our understanding is based on "standard model of cosmology". Informed by Einstein's theory of general relativity, it posits that the most of the mass and energy in the universe is made up of mysterious, invisible substances known as dark matter (making up 80% of the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

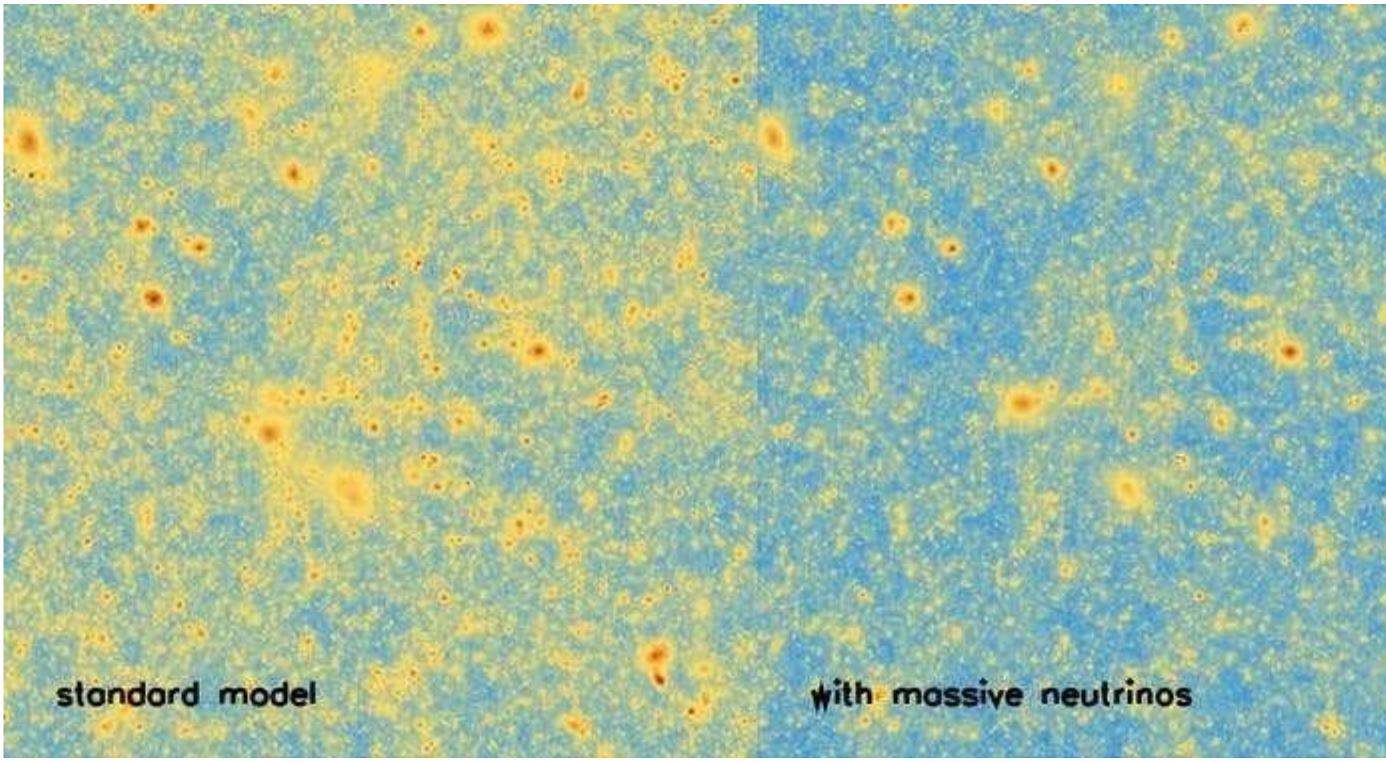
Neutrinos, which whizz around at extremely high velocities, are a good candidate for hot dark matter. In particular, they do not emit or absorb light – making them appear "dark". It was long assumed that neutrinos, which come in three different species, don't have mass. But experiments have demonstrated 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."

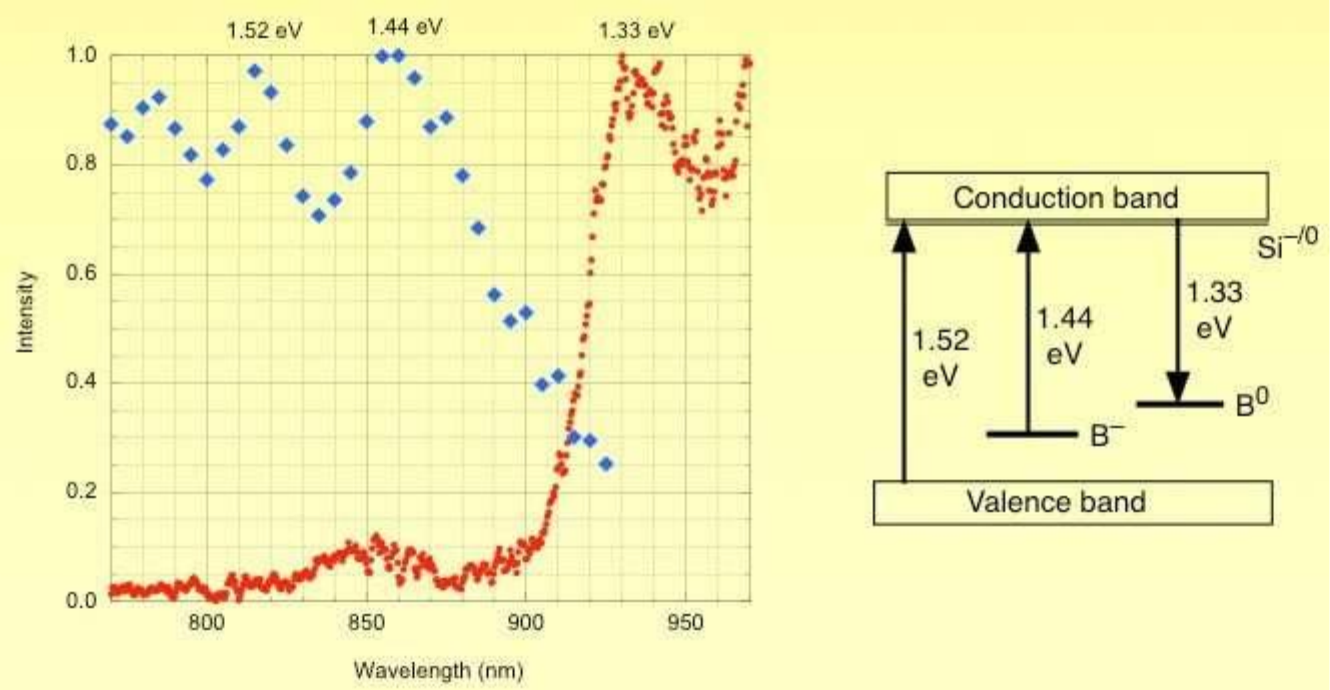
The breakthrough came from Edith Bourret, a senior staff scientist in Berkeley Lab's Materials Sciences Division who decades earlier had researched gallium arsenide's potential use in circuitry. She gave him a sample of gallium arsenide from this previous work that featured added concentrations, or "dopants,"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

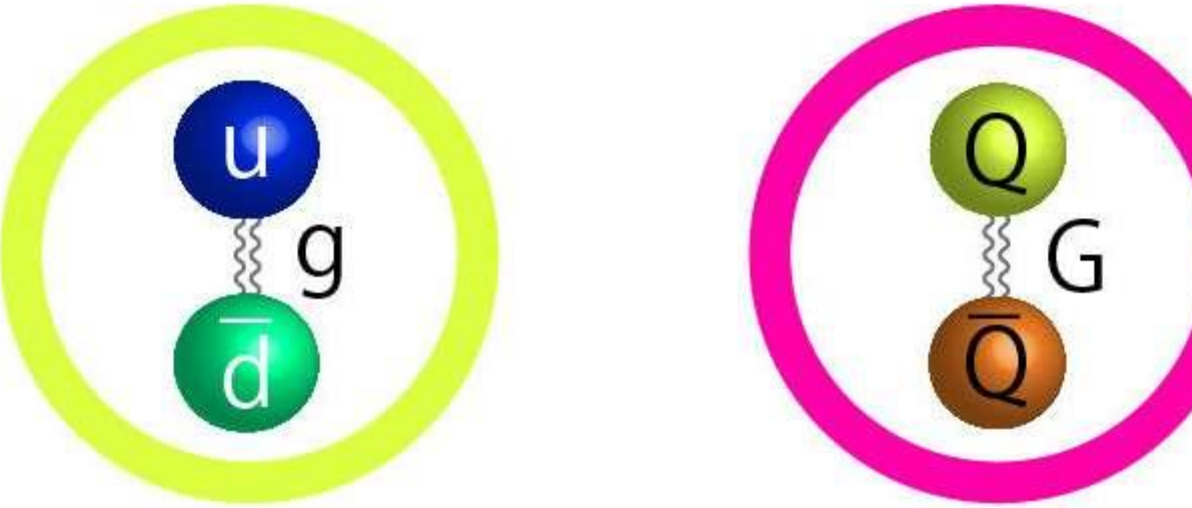
Called SIMPs - strongly interacting massive particles - they were proposed three years ago by University of California, Berkeley theoretical physicist Hitoshi Murayama, a professor of physics and director of the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) in Japan, and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

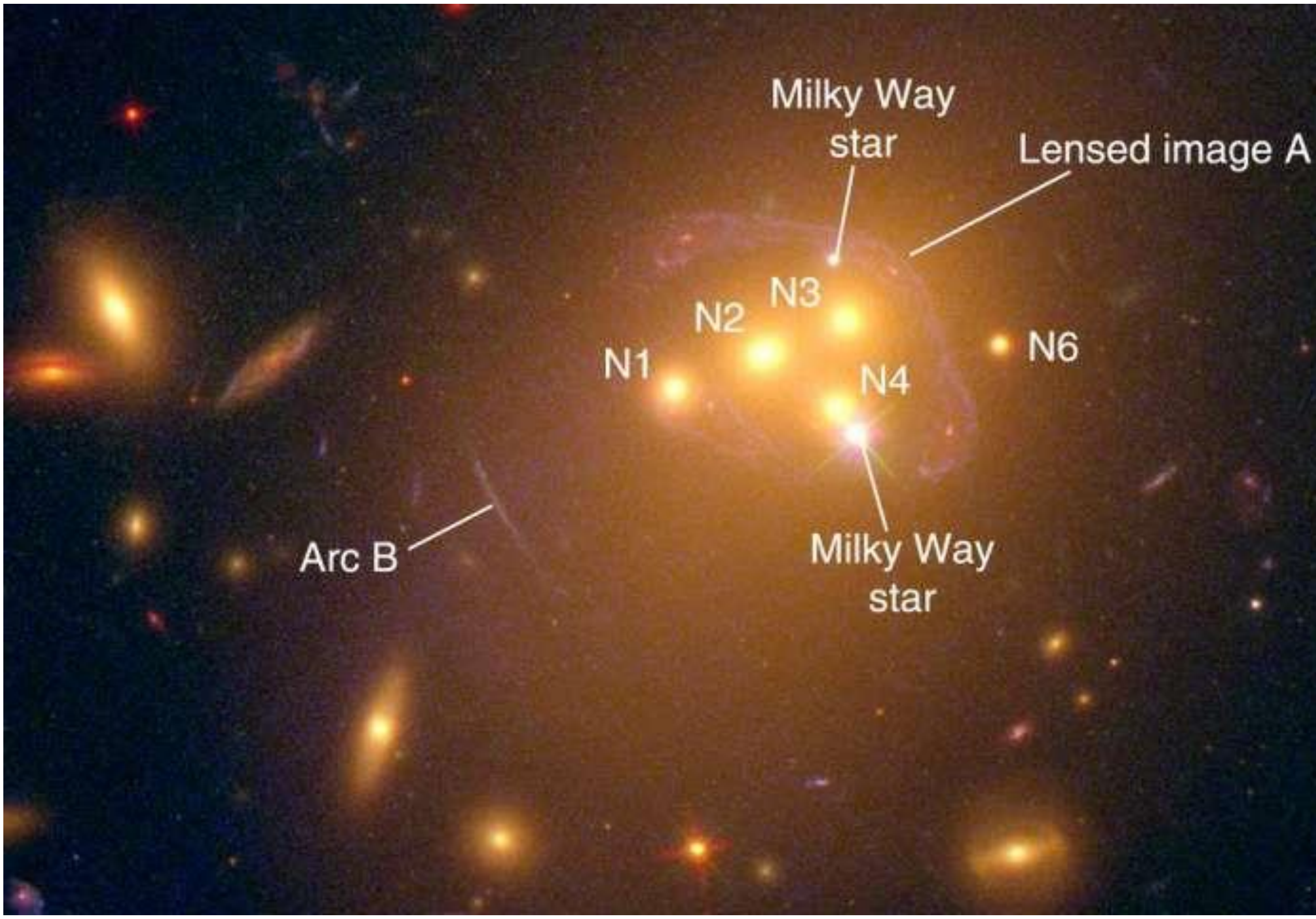
SIMPs also overcome a major failing of WIMP theory: the ability to explain the distribution of dark matter in small galaxies.

"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]

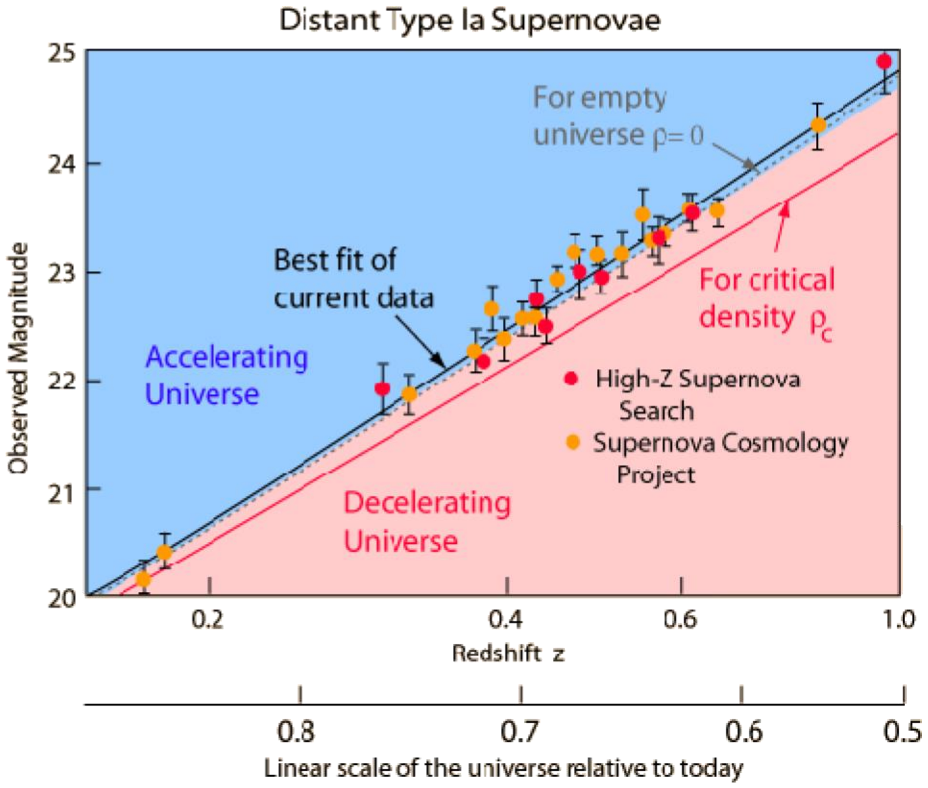
Weakly interacting massive particles

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: $\Lambda = 8\pi\rho_{\text{vac}}$, 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

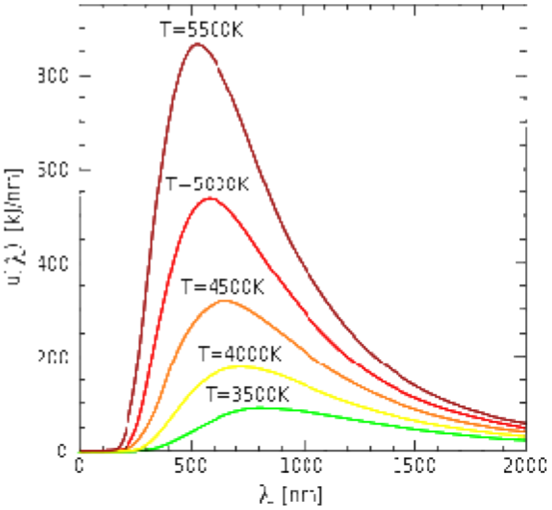
Dark matter is a type of matter hypothesized in astronomy and cosmology to account for a large part of the mass that appears to be missing from the universe. Dark matter cannot be seen directly with telescopes; evidently it neither emits nor absorbs light or other electromagnetic radiation at any significant 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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