

# Indeterministic Physics

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*Classical physics is characterized by the precision of its equations describing the evolution of the world as determined by the initial conditions of the Big Bang—meaning there is no room for chance. [34]*

*There was a period in the very early universe—known as the "cosmic dark ages"—when elementary particles, formed in the Big Bang, had combined to form neutral hydrogen but no stars or galaxies existed yet to light up the universe. [33]*

*New observations and analysis made by a team of astronomers at Yonsei University (Seoul, South Korea), together with their collaborators at Lyon University and KASI, show, however, that this key assumption is most likely in error. [32]*

*Key components for the sky-mapping Dark Energy Spectroscopic Instrument (DESI), weighing about 12 tons, were hoisted atop the Mayall Telescope at Kitt Peak National Observatory (KPNO) near Tucson, Arizona, and bolted into place Wednesday, marking a major project milestone. [31]*

*Scientists at the University of Oxford may have solved one of the biggest questions in modern physics, with a new paper unifying dark matter and dark energy into a single phenomenon: a fluid which possesses 'negative mass.' [30]*

*Researchers at the Max Planck Institute for Radio Astronomy in Bonn, Germany, have proposed a new experiment that makes use of super-dense stars to learn more about the interaction of dark matter with standard matter. [29]*

*CfA astronomer Qirong Zhu led a group of four scientists investigating the possibility that today's dark [HYPERLINK "https://phys.org/tags/matter/"](https://phys.org/tags/matter/) matter is composed of primordial black holes, following up on previously published suggestions. If galaxy halos are made of black holes, they should have a different density distribution than halos made of exotic particles. [28]*

*A signal caused by the very first stars to form in the universe has been picked up by a tiny but highly specialised radio telescope in the remote Western Australian desert. [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 [HYPERLINK "https://phys.org/tags/detector/"](https://phys.org/tags/detector/) 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

The Big Bang.....	6
Indeterminist physics for an open world.....	6
Leaving the language of classical mathematics behind for the language of intuitionistic mathematics .....	7
Open physics based on intuition instead of postulates .....	7
Astronomers detect first stars 'bubbling out' from the cosmic Dark Ages .....	8
New evidence shows that the key assumption made in the discovery of dark energy is in error.....	9
Key components of the Dark Energy Spectroscopic Instrument are installed atop the Mayall Telescope.....	10
Bringing balance to the universe: New theory could explain missing 95 percent of the cosmos .....	13
A new experiment to understand dark matter.....	14
Is dark matter made of primordial black holes? .....	16
Signal detected from the first stars in the universe, with a hint that dark matter was involved .....	17
Tuning in to the signal .....	18
An early result.....	19
Evidence of dark matter?.....	20
Here comes the 'but' .....	21
More desert observations .....	21
Physicists contribute to dark matter detector success.....	22
The search for dark matter—axions have ever-fewer places to hide.....	23
MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs: New candidate for dark matter .....	25
SIMPs interact with themselves, but not others .....	26
Ongoing searches for WIMPs and axions.....	28
Physicists Create Theory on Self-Interacting Dark Matter.....	29
The hunt for light dark matter .....	30
Sensing the unseen.....	31
From idea, to reality, to beyond.....	32
Looking at dark matter .....	33
What's the (dark) matter? .....	33
In the dark.....	33
Dark candidates.....	34

Dark matter turns light .....	35
Scoping the halo .....	35
A silent search for dark matter .....	36
3 knowns and 3 unknowns about dark matter .....	37
What's known:.....	37
What's unknown.....	37
New theory on the origin of dark matter.....	37
Dark Energy Survey reveals most accurate measurement of dark matter structure in the universe.....	38
Mapping dark matter .....	40
Dark matter is likely 'cold,' not 'fuzzy,' scientists report after new simulations .....	41
This New Explanation For Dark Matter Could Be The Best One Yet.....	43
Dark Matter Recipe Calls for One Part Superfluid.....	45
Impossible Superfluids .....	45
XENON1T, the most sensitive detector on Earth searching for WIMP dark matter, releases its first result .....	46
Out with the WIMPs, in with the SIMPs?.....	47
Dark matter composition research - WIMP .....	48
Weakly interacting massive particles .....	49
Evidence for an accelerating universe .....	49
Equation.....	50
Explanatory models .....	51
Dark Matter and Energy .....	51
Cosmic microwave background .....	51
Thermal radiation.....	51
Electromagnetic Field and Quantum Theory .....	52
Lorentz transformation of the Special Relativity .....	53
The Classical Relativistic effect.....	53
Electromagnetic inertia and Gravitational attraction .....	53
Electromagnetic inertia and mass.....	54
Electromagnetic Induction .....	54
Relativistic change of mass .....	54
The frequency dependence of mass.....	54
Electron – Proton mass rate .....	54
Gravity from the point of view of quantum physics .....	55

The Gravitational force .....	55
The Graviton .....	55
Conclusions .....	55
References .....	56

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## 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.

## Indeterminist physics for an open world

Classical physics is characterized by the precision of its equations describing the evolution of the world as determined by the initial conditions of the Big Bang—meaning there is no room for chance. Yet our day-to-day experience and intuition are struck by this deterministic vision of the world: has everything really been written in advance? Is randomness nothing more than an illusion? A physicist from UNIGE, Swizerland, has been analyzing the classical mathematical language used in modern physics. He has thrown light on a contradiction between the equations that are supposed to explain the phenomena that surround us and the finite world. He suggests making changes to the mathematical language to allow randomness and indeterminism to become part of classical physics, thereby bringing it closer to quantum physics. Thanks to these observations, which are published in the journal *Nature Physics*, a revolution is sweeping through classical physics and paving the way for potentially different futures.

In [classical physics](#), or Newton's [physics](#), it is accepted that everything has already been determined since the Big Bang. The evolution of the world is explained by mathematical equations that describe the world as unfolding from these initial conditions in the most precise

way. For this, physicists employ the [language](#) of classical mathematics and represent these initial conditions by real numbers. "These numbers are characterized by an infinite number of decimals that follow the dot," says Nicolas Gisin, professor emeritus at the Department of Applied Physics, UNIGE's Faculty of Science and the author of the observation. "This implies that they contain an infinite amount of information." Such typical real numbers are far more numerous than numbers that have a name, such as Pi, and consist of a series of decimals that are completely random. We do not encounter them in everyday life but their existence is an accepted postulate in classical maths and they are used in many equations in physics. There is a problem, however: given that our world is finite, how can it include numbers that are infinite and that feature an infinite amount of information?

### **Leaving the language of classical mathematics behind for the language of intuitionistic mathematics**

To circumvent the impossibility that the finite contains the infinite, professor Gisin suggests going back to the source of classical physics and changing the [mathematical language](#) so that we no longer have to resort to real numbers. "There is another mathematical language, called intuitionistic, which doesn't believe in the existence of the infinite," continues the Geneva physicist. "But it was completely crushed by the classic mathematical language at the beginning of the twentieth century." Instead of real numbers containing an infinite number of decimals at a given moment, intuitionistic mathematics represents these numbers as a random process that takes place over time, one decimal after the other, so that at each given moment there is only a finite number of decimals, and—it follows—a finite amount of information. " This solves the contradiction of classical physics, which uses infinity to explain the finite," adds professor Gisin.

There is another difference between the two mathematical languages: the truth of propositions. "In classical maths, a proposition is always either true or false, according to the law of excluded middle. But in intuitionistic maths, a proposition is either true, false or indeterminate. So, there is an accepted part of indeterminacy," continues professor Gisin. This indeterminacy is much closer to our everyday experience than the most absolute determinism advocated by classical physics. In addition, randomness is also found in [quantum physics](#). "Some people endeavor to avoid it at all costs by involving other variables based on real numbers. But in my opinion, we shouldn't try to bring quantum physics closer to classical physics by attempting to eliminate randomness. Quite the opposite: we must bring classical physics closer to quantum physics by finally incorporating indeterminacy," says the Geneva-based physicist.

### **Open physics based on intuition instead of postulates**

Our vision of the world is constructed via the language we speak. If we choose the language of classical mathematics, we will talk easily about determinism. If, on the contrary, we choose the language of intuitionistic mathematics, we will easily move towards indeterminism. "I now consider that we have accepted too many postulates in classical physics, meaning we have integrated a form of determinism that wasn't necessarily on any ground. On the other hand, if we choose to base classical physics on intuitionistic mathematics, it will also become indeterminate, like quantum physics, and will be closer to our actual experience, opening up possibilities for our future," explains professor Gisin.

"This change of language wouldn't change the results of research conducted to date but it would make it easier to understand quantum physics and eventually to abandon a worldview where everything is already written, making room for new perspectives, randomness, chance and creativity," concludes professor Gisin. [34]

## **Astronomers detect first stars 'bubbling out' from the cosmic Dark Ages**

Astronomers using the Mayall telescope at Kitt Peak National Observatory, a program of NSF's National Optical-Infrared Astronomy Research Laboratory, have identified several overlapping bubbles of hydrogen gas ionized by the stars in early galaxies, a mere 680 million years after the Big Bang. This is the earliest direct evidence from the period when the first generation of stars formed and began reionizing the hydrogen gas that permeated the universe.

There was a period in the very [early universe](#)—known as the "cosmic dark ages"—when elementary particles, formed in the Big Bang, had combined to form neutral hydrogen but no stars or galaxies existed yet to light up the universe. This period began less than half a million years after the Big Bang and ended with the formation of the first stars. While this stage in the evolution of our universe is indicated by computer simulations, direct evidence is sparse.

Now, astronomers using the infrared imager NEWFIRM on the 4-meter Mayall Telescope at the Kitt Peak National Observatory of NSF's National Optical-Infrared Astronomy Research Laboratory (OIR Lab), have reported imaging a group of galaxies, known as EGS77, that contains these first stars. EGS, or the Extended Groth Strip, is a region imaged by HST in 2005; it corresponds to a narrow strip of the sky about the width of a finger held at arms length. There are at least 50,000 galaxies known within the strip. Their results were announced at a press conference held today at the 235th meeting of the American Astronomical Society (AAS) in Honolulu, Hawai'i.

"The young universe was filled with hydrogen atoms, which so attenuate ultraviolet light that they block our view of early galaxies," said James Rhoads at NASA's Goddard Space Flight Center in Greenbelt, Maryland, who presented the findings at the AAS press conference. "EGS77 is the first galaxy group caught in the act of clearing out this cosmic fog."

The team began with an imaging survey designed to detect high redshift galaxies and combined these data with corresponding images taken by the Hubble Space Telescope. This enabled the team to compute what is known as a photometric redshift, a proxy for estimating distance. At these redshifts, a galaxy's light is shifted completely out of the range of wavelengths to which the human eye is sensitive (the visible spectrum) to longer (infrared) wavelengths. The criteria for selecting distant galaxy candidates included a clear detection of them in the special infrared narrowband filters used with NEWFIRM on the Mayall 4-meter telescope and a complete non-detection in the shorter wavelength optical filter bands used by Hubble. "The discovery of the two fainter galaxies in the group was only possible because of the special narrowband filter used with NEWFIRM," said team leader Vithal Tilvi, a researcher at Arizona State University in Tempe.

"Intense light from galaxies can ionize the surrounding hydrogen gas, forming bubbles that allow starlight to travel freely," said Tilvi. "EGS77 has formed a large bubble that allows its light to travel



to Earth without much attenuation. Eventually, bubbles like these grew around all galaxies and filled intergalactic space, clearing the way for light to travel across the universe."

EGS77 was discovered as part of the Cosmic Deep And Wide Narrowband (Cosmic DAWN) survey, for which Rhoads serves as principal investigator. The team imaged a small area in the constellation of Boötes using a custom-built filter on the National Optical Astronomy Observatory's Extremely Wide-Field InfraRed imager (NEWFIRM). Ron Probst, a DAWN team member who also helped to develop NEWFIRM, adds, "These results show the value of maintaining instruments at our national observatories that are powerful and can flexibly adapt to pursue new scientific questions, questions that may not have been in mind when an instrument was originally built."

Once identified, the distances and hence the ages of these galaxies were confirmed with spectra taken with the MOSFIRE spectrograph at the Keck I telescope at the W. M. Keck Observatory on Maunakea in Hawai'i. All three [galaxies](#) show strong emission lines of hydrogen Lyman alpha at a redshift ( $z = 7.7$ ), which means we are seeing them at about 680 million years after the Big Bang. The size of the ionized bubble around each was derived from computer modeling. These bubbles overlap spatially, but are large enough (about 2.2 million light-years) that Lyman alpha photons are redshifted before they reach the boundary of the bubble and can thus escape unscathed, allowing astronomers to detect them.

"We expected that reionization bubbles from this era in cosmic history would be rare and hard to find," said Sangeeta Malhotra, a collaborator at NASA GSFC, "so confirmation of this transition is important." This "cosmic dawn," the intermediate state between a neutral and an ionized universe, is something that has been predicted. Such discoveries are made possible by the availability of powerful astronomical instruments that can probe the universe in a way unimagined by past generations of astronomers.

This research will be presented in a forthcoming paper and is currently close to acceptance. [33]

## **New evidence shows that the key assumption made in the discovery of dark energy is in error**

The most direct and strongest evidence for the accelerating universe with dark energy is provided by the distance measurements using type Ia supernovae (SN Ia) for the galaxies at high redshift. This result is based on the assumption that the corrected luminosity of SN Ia through the empirical standardization would not evolve with redshift.

New observations and analysis made by a team of astronomers at Yonsei University (Seoul, South Korea), together with their collaborators at Lyon University and KASI, show, however, that this key assumption is most likely in error. The team has performed very high-quality (signal-to-[noise ratio](#)  $\sim 175$ ) spectroscopic observations to cover most of the reported nearby early-type host galaxies of SN Ia, from which they obtained the most direct and reliable measurements of population ages for these host galaxies. They find a significant correlation between

SN [luminosity](#) and stellar population age at a 99.5 percent confidence level. As such, this is the most direct and stringent test ever made for the luminosity evolution of SN Ia. Since SN progenitors in host galaxies are getting younger with redshift (look-back time), this result inevitably indicates a serious systematic bias with redshift in SN cosmology. Taken at face values, the luminosity evolution of SN is significant enough to question the very existence of [dark energy](#). When the luminosity evolution of SN is properly taken into account, the team found that the evidence for the existence of dark [energy](#) simply goes away (see Figure 1).

Commenting on the result, Prof. Young-Wook Lee (Yonsei Univ., Seoul), who led the project said, "Quoting Carl Sagan, extraordinary claims require extraordinary evidence, but I am not sure we have such extraordinary evidence for dark energy. Our result illustrates that dark energy from SN cosmology, which led to the 2011 Nobel Prize in Physics, might be an artifact of a fragile and false assumption."

Other cosmological probes, such as the [cosmic microwave background](#) (CMB) and baryonic acoustic oscillations (BAO), are also known to provide some indirect and "circumstantial" evidence for dark energy, but it was recently suggested that CMB from Planck mission no longer supports the concordance cosmological model which may require new physics (Di Valentino, Melchiorri, & Silk 2019). Some investigators have also shown that BAO and other low-redshift cosmological probes can be consistent with a non-accelerating universe without dark energy (see, for example, Tutusaus et al. 2017). In this respect, the present result showing the luminosity evolution mimicking dark energy in SN cosmology is crucial and very timely.

This result is reminiscent of the famous Tinsley-Sandage debate in the 1970s on luminosity evolution in observational cosmology, which led to the termination of the Sandage project originally designed to determine the fate of the universe.

This work based on the team's 9-year effort at Las Campanas Observatory 2.5-m telescope and at MMT 6.5-m telescope was presented at the 235th meeting of the American Astronomical Society held in Honolulu on January 5th (2:50 PM in cosmology session, presentation No. 153.05). Their paper is also accepted for publication in the *Astrophysical Journal* and will be published in January 2020 issue. [32]

## **Key components of the Dark Energy Spectroscopic Instrument are installed atop the Mayall Telescope**

Key components for the sky-mapping Dark Energy Spectroscopic Instrument (DESI), weighing about 12 tons, were hoisted atop the Mayall Telescope at Kitt Peak National Observatory (KPNO) near Tucson, Arizona, and bolted into place Wednesday, marking a major project milestone.

DESI will create the largest 3-D map of the universe by gathering light from tens of millions of galaxies after its scheduled startup in late 2019. It is designed to provide more precise

measurements of dark energy, which is accelerating the universe's expansion and looms as one of the universe's biggest mysteries.

"Earlier this year we removed the old top-end of the Mayall Telescope, and Wednesday's installation brings this telescope back to life with a new purpose," said DESI Director Michael Levi of the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab), which is leading the project's international collaboration. "The more than 23,000 pounds of instrumentation that was installed represents the final top-end assembly."

The new top-end components include a 3.4-ton barrel-shaped, steel-framed structure, known as a corrector, that houses a precisely stacked array of large (the largest is 1.1 meters in diameter), delicate lenses.

Also, the corrector is attached to a 1.1-ton six-axis "hexapod" that enables precise alignment adjustments; a surrounding ring, cage, and vanes support structure that weighs an additional 5.2 tons; and about 2 tons of other materials, including placeholder weights for DESI's focal plane (see a related video), which is still under assembly and hasn't yet arrived on site.

In this time-lapse video, crews at the Mayall Telescope near Tucson, Arizona, lift and install the top-end components for the Dark Energy Spectroscopic Instrument, or DESI. The components, which include a stack of six lenses and other structures for [...more](#)

A team at Fermi National Accelerator Laboratory built the corrector, hexapod, and other top-end support structures. The structures are designed to align the lenses with an accuracy of tens of microns (millionths of a meter) – similar to the width of the thinnest human hair.

DESI involves more than 450 researchers from more than 70 institutions around the globe. KPNO is part of the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under a cooperative agreement with the National Science Foundation.

The corrector will enable a larger field of view – covering an area more than 40 times larger than the telescope's previous corrector, and more than 40 times the size of the full moon as seen from Earth's surface – for a series of 5,000 robotically positioned fiber-optic cables that will gather light from sequences of targeted galaxies. This light will be analyzed to gather information about their distance and the rate at which the galaxies are moving away from us. Its large field of view will allow DESI to map one-third of the night sky during its planned 5-year survey.

Each of the corrector's six lenses began as a large, thick piece of glass made by either Corning Glass in New York, Ohara Corp. in Japan, or Schott AG in Germany (see a related video). One of the lenses housed in the corrector is among the largest to ever be fielded on a telescope, noted Berkeley Lab's David Schlegel, a DESI project scientist. The lenses traveled the world for polishings and coatings at several companies, and were installed and precisely aligned inside the corrector barrel in a basement at the University College London last spring.



The corrector and associated components are raised above their final resting place. Credit: Robert Besuner/Berkeley Lab, DESI Collaboration

The corrector was then disassembled for transport and flown on a chartered transport plane from England to Tucson, Arizona. Then, it was trucked to the Kitt Peak summit, at an elevation of 6,800 feet. Once reassembled, the corrector was connected to its mechanical support system.

In June, a 250-foot mobile crane was used to lift the old top-end off of the telescope and out of the dome. A 50-ton crane in the dome of the Mayall Telescope was used to lift all the DESI top-end components up to the dome floor from the ground level, where they were assembled. The same dome crane was then used to lift the assembled DESI top-end into position atop the telescope.

David Sprayberry, the KPNO site director for DESI, said, "This was a complex lift that went without a hitch. We had a dozen of our technical personnel ensuring that the new top-end would be positioned exactly onto the center of the telescope. I'm very proud of my team for pulling this off flawlessly."

Early next year, researchers will mount a set of cameras and other instruments onto DESI's focal plane to test how the lenses perform across the entire imaging field. This commissioning camera array was built at Ohio State University.



The corrector is lowered onto its telescope mount. Credit: Robert Besuner/Berkeley Lab, DESI Collaboration "This will be a real test to determine if all the lenses are working together perfectly," said Paul Martini, a professor at Ohio State University who oversaw the development of the commissioning camera.

Then, other DESI systems will be tested over the next several months until the entire instrument is ready to begin its sky survey. [31]

## **Bringing balance to the universe: New theory could explain missing 95 percent of the cosmos**

Scientists at the University of Oxford may have solved one of the biggest questions in modern physics, with a new paper unifying dark matter and dark energy into a single phenomenon: a fluid which possesses 'negative mass.' If you were to push a negative mass, it would accelerate towards you. This astonishing new theory may also prove right a prediction that Einstein made 100 years ago.

Our current, widely recognised model of the Universe, called LambdaCDM, tells us nothing about what dark matter and dark energy are like physically. We only know about them because of the gravitational effects they have on other, observable matter.

This new model, published today in *Astronomy and Astrophysics*, by Dr. Jamie Farnes from the Oxford e-Research Centre, Department of Engineering Science, offers a new explanation. Dr. Farnes says: "We now think that both dark matter and dark energy can be unified into a fluid which possesses a type of 'negative gravity,' repelling all other material around them. Although this matter is peculiar to us, it suggests that our cosmos is symmetrical in both positive and negative qualities."

The existence of negative matter had previously been ruled out as it was thought this material would become less dense as the Universe expands, which runs contrary to our observations that show dark energy does not thin out over time. However, Dr. Farnes' research applies a 'creation tensor,' which allows for negative masses to be continuously created. It demonstrates that when more and more negative masses are continually bursting into existence, this negative mass fluid does not dilute during the expansion of the cosmos. In fact, the fluid appears to be identical to dark energy.

Dr. Farnes's theory also provides the first correct predictions of the behaviour of dark matter halos. Most galaxies are rotating so rapidly they should be tearing themselves apart, which suggests that an invisible 'halo' of dark matter must be holding them together. The new research published today features a computer simulation of the properties of negative mass, which predicts the formation of dark matter halos just like the ones inferred by observations using modern radio telescopes.

Albert Einstein provided the first hint of the dark universe exactly 100 years ago, when he discovered a parameter in his equations known as the 'cosmological constant,' which we now know to be synonymous with dark energy. Einstein famously called the cosmological constant his 'biggest blunder,' although modern astrophysical observations prove that it is a real phenomenon. In notes dating back to 1918, Einstein described his cosmological constant, writing that 'a modification of the theory is required such that "empty space" takes the role of gravitating negative masses which are distributed all over the interstellar space.' It is therefore possible that Einstein himself predicted a negative-mass-filled universe.

Dr. Farnes says: "Previous approaches to combining dark energy and dark matter have attempted to modify Einstein's theory of general relativity, which has turned out to be incredibly challenging. This new approach takes two old ideas that are known to be compatible with Einstein's theory—negative masses and matter creation—and combines them together.

"The outcome seems rather beautiful: dark energy and dark matter can be unified into a single substance, with both effects being simply explainable as positive mass matter surfing on a sea of negative masses."

Proof of Dr. Farnes's [theory](#) will come from tests performed with a cutting-edge radio telescope known as the Square Kilometre Array (SKA), an international endeavour to build the world's largest telescope in which the University of Oxford is collaborating.

Dr. Farnes adds: "There are still many theoretical issues and computational simulations to work through, and LambdaCDM has a nearly 30 year head start, but I'm looking forward to seeing whether this new extended version of LambdaCDM can accurately match other observational evidence of our cosmology. If real, it would suggest that the missing 95% of the cosmos had an aesthetic solution: we had forgotten to include a simple minus sign." [30]

## **A new experiment to understand dark matter**

Is dark matter a source of a yet unknown force in addition to gravity? The mysterious dark matter is little understood and trying to understand its properties is an important challenge in modern physics and astrophysics. Researchers at the Max Planck Institute for Radio Astronomy in Bonn,

Germany, have proposed a new experiment that makes use of super-dense stars to learn more about the interaction of dark matter with standard matter. This experiment already provides some improvement in constraining dark matter properties, but even more progress is promised by explorations in the centre of our Milky Way that are underway.

The findings are published in the journal *Physical Review Letters*.

Around 1600, Galileo Galilei's experiments brought him to the conclusion that in the gravitational field of the Earth all bodies, independent of their mass and composition feel the same acceleration. Isaac Newton performed pendulum experiments with different materials in order to verify the so-called universality of free fall and reached a precision of 1:1000. More recently, the satellite experiment MICROSCOPE managed to confirm the universality of free fall in the gravitational field of the Earth with a precision of 1:100 trillion.

These kind of experiments, however, could only test the universality of free fall towards ordinary matter, like the Earth itself whose composition is dominated by iron (32 percent), oxygen (30 percent), silicon (15 percent) and magnesium (14 percent). On large scales, however, ordinary matter seems to be only a small fraction of matter and energy in the universe.

It is believed that the so-called dark matter accounts for about 80 percent of the matter in our universe. Until today, dark matter has not been observed directly. Its presence is only indirectly inferred from various astronomical observations like the rotation of galaxies, the motion of galaxy clusters, and gravitational lenses. The actual nature of dark matter is one of the most prominent questions in modern science. Many physicists believe that dark matter consists of so far undiscovered sub-atomic particles.

With the unknown nature of dark matter another important question arises: is gravity the only long-range interaction between normal matter and dark matter? In other words, does matter only feel the space-time curvature caused by dark matter, or is there another force that pulls matter towards dark matter, or maybe even pushes it away and thus reduces the overall attraction between normal matter and dark matter. That would imply a violation of the universality of free fall towards dark matter. This hypothetical force is sometimes labeled as "fifth force," besides the well-known four fundamental interactions in nature (gravitation, electromagnetic & weak interaction, strong interaction).

At present, there are various experiments setting tight limits on such a fifth force originating from dark matter. One of the most stringent experiments uses the Earth-Moon orbit and tests for an anomalous acceleration towards the galactic center, i.e. the center of the spherical dark matter halo of our galaxy. The high precision of this experiment comes from Lunar Laser Ranging, where the distance to the Moon is measured with centimeter precision by bouncing laser pulses of the retro reflectors installed on the Moon.

Until today, nobody has conducted such a fifth force test with an exotic object like a neutron star. "There are two reasons that binary pulsars open up a completely new way of testing for such a fifth force between normal matter and dark matter," says Lijing Shao from the Max Planck Institute for Radio Astronomy (MPIfR) in Bonn, Germany, the first author of the publication in *Physical Review Letters*. "First, a neutron star consists of matter which cannot be constructed in a laboratory, many

times denser than an atomic nucleus and consisting nearly entirely of neutrons. Moreover, the enormous gravitational fields inside a neutron star, billion times stronger than that of the Sun, could in principle greatly enhance the interaction with dark matter."

The orbit of a binary pulsar can be obtained with high precision by measuring the arrival time of the radio signals of the pulsar with radio telescopes. For some pulsars, a precision of better than 100 nanoseconds can be achieved, corresponding to a determination of the pulsar orbit with a precision better than 30 meters.

To test the universality of free fall towards dark matter, the research team identified a particularly suitable binary pulsar, named PSR J1713+0747, which is at a distance of about 3800 light years from the Earth. This is a millisecond pulsar with a rotational period of just 4.6 milliseconds and is one of the most stable rotators amongst the known pulsar population. Moreover, it is in a nearly circular 68-day orbit with a white dwarf companion.

While pulsar astronomers usually are interested in tight binary pulsars with fast orbital motion when testing general relativity, the researchers were now looking for a slowly moving millisecond pulsar in a wide orbit. The wider the orbit, the more sensitive it reacts to a violation of the universality of [free fall](#). If the pulsar feels a different acceleration towards dark matter than the white dwarf companion, one should see a deformation of the binary orbit over time, i.e. a change in its eccentricity.

"More than 20 years of regular high precision timing with Effelsberg and other radio telescopes of the European Pulsar Timing Array and the North American NANOGrav [pulsar](#) timing projects showed with high precision that there is no change in the eccentricity of the orbit," explains Norbert Wex, also from MPIfR. "This means that to a high degree the neutron star feels the same kind of attraction towards dark matter as towards other forms of standard [matter](#)."

"To make these tests even better, we are busily searching for suitable pulsars near large amounts of expected [dark matter](#)," says Michael Kramer, director at MPIfR and head of its "Fundamental Physics in Radio Astronomy" research group. "The ideal place is the galactic centre where we use Effelsberg and other telescopes in the world to have a look as part of our Black Hole Cam project. Once we will have the Square Kilometre Array, we can make those tests super-precise," he concludes. [29]

## **Is dark matter made of primordial black holes?**

Astronomers studying the motions of galaxies and the character of the cosmic microwave background radiation came to realize in the last century that most of the matter in the universe was not visible. About 84 percent of the matter in the cosmos is dark matter, much of it located in halos around galaxies. It was dubbed dark matter because it does not emit light, but it is also mysterious: it is not composed of atoms or their usual constituents like electrons and protons.



Meanwhile, astronomers have observed the effects of black holes and recently even detected gravitational waves from a pair of merging black holes. Black holes usually are formed in the explosive death of massive stars, a process that can take many hundreds of millions of years as a star coalesces from ambient gas, evolves and finally dies. Some black holes are inferred to exist in the early universe, but there is probably not enough time in the [early universe](#) for the normal formation process to occur. Some alternative methods have been proposed, like the direct collapse of primordial gas or processes associated with cosmic inflation, and many of these primordial black holes could have been made.

CfA astronomer Qirong Zhu led a group of four scientists investigating the possibility that today's dark [matter](#) is composed of primordial black holes, following up on previously published suggestions. If galaxy halos are made of black holes, they should have a different density distribution than halos made of exotic particles. There are some other differences as well—black hole halos are expected to form earlier in a galaxy's evolution than do some other kinds of halos.

The scientists suggest that looking at the stars in the halos of faint dwarf galaxies can probe these effects because dwarf galaxies are small and faint (they shine with a mere few thousand solar luminosities) where slight effects can be more easily spotted.

The team ran a set of computer simulations to test whether dwarf galaxy halos might reveal the presence of [primordial black holes](#), and they find that they could: interactions between stars and primordial [halo](#) black holes should slightly alter the sizes of the stellar distributions.

The astronomers also conclude that such black holes would need to have masses between about two and fourteen solar masses, right in the expected range for these exotic objects (although smaller than the [black holes](#) recently spotted by gravitational wave detectors) and comparable to the conclusions of other studies.

The team emphasizes, however, that all the models are still inconclusive and the nature of [dark matter](#) remains elusive. [28]

## **Signal detected from the first stars in the universe, with a hint that dark matter was involved**

A signal caused by the very first stars to form in the universe has been picked up by a tiny but highly specialised radio telescope in the remote Western Australian desert.

Details of the detection are revealed in a paper [published today in Nature](#) and tell us these stars formed only 180 million years after the Big Bang.

It's potentially one of the most exciting astronomical discoveries of the decade. A [second Nature paper out today](#) links the finding to possibly the first detected evidence that dark matter, thought to make up much of the universe, might interact with ordinary atoms.

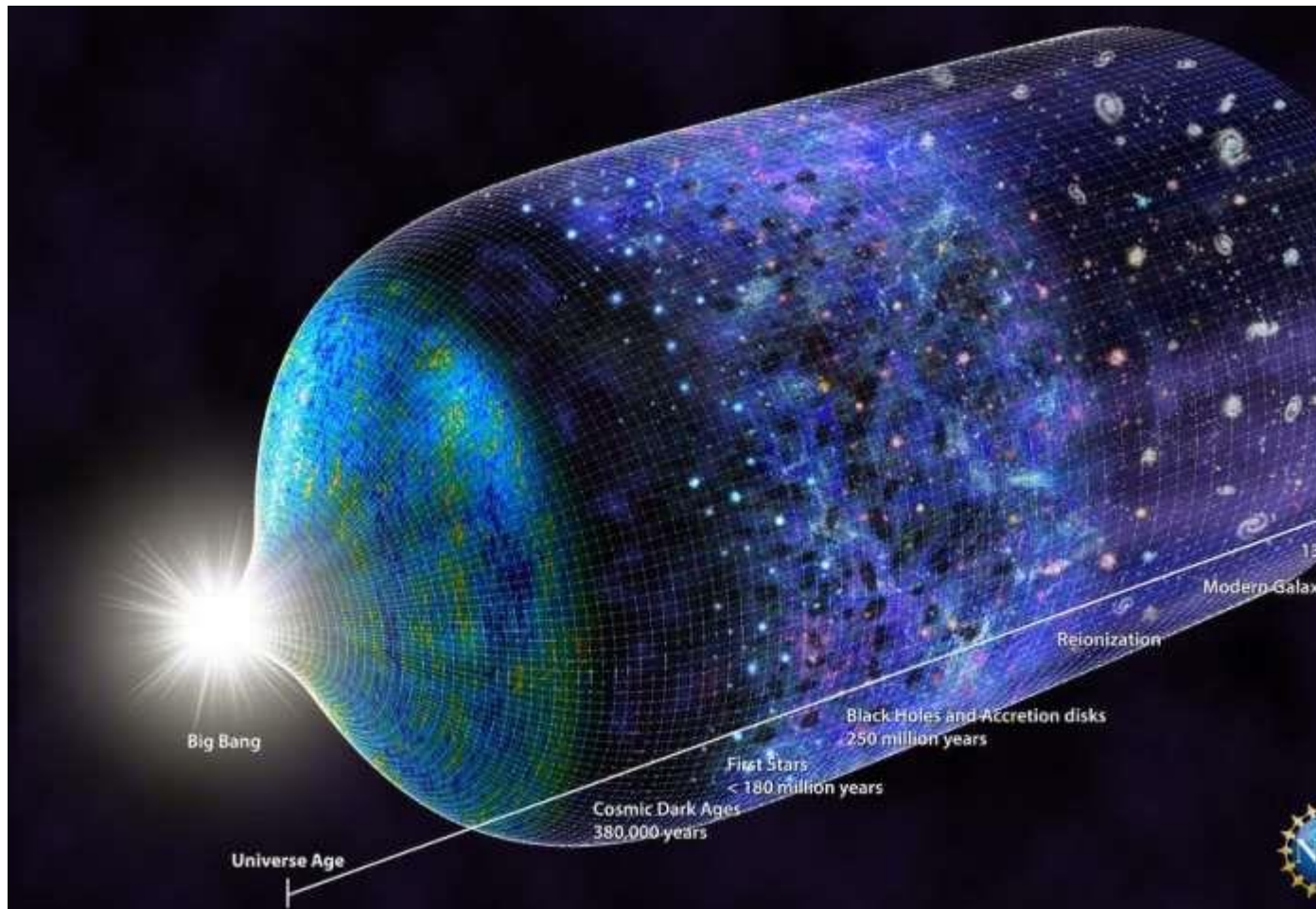
## Tuning in to the signal

This discovery was made by a small radio antenna operating in the band of 50-100MHz, which overlaps some well known FM radio stations (which is why the telescope is located in the remote WA desert).

What has been detected is the absorption of light by neutral atomic hydrogen gas, which filled the early universe after it cooled down from the hot plasma of the Big Bang.

At this time (180 million years after the Big Bang) the early universe was expanding, but the densest regions of the universe were collapsing under gravity to make the first stars.

The formation of the first stars had a dramatic effect on the rest of the universe. Ultraviolet radiation from them changed the electron spin in the hydrogen atoms, causing it to absorb the background radio emission of the universe at a natural resonant frequency of 1,420MHz, casting a shadow so to speak.



A timeline of the universe, updated to show when the first stars emerged emerged by 180 million years after the Big Bang. Credit: N.R. Fuller, National Science Foundation

Now, 13 billion years later, that shadow would be expected at a much lower frequency because the universe has expanded nearly 18-fold in that time.

## An early result

Astronomers had been predicting this phenomenon for nearly 20 years and searching for it for ten years. No one quite knew how strong the signal would be or at what frequency to search.

Most expected it would take quite a few more years post 2018.

But the shadow was detected at 78MHz by a team led by astronomer Judd Bowman from Arizona State university.

Amazingly this radio signal detection in 2015-2016 was done by a small aerial (the [EDGES](#) experiment), only a few metres in size, coupled to a very clever radio receiver and signal processing system. It's only been published now after rigorous checking.

This is the most important astronomical discovery since the detection of gravitational waves in 2015. The first stars represent the start of everything complex in the universe, the beginning of the long journey to galaxies, solar systems, planets, life and brains.



The EDGES ground-based radio spectrometer, CSIRO's Murchison Radio-astronomy Observatory in Western Australia. Credit: CSIRO

Detecting their signature is a milestone and pinning down the exact time of their formation is an important measurement for cosmology.

This is an amazing result. But it gets better and even more mysterious and exciting.

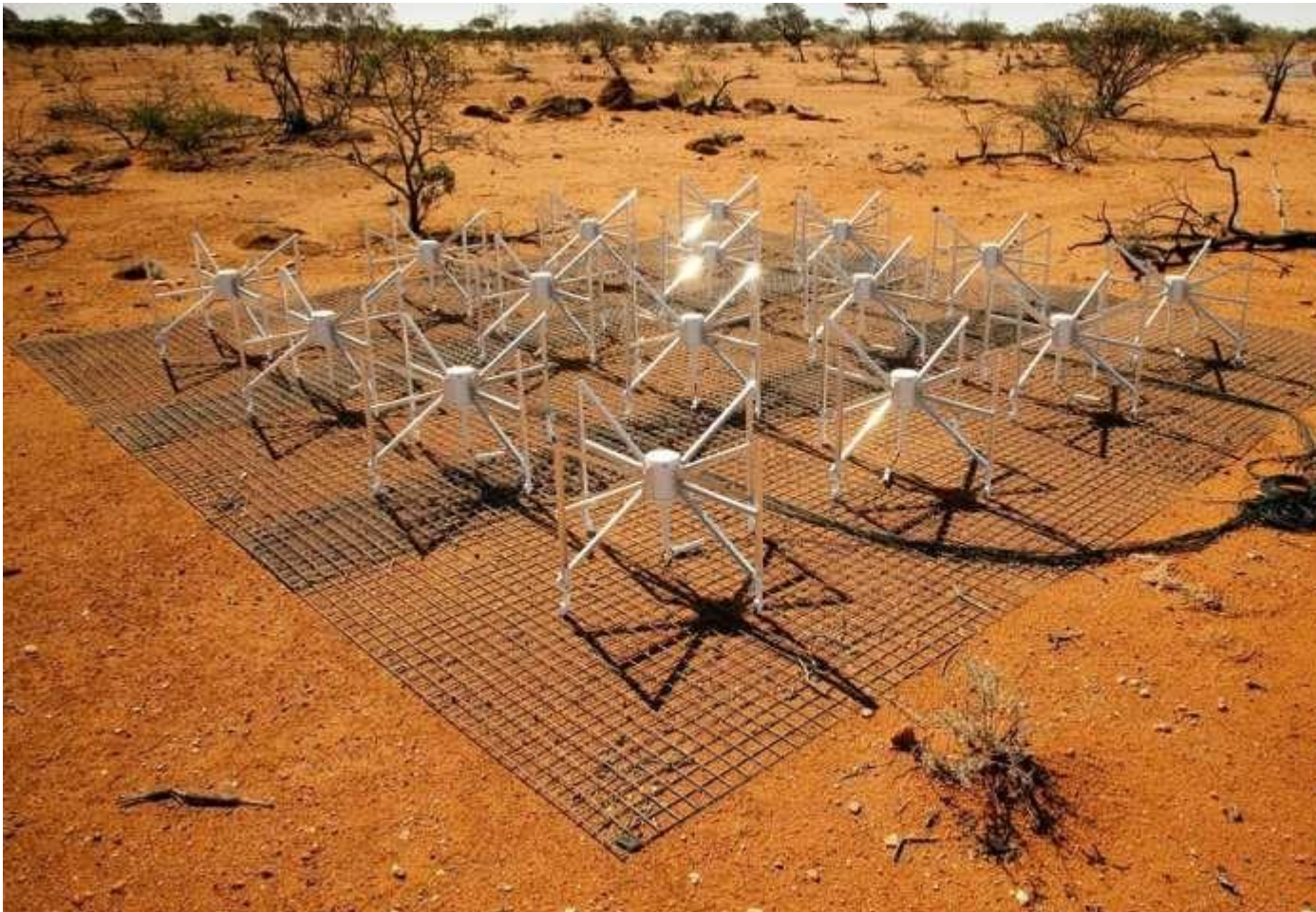
### **Evidence of dark matter?**

The signal is twice as strong as expected, which is why it has been detected so early. In the [second Nature paper](#), astronomer Rennan Barkana, from the Tel Aviv University, said it is quite hard to explain why the signal is so strong, as it tells us the hydrogen gas at this time is significantly colder than expected in the standard model of cosmic evolution.

Astronomers like to introduce new kinds of exotic objects to explain things (e.g. super massive stars, black holes) but these generally produce radiation that makes things hotter instead.

How do you make the atoms colder? You have to put them in thermal contact with something even colder, and the most viable suspect is what is known as [cold dark matter](#).

Cold dark matter is the bedrock of modern cosmology. It was introduced in the 1980s to explain how galaxies rotate—they seemed to spin much faster than could be explained by the visible stars and an extra gravitational force was needed.



One of 128 tiles of the Murchison Widefield Array (MWA) telescope. Credit: Flickr/Australian SKA Office/WA Department of Commerce, CC BY-ND

We now think that dark matter has to be made of a new kind of fundamental particle. There is about six times more dark matter than ordinary matter and if it was made of normal atoms the Big Bang would have looked quite different to what is observed.

As for the nature of this particle, and its mass, we can only guess.

So if cold dark matter is indeed colliding with hydrogen atoms in the early universe and cooling them, this is a major advance and could lead us to pin down its true nature. This would be the first time dark matter has demonstrated any interaction other than gravity.

### Here comes the 'but'

A note of caution is warranted. This hydrogen signal is very difficult to detect: it is thousands of times fainter than the background radio noise even for the remote location in Western Australia.

The authors of the first Nature paper have spent more than a year doing a multitude of tests and checks to make sure they have not made a mistake. The sensitivity of their aerial needs to be exquisitely calibrated all across the bandpass. The detection is an impressive technical achievement but astronomers worldwide will be holding their breath until the result is confirmed by an independent experiment.

If it is confirmed then this will open the door to a new window on the early universe and potentially a new understanding of the nature of dark matter by providing a new observational window in to it.

This signal has been detected coming from the whole sky, but in the future it can be mapped on the sky, and the details of the structures in the maps would then give us even more information on the physical properties of the dark matter.

### More desert observations

Today's publications are exciting news for Australia in particular. Western Australia is the most radio quiet zone in the world, and will be the prime location for future mapping observations. The Murchison Widefield Array is in operation right now, and future upgrades could provide exactly such a map.

This is also a major science goal of the multi-billion dollar Square Kilometre Array, located in Western Australia, that should be able to provide much greater fidelity pictures of this epoch.

It is extremely exciting to look forward to a time when we will be able to reveal the nature of the first stars and to have a new approach via radio astronomy to tackle [dark matter](#), which has so far proved intractable.

Let's hope the governments of the world, or at least Australia, can keep the frequency of 78 MHz clean of pop music and talk shows so we can continue to observe the birth of the universe.

## 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.

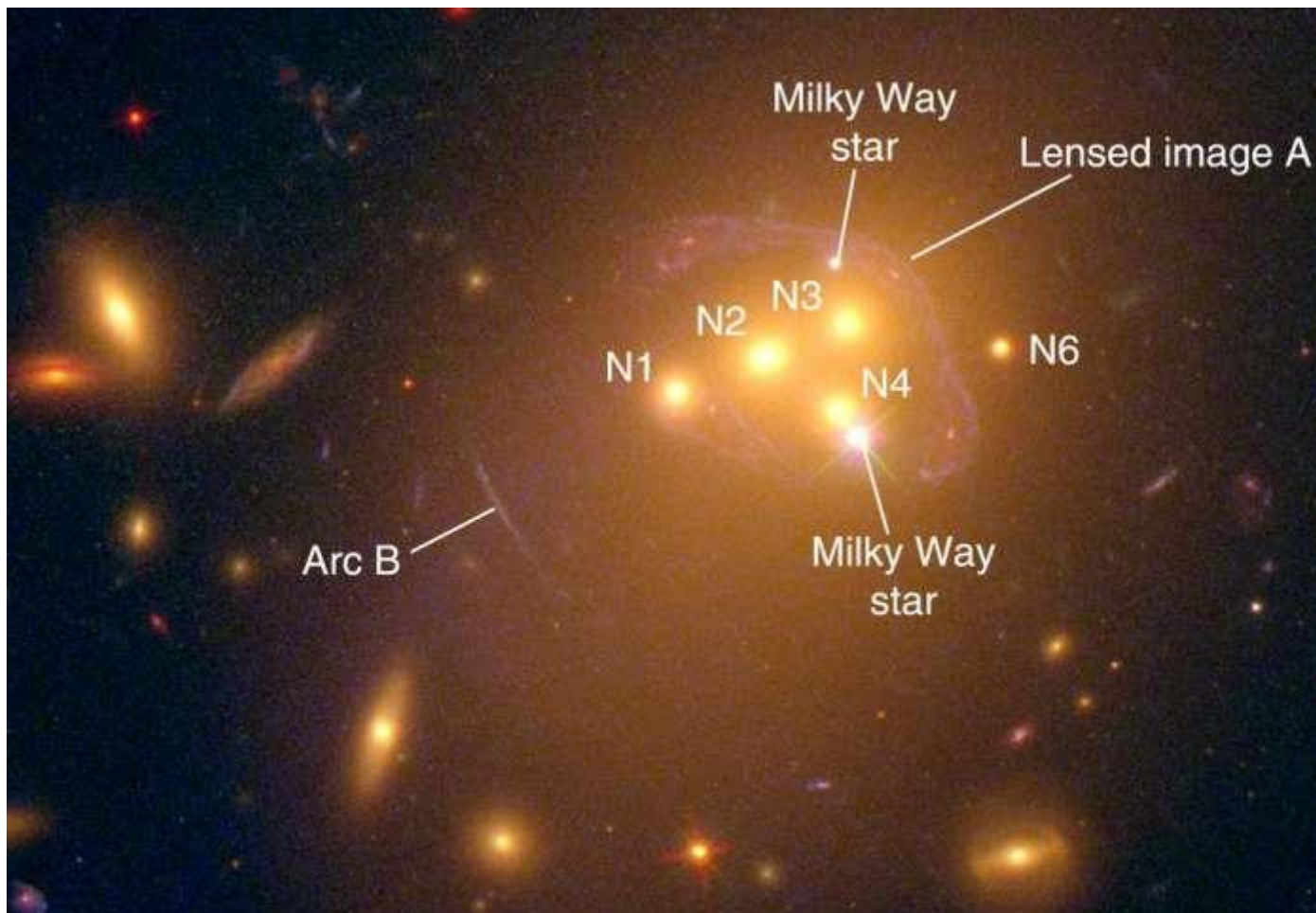
"There has been this longstanding puzzle: If you look at dwarf galaxies, which are very small with rather few stars, they are really dominated by dark matter. And if you go through numerical simulations of how dark matter clumps together, they always predict that there is a huge concentration towards 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 of 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 to 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 like a 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-to-day 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 begun 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 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 Institute 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 Iršič, 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, Iršić 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, Iršić 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 Iršić.

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 Iršić. 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 Iršić 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, Iršić added.

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

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](https://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 so-called "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 its 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  $-95^{\circ}\text{C}$  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 begun 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 supersymmetric 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 differs 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 superparticles 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]



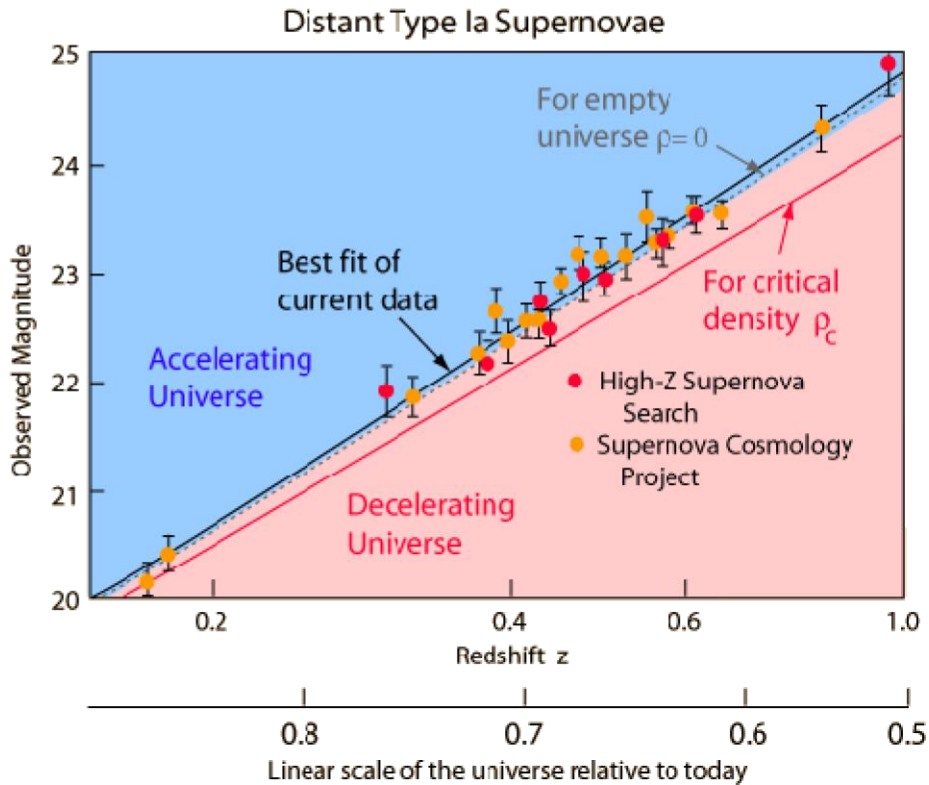
## Weakly interacting massive particles

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 Ia supernovae around  $z=0.6$ , which with a Hubble constant of 71 km/s/pc is a distance of about 5 billion light years.

### Equation

The cosmological constant  $\Lambda$  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  $\Lambda$  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,  $\rho_{\text{vac}}$  (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  $8\pi$ :  $\Lambda = 8\pi\rho_{\text{vac}}$ , 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

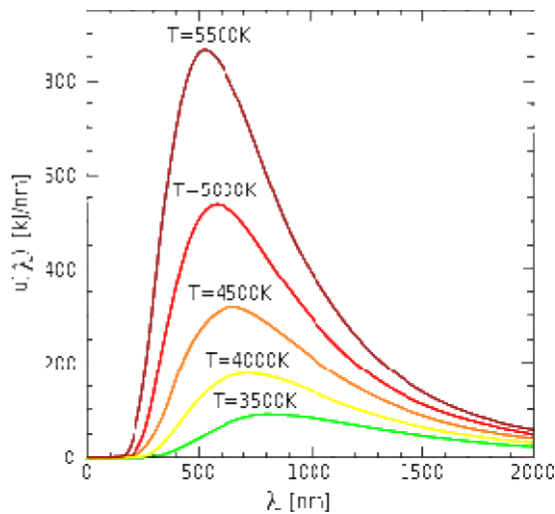
Dark matter is a type of matter hypothesized in astronomy and cosmology to account for a large part of the mass that appears to be missing from the universe. Dark matter cannot be seen directly with telescopes; evidently it neither emits nor absorbs light or other electromagnetic radiation at any significant 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  $\underline{A}$  vector potential experienced by the electrons moving by  $\underline{v}$  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  $\underline{E}$  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  $E = h\nu$  and  $E = mc^2$ ,  $m = h\nu/c^2$  that is the  $m$  depends only on the  $\nu$  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  $m_0$  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

Since  $E = h\nu$  and  $E = mc^2$ ,  $m = h\nu/c^2$  that is the  $m$  depends only on the  $\nu$  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  $m_0$  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.

### 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 Big 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 ratio  $M_p=1840 M_e$ . 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]

## References

- [1] 3 Dimensional String Theory

Author: George Rajna

Publisher: Academia.edu

[http://www.academia.edu/3834454/3\\_Dimensional\\_String\\_Theory](http://www.academia.edu/3834454/3_Dimensional_String_Theory)

- [2] Graviton Production By Two Photon and Electron-Photon Processes In Kaluza-Klein Theories With Large Extra Dimensions <http://arxiv.org/abs/hep-ph/9909392>

- [3] Higgs Field and Quantum Gravity

Author: George Rajna

Publisher: Academia.edu

[http://www.academia.edu/4158863/Higgs\\_Field\\_and\\_Quantum\\_Gravity](http://www.academia.edu/4158863/Higgs_Field_and_Quantum_Gravity)

- [4] The Magnetic field of the Electric current

Author: George Rajna

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[https://www.academia.edu/3833335/The\\_Magnetic\\_field\\_of\\_the\\_Electric\\_current](https://www.academia.edu/3833335/The_Magnetic_field_of_the_Electric_current)

- [5] [http://en.wikipedia.org/wiki/Einstein\\_field\\_equations](http://en.wikipedia.org/wiki/Einstein_field_equations)

- [6] [http://en.wikipedia.org/wiki/Dark\\_matter](http://en.wikipedia.org/wiki/Dark_matter)

- [7] [http://en.wikipedia.org/wiki/Cosmic\\_microwave\\_background](http://en.wikipedia.org/wiki/Cosmic_microwave_background)

- [8] [http://en.wikipedia.org/wiki/Thermal\\_radiation](http://en.wikipedia.org/wiki/Thermal_radiation)



- [9] <http://hyperphysics.phy-astr.gsu.edu/hbase/astro/univacc.html>
- [10] [http://en.wikipedia.org/wiki/Weakly\\_interacting\\_massive\\_particles](http://en.wikipedia.org/wiki/Weakly_interacting_massive_particles)
- [11] <http://www.darkmatterphysics.com/WIMP.htm>
- [12] <http://news.sciencemag.org/physics/2014/10/dark-matter-out-wimps-simps>
- [13] XENON1T, the most sensitive detector on Earth searching for WIMP dark matter, releases its first result  
<https://phys.org/news/2017-05-xenon1t-sensitive-detector-earth-wimp.html>
- [14] Dark Matter Recipe Calls for One Part Superfluid  
<https://www.quantamagazine.org/dark-matter-recipe-calls-for-one-part-superfluid-20170613/>
- [15] This New Explanation For Dark Matter Could Be The Best One Yet  
<http://www.sciencealert.com/this-new-explanation-for-dark-matter-could-be-the-best-one-yet>
- [16] Dark matter is likely 'cold,' not 'fuzzy,' scientists report after new simulations  
<https://phys.org/news/2017-07-dark-cold-fuzzy-scientists-simulations.html>
- [17] Mapping dark matter  
[https://phys.org/news/2017-07-dark\\_1.html](https://phys.org/news/2017-07-dark_1.html)
- [18] Dark Energy Survey reveals most accurate measurement of dark matter structure in the universe  
<https://phys.org/news/2017-08-dark-energy-survey-reveals-accurate.html>
- [19] New theory on the origin of dark matter  
<https://phys.org/news/2017-08-theory-dark.html>
- [20] 3 knowns and 3 unknowns about dark matter <https://phys.org/news/2016-06-knowns-unknowns-dark.html>
- [20] A silent search for dark matter  
<https://phys.org/news/2017-08-silent-dark.html>
- [21] Looking at dark matter  
<https://phys.org/news/2017-09-dark.html>
- [22] The hunt for light dark matter  
[https://phys.org/news/2017-09-dark\\_1.html](https://phys.org/news/2017-09-dark_1.html)
- [23] Physicists Create Theory on Self-Interacting Dark Matter  
<http://trendintech.com/2017/09/17/physicists-create-theory-on-self-interacting-dark-matter/>
- [24] MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs: New candidate for dark matter

<https://phys.org/news/2017-12-machos-dead-wimps-no-showsay-simps.html>

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

<https://phys.org/news/2018-02-dark-matteraxions-ever-fewer.html>

[26] Physicists contribute to dark matter detector success

<https://phys.org/news/2018-02-physicists-contribute-dark-detector-success.html>

[27] Signal detected from the first stars in the universe, with a hint that dark matter was involved

<https://phys.org/news/2018-03-stars-universe-hint-dark-involved.html>

[28] Is dark matter made of primordial black holes?

<https://phys.org/news/2018-04-dark-primordial-black-holes.html>

[29] A new experiment to understand dark matter

<https://phys.org/news/2018-06-dark.html>

[30] Bringing balance to the universe: New theory could explain missing 95 percent of the cosmos

<https://phys.org/news/2018-12-universe-theory-percent-cosmos.html>

[31] Key components of the Dark Energy Spectroscopic Instrument are installed atop the Mayall Telescope

<https://phys.org/news/2018-12-key-components-dark-energy-spectroscopic.html>

[32] New evidence shows that the key assumption made in the discovery of dark energy is in error

<https://phys.org/news/2020-01-evidence-key-assumption-discovery-dark.html>

[33] Astronomers detect first stars 'bubbling out' from the cosmic Dark Ages

<https://phys.org/news/2020-01-astronomers-stars-cosmic-dark-ages.html>

[34] Indeterminist physics for an open world

<https://phys.org/news/2020-01-indeterminist-physics-world.html>