Dark Matter and the WIMPs as its Prime Candidates By Yuvraj Arora

Abstract

This paper explores the enigmatic Dark Matter, emphasising the Weakly Interacting Massive Particles, or WIMPs, as potential candidates. Since dark matter, which makes up a significant portion of the universe's mass, cannot be detected by conventional physics, new theoretical models may be required. The WIMPs are intriguing because they show some agreement with the Standard Model's extensions, particularly supersymmetry, and provide answers to a variety of cosmological puzzles, such as how galaxies arise and the universe's large-scale structure. Due to the intricate interactions between particle physics and cosmology, the study discusses theoretical motives, experimental searches, and advancements in the quest for WIMP. The difficulties in detecting and developing theoretical frameworks to solve one of the universe's biggest mysteries are ultimately highlighted by this research.

Introduction

Before we start with Dark Matter, let's first talk about Normal Matter. Everything that we can see with the naked eye is made of normal matter. We can see it with our own eyes in visible light or using a telescope that can pick up invisible light, such as infrared or ultraviolet. Protons, neutrons, and electrons are the atomic particles that make up the majority of normal matter. It can exist as a liquid, solid, gas, or charged particle plasma. Even though we encounter normal matter on a daily basis, it makes up less than 5% of the universe. With that out of the way, let's get to the key matter of this paper.

Dark matter occupies space and has mass, much like ordinary matter. However, it doesn't emit, absorb, or reflect light—at least not enough for us to notice just yet. Although measurements indicate that dark matter accounts for around 27% of the universe, scientists are unsure of its nature. Several sorts of particles that are still unknown and hardly interact with regular matter are included in the theories (NASA).[1]

There's always been a debate about who actually discovered Dark Matter, and two of the scientists that this discovery has been attributed to the most are Fritz Zwicky and Vera Rubin. In order to explain the fast-moving galaxies in the Coma Cluster, Fritz Zwicky of the California Institute of Technology first used the term "dark matter" in 1933. When Vera Rubin of the Carnegie Institution studied galaxy rotation in the 1970s, she discovered evidence for dark matter. The existence of dark matter in galaxies, the interaction of dark matter halos during galactic cluster mergers, and the distribution of dark matter—or perhaps its absence—across various galaxy types are all supported by a lot more data today (Office of Science).[2]

The reasoning Fritz Zwicky gave to explain the existence of Dark Matter was along the lines of, 'as astronomers, we know how stars work, and if we measure the starlight from all the galaxies in the cluster that we see, we can determine how much mass is in these galaxies and in the whole cluster, we also know how gravity and the expanding Universe works, so if we measure the average redshift of the cluster, we know how far away it is, and based on how fast we see these galaxies moving, there must be at least a certain amount of mass in there due to gravity.' (Siegel)[3]

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[1] NASA. "Building Blocks - NASA Science." *Science.nasa.gov*, 2024, science.nasa.gov/universe/overview/building-blocks/#dark-matter. Accessed 27 Oct. 2024.
[2] Office of Science. "DOE Explains...Dark Matter." *Energy.gov*, www.energy.gov/science/doe-explainsdark-matter. Accessed 27 Oct. 2024.
[3] Siegel, Ethan. "Who Really Discovered Dark Matter: Fritz Zwicky or Vera Rubin?" *Forbes*, 24 Aug. 2021, www.forbes.com/sites/startswithabang/2021/08/24/who-really-discovered-dark-matter-fritz-zwicky-or-vera-rubin/. Accessed 27 Oct. 2024.

The mysterious movements of stars within galaxies are thought to be caused by dark matter, according to scientists. The search for dark matter data heavily relies on computers. They enable researchers to develop models that forecast the behaviour of galaxies. Additionally, satellites are collecting dark matter data. In 1997, a photograph taken with the Hubble Space Telescope showed that light from a distant galaxy cluster was being twisted by another galaxy cluster in the foreground. Scientists calculated that the foreground cluster's mass was 250 times more than the visible objects inside the cluster based on the way the light was bent. The cluster's dark matter is thought to be the cause of the unexplained mass (StarChild).[4]

Since acoustic oscillations in the Cosmic Microwave Background (CMB) reflect density variations that may eventually result in large-scale structures in the cosmos, they have been a significant indicator of the presence of Cold Dark Matter (CDM). These oscillations are shown by the different peaks in the CMB power spectrum, which are evidence of the interaction between CDM and baryonic matter. The former provides pressure against which the latter's gravity will bind structures. It highlights how the nature of CDM, which is non-relativistic, permits the density peaks to collapse into clusters and galaxies.

In contemporary cosmology, the CMB is mapped by high-precision observations from missions like Planck, which reveal information on the acoustic peaks in the power spectrum. Cosmologists can better understand how the universe evolves by deriving key attributes of CDM, such as its density and interaction characteristics, from the analysis of these peaks. This data confirms the existence of CDM and highlights its essential function in the early structure creation of the universe (Ghosh et al.).[5]

Galaxies can be discovered in clusters of hundreds or thousands, each with its own dark matter halo. The dark matter of the cluster, however, is not just the sum of its constituents. Both the movement of hot gas inside the cluster and individual galaxies are impacted by this dark matter. Similar to galaxies, astronomers can use the velocity of the visible material in a cluster to estimate the amount of unseen mass there. By analysing the gravitational attraction of the matter on light, researchers may also be able to estimate the amount of cluster dark matter. This process, called gravitational lensing, provides a separate indicator of a cluster's mass and position ("Dark Energy and Dark Matter | Center for Astrophysics").[6]

Now, I'll be discussing two examples of the aforementioned galaxy clusters in depth:

1. The Bullet Cluster

   Two sizable clusters of galaxies, separated by around 3.8 billion light-years, make up the enormous Bullet Cluster. The two groups seem to have collided in one of the most violent collisions in the universe since the Big Bang. Strong evidence for the existence of dark matter has been shown by the aftermath. According to a 2006 analysis by astronomers at NASA's Chandra X-ray Observatory, the impact heated the preexisting plasma to millions of degrees. Additionally, they used the Very Large Telescope, Magellan Telescope, and Hubble Space Telescope to acquire optical photos in Chile. Astronomers determined the mass of the Bullet Cluster by examining the gravitational lensing effects of the merged cluster, which are the bending and amplification of light from objects behind it. The observed gravitational

[4] StarChild. "StarChild: Dark Matter." *Nasa.gov*, 2019, starchild.gsfc.nasa.gov/docs/StarChild/universe_level2/darkmatter.html. Accessed 27 Oct. 2024.

[5] Ghosh, Subhajit, et al. "Dark Matter-Radiation Scattering Enhances CMB Phase Shift through Dark Matter-Loading." *ArXiv.org*, 2024, arxiv.org/abs/2405.08064. Accessed 14 Nov. 2024.

[6] "Dark Energy and Dark Matter | Center for Astrophysics." *Www.cfa.harvard.edu*, www.cfa.harvard.edu/research/topic/dark-energy-and-dark-matter. Accessed 27 Oct. 2024.

lensing must have been produced by unseen, or dark, matter, which is not subject to the same drag forces as the gas, as this map's mass does not match the visible matter, according to an overlay of it over the combined X-ray and optical pictures (O'Meara).[7] When looking at the area just in visible light, it is unclear that the Bullet Cluster is made up of two clusters of galaxies that collided and passed one another. The Bullet Cluster's multi-wavelength measurements provide the first concrete, observable proof that dark matter, which makes up the bulk of a galaxy cluster's mass, does not interact with either normal matter or with itself. X-rays reveal that the bulk of normal matter, in this instance gas, trails behind and is located in a different position than each cluster's dark matter. This is because the dark matter of the two galaxy clusters continued to move forward without any interaction while the normal matter collided ("ViewSpace | Dark Matter: Bullet Cluster"). [8]

2. Cl 0024+17 (ZwCl 0024+1652)

A blue map of the cluster's dark matter dispersion shows a ring-like shape. A Hubble picture of the cluster is placed on the map. One of the most compelling pieces of evidence supporting the presence of dark matter—an unidentified material that permeates the universe—to date is the ring. The map was created using Hubble observations of gravitational lensing, an optical illusion caused by the cluster Cl 0024+17's gravity distorting the light of galaxies farther away. By analysing the warped forms of the background galaxies, astronomers can deduce the existence of dark matter even if they cannot see it. The distribution of dark matter within the cluster is also depicted by the mapping. According to astronomers, the dark-matter ring was created when two enormous clusters collided ("Hubble Finds Dark Matter Ring in Galaxy Cluster").[9] Cl 0024+17 (ZwCl0024+1652) is the first cluster to have a distribution of dark matter that is substantially different from the distribution of the hot gas and galaxies ("Hubble Sees Dark Matter Ring in a Galaxy Cluster").[10]

Additionally, the Lambda Cold Dark Matter Model (abbreviated ΛCDM) goes into great detail on Dark Matter. The ΛCDM is one of the most established and reputable theories, even if new models and hypotheses for cosmic events are being developed daily. Certain galactic occurrences may be adequately described while adhering to the principles of general and special relativity by using the ΛCDM's determination of dark matter, dark energy, and cosmological constants. While other forms of dark matter have been proposed in various theories, the most prevalent kind—cold dark matter—is addressed by the ΛCDM model. Non-baryonic (not composed of protons, neutrons, and electrons like conventional matter) and cold (unable to achieve the speed of light at maximal radiation absorption) matter is referred to as cold dark matter. In addition, cold dark matter is collisionless (interacts with other particles exclusively through gravity and the weak force) and dissipationless (cannot

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[7] O'Meara, Stephen James. "The Bullet Cluster." *Astronomy Magazine*, 1 Jan. 2024, www.astronomy.com/science/the-bullet-cluster/. Accessed 27 Oct. 2024.

[8] "ViewSpace | Dark Matter: Bullet Cluster." *Viewspace.org*, viewspace.org/interactives/unveiling_invisible_universe/dark_matter/bullet_cluster. Accessed 28 Oct. 2024.

[9] "Hubble Finds Dark Matter Ring in Galaxy Cluster." *HubbleSite*, Q Starter Kit, 15 May 2007, hubblesite.org/contents/media/images/2007/17/2120-Image.html. Accessed 28 Oct. 2024.

[10] "Hubble Sees Dark Matter Ring in a Galaxy Cluster." *Www.esa.int*, 15 May 2007, www.esa.int/Science_Exploration/Space_Science/Hubble_sees_dark_matter_ring_in_a_galaxy_cluster. Accessed 28 Oct. 2024.

emit photons). These characteristics of cold dark matter enable it to influence specific astronomical object properties without heavily interacting with other matter (Perera).[11]

Theoretical Motivation

As far as physicists are concerned, the Standard Model of Particle Physics provides the best explanation for the most basic elements of the universe. According to this interpretation, all known matter is composed of particles known as quarks, which include protons and neutrons, and leptons, which include electrons. It also describes the interactions between quarks and leptons and force-carrying particles, which are members of a larger family of bosons. Even while the Standard Model has been effective in explaining the universe, it has drawbacks. For instance, the Higgs boson provides mass to the W and Z bosons, as well as to quark-charged leptons (such as electrons). Neutrinos are ethereal particles that seldom interact with other matter in the universe, however it is still unclear if the Higgs boson also gives mass to them. Furthermore, scientists know that conventional matter as we know it makes up just roughly 95% of the cosmos. Rather, a large portion of the cosmos is made up of dark energy and dark matter that defy the Standard Model (Murayama and Riesselmann).[12]

The basic particles and the forces that hold them together have been successfully described by the Standard Model of Particle Physics. However, Big Bang theorists face some serious issues with the Standard Model. This is due to the fact that the neutrinos in the Standard Model are represented as precisely massless and that there are no Dark-Matter particles present. This indicates that, as needed by several observations, it is obviously inconsistent with the Big Bang model in its current form (Hartnett).[13]

An interpretation of particle physics that the Standard Model is unable to provide is increasingly favouring the presence of dark matter, which is demonstrated by astrophysical data like galaxy rotation curves ("Physics beyond the Standard Model").[14]

The concept of relic density in the early Universe may have some clues regarding Dark Matter's persistence.

Massive, very energetic particles were produced and maintained in thermal equilibrium in the early cosmos (via mechanisms such as pair creation or collisions/interactions with other particles). Stated differently, the rate at which heavy particles were transformed into lighter ones and vice versa was the same. But two things happened when the cosmos cooled and expanded: The expansion of the cosmos reduced the number of particles, making interactions less frequent or non-existent, and smaller particles lacked the kinetic energy (thermal energy) necessary to interact with heavier particles.

When conditions for thermal equilibrium are broken, and the density of heavier particles or a specific species of particles becomes too low to sustain frequent interactions, the particles are called to "freeze out", and their number density (which is no longer impacted by interactions) stays constant. By matching the response rate with the Hubble (expansion) rate, the precise temperature or moment of freeze-out may be determined. Since a particle's

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[11] Perera, Maneth. "Hidden Matter: The Lambda CDM Model of Our Universe – Hadron." *Imsa.edu*, 23 Sept. 2024, sites.imsa.edu/hadron/2024/09/23/hidden-matter-the-lambda-cdm-model-of-our-universe/. Accessed 28 Oct. 2024.

[12] Murayama, Hitoshi, and Kurt Riesselmann. "DOE Explains...The Standard Model of Particle Physics." *Energy.gov*, 2022, www.energy.gov/science/doe-explainsthe-standard-model-particle-physics. Accessed 28 Oct. 2024.

[13] Hartnett, John G. "DarkMatter and Standard Model of Particle Physics." *Creation.com*, 28 Sept. 2014, creation.com/darkmatter-and-standard-model-of-particle-physics. Accessed 28 Oct. 2024.

[14] "Physics beyond the Standard Model." *Particle-Nuclear.lu.se*, 2020, www.particle-nuclear.lu.se/theoretical-particle-physics/bsm. Accessed 28 Oct. 2024.

abundance doesn't change, its density at the moment of freeze-out is referred to as its relic density (Garrett and Duda).[15]

From the very beginning of the Universe, dark matter particles interacted with the thermal bath before decoupling from it. They then decayed or were annihilated, and now we see the particles that have persisted to this day, known as relics. This basic scenario illustrates the relationship between the dark matter relic density and the primordial Universe; however, there are several ways to modify the Standard Model. Because cosmic measurements have detected dark matter density with such precision, they may be used to limit early Universe scenarios as well as particle physics models. (Arbey and Mahmoudi).[16]

As dark regions typically split from kinetic equilibrium with the Standard Model plasma, a clear temperature history can be observed. Since the lightest composite particles, like pions or glueballs, always have number-changing interactions, the sequestered sector plasma warms up until the number-changing processes disengage. This phenomena causes the entropy evolution and the Hubble rate to rely abnormally on the dark sector temperature (Dondi et al.).[17]

A prominent framework is thermal freeze-out, which produces prediction models that can be tested using a wide range of complementing experimental search techniques. However, it is predicated on the normal cosmic history being in place at the time of Dark Matter formation. Such an assumption should not be enforced for any a priori considerations (Arcadi).[18]

However, the Cosmic Relic Density does not align with what Baryonic Matter can explain; Baryonic Matter falls short – calling for further investigations of the composition of the Universe.

At least part of the dark matter must be made up of common atoms and molecules, such as that found in planets and "failed stars" that are too faint to view. Dust and dark gas are similarly affected, though they can occasionally be observed in absorption rather than emission. When combined with luminous matter, these contributions form baryonic dark matter (BDM), which has a total density equal to the sum of the densities of BDM and Luminous Matter. If we correctly grasp the big-bang theory and the generation of light elements, we may show that the density of baryonic matter cannot explain more than 5 percent of the critical density.

Three different types of dark matter now seem to be involved in addition to the dark baryons. The behaviour of observable matter on sizes bigger than the solar system (such as galaxies and clusters of galaxies) has led to the inference of the presence of cold dark matter (CDM). It is believed that CDM is made up of particles (also called "exotic" dark-matter particles) that are mostly visible due to their gravitational pull because of their extremely weak interactions with regular matter. Such particles are anticipated in tenable extensions of the standard model despite the fact that they have not been observed (and are, by definition, difficult to detect). A large number of cosmologists estimate that the total CDM density is at least an order of magnitude higher than the baryons (Overduin and Wesson).[19]

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[15] Garrett, Katherine, and Gintaras Duda. "Dark Matter: A Primer - Katherine Garrett & Gintaras Duda." *Ned.ipac.caltech.edu*, ned.ipac.caltech.edu/level5/March10/Garrett/Garrett7.html. Accessed 28 Oct. 2024.
[16] Arbey, A., and F. Mahmoudi. "Dark Matter and the Early Universe: A Review." *Progress in Particle and Nuclear Physics*, Apr. 2021, p. 103865, https://doi.org/10.1016/j.ppnp.2021.103865. Accessed 28 Oct. 2024.
[17] Dondi, Nicola Andrea, et al. "Thermal History of Composite Dark Matter." *Physical Review. D/Physical Review. D.*, vol. 101, no. 10, 8 May 2020, https://doi.org/10.1103/physrevd.101.103010. Accessed 28 Oct. 2024.
[18] Arcadi, Giorgio. "Thermal and Non-Thermal DM Production in Non-Standard Cosmologies: A Mini Review." *Frontiers in Physics*, vol. 12, 26 June 2024, https://doi.org/10.3389/fphy.2024.1425838. Accessed 28 Oct. 2024.
[19] Overduin, J.M., and P.S. Wesson. "Dark Matter and Background Light - J.M. Overduin & P.S. Wesson." *Caltech.edu*, 2024, ned.ipac.caltech.edu/level5/March06/Overduin/Overduin_contents.html. Accessed 29 Oct. 2024.

The Big Bang Nucleosynthesis and the Cosmic Microwave Background help set constraints on this type of matter.

In contrast to typical predictions of the Big Bang Nucleosynthesis (BBN), the constraints show the influence of relic dark matter annihilations on primordial nuclei abundances. In particular, computations show that the upper bound on the average annihilation cross-section for low dark matter (DM) mass regions (between MeV and 10 GeV) is obtained by extending current restrictions for higher masses. The scaling equation assumed in this extrapolation is valid as long as annihilations generate energetic nucleons capable of dissociating primordial helium. However, this scaling is projected to diminish when the DM mass gets closer to 1 GeV, especially since energetic nucleons are no longer produced by annihilations at these energies.

Furthermore, calculations show that the DM mass is exactly proportional to the limitations on the average annihilation cross-section from electromagnetic energy injection. Primordial abundances are mostly influenced by electromagnetic radiation through the photo-dissociation of helium, which increases the creation of other nuclides. According to the estimations, the noticeable effects of overproduction, particularly for helium, can be substantial but lessened when there are not enough electrons from DM annihilation to provide the required energy photons. Furthermore, although distinct annihilation channels have differing effects on nucleosynthesis, it is generally accepted that DM annihilation mechanisms interact intricately with BBN, requiring meticulous numerical simulations to precisely assess their effects (Henning and Murayama).[20]

The cosmic microwave background (CMB) temperature and polarisation spectra are affected by energy deposition from dark matter (DM) annihilation, namely from weakly interacting massive particles (WIMPs) of mass 1–20 GeV annihilating into leptons. Experts used a modified Monte Carlo Markov Chain analysis in cosmomc software to investigate these impacts, using CMB data from the South Pole Telescope (SPT), the QUEST at DASI (QUaD), and the Wilkinson Microwave Anisotropy Probe (WMAP). They determined limitations on the annihilation cross-section for each annihilation channel by marginalising background cosmological parameters.

Results show that the electron-positron ($e^+ - e^-$) channel substantially restricts DM annihilation when accessible data sets are combined up to an angular scale of $\ell max = 3100$, ruling out a light WIMP within the studied mass range as a promising DM candidate. WIMPs over 5 GeV, on the other hand, are made possible by annihilation via the muon ($\mu^+ - \mu^-$) or tau ($\tau^+ - \tau^-$) channels. Up to 60% more limitations are impacted by a more realistic approach to energy deposition, according to a comparison with simpler models. Additional refining is likely to improve comprehension and confine this possible source of ionisation (Evoli et al.).[21]

Experiments at the Large Hadron Collider (LHC) could provide a more direct demonstration of dark matter. According to a number of ideas, the dark matter particles would be sufficiently light to be created at the LHC. They wouldn't be detected by the detectors if they were made at the LHC. However, since they would erase momentum and energy, scientists may utilise the amount that would be "missing" after a collision to infer their existence. Theories that imply physics outside of the Standard Model, such supersymmetry (discussed in greater detail later) and extra dimensions, can give rise to dark matter candidates. A "Hidden Valley," a parallel world made of dark matter that is drastically

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[20] Henning, Brian, and Hitoshi Murayama. "Constraints on Light Dark Matter from Big Bang Nucleosynthesis." *Arxiv*, 29 May 2012, arxiv.org/pdf/1205.6479. Accessed 29 Oct. 2024.

[21] Evoli, C., et al. "Cosmic Microwave Background Constraints on Light Dark Matter Candidates." *Monthly Notices of the Royal Astronomical Society*, vol. 433, no. 2, 11 June 2013, pp. 1736–1744, https://doi.org/10.1093/mnras/stt849. Accessed 30 Oct. 2024.

different from matter as we know it, could exist, according to one theory. Scientists could learn more about the makeup of our universe and, in particular, how galaxies keep together if one of these ideas turns out to be accurate (CERN).[22]

The fact that dark matter, which scientists estimate to be five times more common than visible stuff in the universe, is not taken into account by the Standard Model is another indication that there is physics beyond it. There is a lot of evidence that dark matter exists, even if it has never been directly detected. For instance, physicists believe that galaxies revolve at rates that cannot be explained by the impact of visible matter because of the gravitational attraction of dark matter. There is still a lot of stuff and energy in our universe that needs to be discovered, so the hunt for physics outside of the Standard Model is an exciting one (Miller).[23]

It is obvious that new physics is required to fill in these gaps as baryonic matter and the Standard Model by themselves are unable to explain the observed cosmic density. This has given rise to theories about non-baryonic particles that may not be part of the Standard Model. Weakly Interacting Massive Particles (WIMPs) are the most promising options to close this gap.

The majority of dark matter, or around 22% of the cosmos, is thought to be composed of heavy, electromagnetically neutral subatomic particles known as WIMPs. Dark matter particles are thought to be slow-moving and heavy because the density fluctuations from which galaxies and clusters of galaxies formed would not have caused them to clump together if they were light and fast-moving. These particles' lack of light further suggests that they are electromagnetically neutral. The particles are commonly referred to as weakly interacting massive particles because of their characteristics. WIMPs have been classified as "nonbaryonic," meaning they are something other than baryons, which are massive particles made up of three quarks, such as the proton and neutron. This is because the abundance of elements heavier than hydrogen that were formed in the initial few minutes following the Big Bang has been used to determine the number of baryons in the universe (“Weakly Interacting Massive Particle | Astrophysics”).[24]

Now, I will be discussing WIMPs in further depth.

The Weakly Interacting Massive Particles

The possibilities for particle dark matter vary depending on whether they were created non-thermally at a phase transition or thermally in the early universe. The difference between thermal and nonthermal relics is essential for identifying dark matter because of their differences in amount, mass, and couplings. While dark matter axions are mostly created by non-thermal methods, WIMP particles are thermally made. Despite being thermally generated, light neutrinos have a distinct history because of their small mass.

At high temperatures, thermal creation posits that the density of WIMPs (or other particle species) is almost equal to that of photons (light particles), indicating that the universe has reached thermal equilibrium. This is just how energy is distributed across every possible degree of freedom. WIMP and photon densities decreased in tandem as the universe cooled. WIMP creation decreased, but destruction persisted as the temperature fell below the WIMP mass. The number density of WIMPs dropped exponentially in equilibrium: $\exp(-m_{WIMP}/T)$. Few WIMPs would exist if equilibrium was preserved till now. Finding another to

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[22] CERN. “Dark Matter | CERN.” *Home.cern*, CERN, home.cern/science/physics/dark-matter. Accessed 30 Oct. 2024.
[23] Miller, Katrina. “Beyond the Standard Model | Symmetry Magazine.” *Www.symmetrymagazine.org*, 22 Feb. 2022, symmetrymagazine.org/article/beyond-the-standard-model?language_content_entity=und. Accessed 30 Oct. 2024.
[24] “Weakly Interacting Massive Particle | Astrophysics.” *Encyclopedia Britannica*, www.britannica.com/science/weakly-interacting-massive-particle. Accessed 30 Oct. 2024.

destroy, however, became less likely as the density of WIMPs dropped. It should be noted that we have to assume that a WIMP is stable in order for it to become dark matter. There are a lot of WIMPs now since the WIMP number density has steadied at this point. (Griest)[25]

Now, let's talk about WIMPs in supersymmetry (SUSY). But first, we actually need to understand what SUSY is. The goal of SUSY is to close some of the gaps in the Standard Model. For every particle in the Standard Model, it forecasts a companion particle. Fixing the mass of the Higgs boson, a significant issue with the Standard Model would be resolved by these new particles. Supersymmetric particles should show up in collisions at the LHC if the theory is accurate.

In contrast to what we see around us, the Standard Model first seems to suggest that all particles should be massless. Theorists have developed a method for assigning masses to particles that necessitates the Higgs boson, a new particle. However, interactions with Standard-Model particles would seem to make the Higgs boson exceedingly heavy therefore, it is puzzling why it should be light. A light Higgs boson might be attainable as a result of the additional particles predicted by SUSY cancelling out the contributions to the Higgs mass from their Standard-Model companions. Despite having differing masses, the new particles would interact using the same forces as Standard-Model particles. The interactions of the Standard Model's three forces—electromagnetism, the strong and weak nuclear forces, and the standard model—could be just as strong at extremely high energies as they were in the early universe if supersymmetric particles were incorporated. Grand unified theory, a goal of physicists like Einstein, is a theory that mathematically unifies the forces (CERN).[26]

A lovely dark matter candidate particle is spewed forth by SUSY. This particle must be consistent with our theory of dark matter, a type of non-luminous stuff that appears to interact weakly and accounts for 85% of the mass of the universe. The existence of the...drumroll...WIMPs are predicted by SUSY, or more precisely, the Minimal Supersymmetric Standard Model! The existence of WIMPs is due to a conserved quantity known as "R-parity," where SM particles have a value of P=+1, and SUSY particles have a value of P=-1. According to this symmetry, there will be a huge, neutral particle with weak interactions that is stable since it cannot decay further into anything else. For physicists searching for dark matter, this is incredibly attractive. (Forman)[27]

However, recent searches at the LHC raise doubts about the viability of WIMP candidates and fail to verify SUSY's attractive predictions. A reconstruction of ideas challenges the conservation of R-parity and argues that other dark matter candidates, like axions or sterile neutrinos, might be involved since neutralinos are not being identified. The creation of new theoretical frameworks and the improvement of experimental methods could theoretically lead to new pathways for investigation in the future. In fact, scientists might discover some surprising findings that challenge our understanding of dark matter and its complex relationship to supersymmetry, opening up new avenues for investigation (Kadan).[28]

In SUSY, a neutralino is one of the suggested particle types. Some of these superparticles undergo quantum mixing, which produces the four neutralinos (just like quarks or neutrinos do). The lightest of the four neutralinos would be stable, while the other three would decay rapidly. Neutrinos are a candidate particle to act as a WIMP because, in some models of the universe's formation (Big Bang nucleosynthesis in light of supersymmetry),

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[25] Griest, Kim. *WIMPs and MACHOs ENCYCLOPEDIA of ASTRONOMY and ASTROPHYSICS*. 2002.
[26] CERN. "Supersymmetry | CERN." *Home.cern*, CERN, 24 May 2019, home.cern/science/physics/supersymmetry. Accessed 11 Nov. 2024.
[27] Forman, Matthew. "Supersymmetry: A Love Story." *The Startup*, 18 Apr. 2020, medium.com/swlh/supersymmetry-a-love-story-6cb5e751fb9b. Accessed 11 Nov. 2024.
[28] Kadan, Sophie. "Searches for Supersymmetry (SUSY) at the Large Hadron Collider." *ArXiv.org*, 2024, arxiv.org/abs/2404.16922. Accessed 14 Nov. 2024.

their total mass would equal, within reasonable bounds, the present-day aggregate quantity of the universe's mass credited to dark matter. The WIMP miracle is the name given to this coincidence (The WIMP miracle is discussed in depth later in this section). ("Neutralino")[29]

The lightest neutralino in the minimum supersymmetric standard model (MSSM) can be the WIMP DM candidate if the R-parity is maintained. Depending on its composition, the lightest neutralino can be either wino-like, higgsino-like, bino-like, or mixed. Their masses must be in the TeV region to saturate the reported DM relic density, as their annihilation rates are large if the lightest neutralino is in a wino-like or higgsino-like form. On the other hand, the lightest neutralino will interact weakly with the SM particles if it is in a bino-like form, which frequently leads to an excess of DM. The coannihilation of the lightest neutralino with a light sparticle is an interesting way to solve this problem. (Murat Abdughani and Wu)[30]

Given our present understanding of particle physics, the neutralino makes perfect sense. The special extension of Poincaré space-time symmetry is called supersymmetry. To calculate the symmetry-breaking potential of the Higgs boson, we need new physics interactions at the teraelectronvolt mass scale. This is accomplished naturally by extending space-time symmetry to supersymmetry. When calculated, the massive magnitude of the top quark Yukawa coupling is associated with the symmetry-breaking form of the Higgs potential. The predictions for the extremely short distance values of the strong, weak, and electromagnetic couplings are altered by the supersymmetric introduction of additional particles linked to the known fundamental particles. The idea of a massive unification of couplings at this mass scale is supported by the modifications that make these couplings nearly equal at about 10^{16} GeV (Peskin).[31]

The hierarchy problem motivates the existence of WIMPs. The magnitude of the non-zero Higgs field, which in turn determines the mass of the W and Z particles, is the difficulty, which is now known as the hierarchy riddle or hierarchy problem. The W and Z particles have masses of around 100 GeV, which is the size of the non-zero Higgs field, which is around 250 GeV. However, it turns out that quantum physics would predict that a Higgs field of this magnitude would be unstable, akin to a car dangling at the edge of a cliff. According to the physics we currently understand, the jitter of quantum mechanics would seem to indicate that there are two inherent characteristics for the Higgs field, like the two natural places for the automobile, put securely on edge or smashed into several fragments on the ground. Idiotically, the Higgs field should be 10,000,000,000,000,000 times greater than what is measured, or it should be equal to the Planck Energy. Why does it have a non-zero, little value that appears, at least intuitively, so out of place? (Strassler)[32]

Based on a symmetry solution to the hierarchy issue, a WIMP is defined as follows: New particles with electroweak coupling strengths are introduced via new symmetries. The masses of the lightest of these particles are around the electroweak scale. To stop the unwanted interactions, these new particles create troublesome processes that call for additional "small" symmetries, such as a new parity.

WIMP's top-down motivation—the resolution of the hierarchy problem—is highlighted in this description. This provides some insight into the viability of WIMPs: is

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[29] "Neutralino." *Vaporia.com*, 2024, astro.vaporia.com/start/neutralino.html. Accessed 11 Nov. 2024.

[30] Murat Abdughani, and Lei Wu. "On the Coverage of Neutralino Dark Matter in Coannihilations at the Upgraded LHC." *The European Physical Journal C*, vol. 80, no. 3, 1 Mar. 2020, link.springer.com/article/10.1140/epjc/s10052-020-7793-1, https://doi.org/10.1140/epjc/s10052-020-7793-1. Accessed 11 Nov. 2024.

[31] Peskin, Michael E. "Supersymmetric Dark Matter in the Harsh Light of the Large Hadron Collider." *Proceedings of the National Academy of Sciences*, vol. 112, no. 40, 20 Oct. 2014, pp. 12256–12263, https://doi.org/10.1073/pnas.1308787111.

[32] Strassler, Matt. "The Hierarchy Problem." *Of Particular Significance*, 12 Feb. 2011, profmattstrassler.com/articles-and-posts/particle-physics-basics/the-hierarchy-problem/. Accessed 11 Nov. 2024.

dark matter a distinct area of fundamental physics, or is it closely related to the resolution of the hierarchy problem? (Tanedo)[33]

When the universe was very hot and the number density of WIMPs (or other kinds of particle class) was about equivalent to the number density of photons, thermal equilibrium was attained early on, according to thermal creation. As long as the temperature was higher than the WIMP mass, the number of WIMPs and photons would both decline as the universe cooled. Since WIMP creation would require being on the tail of the thermal distribution when the temperature finally fell below the WIMP mass, the numerical density of WIMPs would decline exponentially in equilibrium. There would be very few WIMPs remaining if equilibrium were maintained until today, but eventually, the WIMP density would decrease to the point where it would be unlikely for one WIMP to locate another to destroy. We would be left with a significant number of WIMPs today if the WIMP number density were to "freeze out" at this time. (Griest, "Thermal Relics as Dark Matter (Wimps)")[34]

In the typical WIMP scenario, DM has an electroweak mass and interacts with the standard model (SM) thermal plasma with a high strength, which is typical of electroweak interactions. When WIMPs reach thermal equilibrium with the SM thermal plasma and then freeze out, the measured DM relic abundance is the result. It is generally believed that this DM freeze-out happens long after reheating is finished, and SM radiation dominates the Universe's energy density. Usually, a thermally averaged annihilation cross-section is needed to match data. Direct, indirect, and collider probes are some of the complementing methods that may be used to verify the WIMP process, which makes it especially intriguing. (Bernal and Xu)[35]

An equation called the Boltzmann Equation is applied to describe the thermal evolution of WIMPs in the early Universe. Let χ be a stable particle and $\bar{\chi}$ be its antiparticle. We know that only annihilation and production processes may alter the quantity of ψ and $\bar{\psi}$ in a comoving volume. Using ψ to represent every conceivable final state, we may write: $\chi\bar{\chi} \leftrightarrow \psi\bar{\psi}$.

The Boltzmann equation that governs the growth of the number density n for ψ may be expressed as follows, with specific simplifying assumptions:

$$\frac{dn_x}{dt} = -3Hn - \langle\sigma_{ann}v\rangle(n^2 - n_{eq}^2)$$

$$\frac{ds}{dt} = -3Hs$$

n_{eq} is the WIMP equilibrium number density, t is the time, s is the entropy, H is the Hubble parameter, and $\langle\sigma_{ann}v\rangle$ is the thermally averaged total annihilation cross-section. (Lindner et al.)[36]

This equation, which models the one-particle phase space distribution of WIMPs and accounts for interactions with all standard model particles—science that must be resolved in order to comprehend how such WIMPs can maintain thermal equilibrium at high temperatures—is fundamental to understanding the thermal evolution of WIMPs in the early universe.

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[33] Tanedo, Flip. *Snowmass LOI: Defining the WIMP*.
[34] Griest, Kim. "Thermal Relics as Dark Matter (Wimps)." *Mit.edu*, 15 July 1996, web.mit.edu/redingtn/www/netadv/specr/345/node2.html. Accessed 12 Nov. 2024.
[35] Bernal, Nicolás, and Yong Xu. "WIMPs during Reheating." *Journal of Cosmology and Astroparticle Physics*, vol. 2022, no. 12, 1 Dec. 2022, pp. 017–017, arxiv.org/abs/2209.07546, https://doi.org/10.1088/1475-7516/2022/12/017. Accessed 12 Nov. 2024.
[36] Lindner, Priv, et al. *Dark Matter -Exercise 4*.

When the universe cools and expands, WIMPs undergo kinetic decoupling, which is described by the Boltzmann equation. This causes them to transition from a state of thermal equilibrium to one that is no longer in thermal equilibrium. The collision integral, which incorporates slow and rapid processes that modify the WIMP distributions, is found by solving the Boltzmann equation. In this manner, the WIMP temperature, together with its decoupling scales and implications for the density of dark matter relics in the universe, maybe precisely determined. (Torsten Bringmann and Hofmann)[37]

Because it establishes the efficiency with which dark matter particles are annihilating into lighter particles, the annihilation cross-section is a crucial discriminator of relic density in dark matter. Sommerfeld enhancement will be crucial in increasing the annihilation cross-section at low velocities in the asymmetric dark matter scenario. This would imply a higher rate of dark matter particle reduction over time, which is necessary to reach the observed relic density.

In this situation, the relic density is comparatively less susceptible to mass changes since the annihilation cross-section is modest. However, in order to give a satisfactory degree of satisfaction for the measured relic density, the cross-section must be sufficient towards a maximum value of the mass. Consequently, it appears that in order to satisfy the criterion set by the Planck measurements, asymmetric DM must couple considerably more strongly than in the symmetric scenario. This highlights the delicate relationship between annihilation processes and the cosmic abundance of dark matter once more. (Qiu et al.)[38]

There are multiple steps involved in calculating the Relic Abundance of the Weakly Interacting Massive Particles. They are:

1. Establish the Equation of Evolution:

   The WIMP evolution equation, which explains how the WIMP density changes over time as the cosmos expands, should be written down in a dimensionless format.

2. Determine the initial conditions:

   Determine the WIMPs' starting temperature and density. Here, we'll want to set up the WIMPs' equilibrium values.

3. Integration of numbers:

   The evolution equation will be numerically integrated across time, accounting for variations in the universe's density and temperature.

4. Determination of the Annihilation Cross Section:

   Using the WIMP density, establish a connection between this quantity and the mass-dependent annihilation cross-section, which in turn yields a value for the cross-section assessed at the current relic density.

5. Uncertainty Inputs:

   To enhance the final result, assess and include uncertainties in various inputs and assumptions, such as quark masses and temperature during the Quark-Hardon transition. The Quark-Hardon transition is a transition at high temperatures and densities from regular hadronic matter (protons and neutrons) to quark-gluon matter. (Olive)[39]

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[37] Torsten Bringmann, and Stefan Hofmann. "Thermal Decoupling of WIMPs from First Principles." *ArXiv (Cornell University)*, 19 Apr. 2016, arxiv.org/abs/hep-ph/0612238, https://doi.org/10.1088/1475-7516/2007/04/016;. Accessed 12 Nov. 2024.

[38] Qiu, Sujuan, et al. "Asymmetric Dark Matter and Sommerfeld Enhancement." *ArXiv.org*, 2024, arxiv.org/abs/2403.01682. Accessed 12 Nov. 2024.

[39] Olive, K A. "The Quark-Hadron Transition in Cosmology and Astrophysics." *Science (New York, N.Y.)*, vol. 251, no. 4998, Aug. 1991, pp. 1194–9, pubmed.ncbi.nlm.nih.gov/17799279/, https://doi.org/10.1126/science.251.4998.1194. Accessed 12 Nov. 2024.

6. Analyse and Compare Outcomes:

Analyse the outcomes and compare the analytical approximations for an accuracy of greater than 3%. (Steigman et al.)[40]

Since WIMPs are present in several beyond-the-SM (BSM) models intended to provide insight into particle physics mysteries, they are inspired by particle theory. In the sense that they are at the current frontier, not precluded by current constraints, but visible at near future experiments, WIMPs are likewise prompted by particle experiments. Last but not least, WIMPs are driven by cosmology: WIMPs are created with the proper relic density to be dark matter, assuming the straightforward production method of thermal freezeout. WIMPs, or particles with couplings of $g \sim 1$ and masses of $m \sim 10$ GeV − 10 TeV, are motivated by particle theory, particle experiments, and cosmology. This amazing threefold coincidence is frequently referred to as the WIMP miracle. WIMPs are highly motivated among the various dark matter hypotheses because it is fascinating that investigations of nature at both the tiniest and biggest length scales should point to particles with the same features. (Feng)[41]

The dynamical interactions of the particles during the early cosmos are the source of the coincidence between the WIMP interaction strength and the dark matter abundance. The numerical density of the WIMPs diminishes as they destroy themselves, but they ultimately "freeze out" and provide a stable relic density as soon as the universe's expansion rate surpasses the interaction rate. The typical cross-section for WIMP interactions tends to be located in an area that naturally contributes to the known dark matter density due to the features of weak-scale physics and the thermal history of the cosmos. It implies that WIMPs, if they exist at all, would provide an unparalleled link between the cosmic data of dark matter abundance and the basic interactions of these particles, in addition to being a completely legitimate candidate for dark matter. (Arakawa and Tim)[42]

Experimental Searches for WIMPs

WIMPs are sought after by the LUX-ZEPLIN (LZ) project, a premier dark matter direct detection experiment. The goal is to quantify how dark matter particles interact with conventional matter (known matter) atomic nuclei. If this interaction is found, it would reveal important information on the mass, nature, and cross-section of interactions between dark matter and ordinary matter. A huge 7-ton liquid xenon detector is used by LZ. Particles of dark matter seek the liquid xenon. The detector would record and quantify the tiny burst of light (scintillation) and ionisation that would result after a collision between a dark matter particle and a xenon nucleus. LZ is situated in the Sanford Underground Research Facility (SURF) in South Dakota, USA, 1.5 km below the surface of the earth, to reduce interference from cosmic rays and other background sources. ("Quest for Dark Matter - Lux Zeplin Experiment - Rau's IAS")[43]

WIMPs are predicted to interact with conventional matter by elastic scattering with nuclei, necessitating the discovery of nuclear recoil energies between 1 and 100 keV. Given the intimidating backgrounds from electron recoil interactions and neutrons that resemble the nuclear recoil signal of WIMPs, these low energies and cross-sections provide significant experimental difficulty. The existence of WIMPs and their origin in our galaxy's dark matter

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[40] Steigman, Gary, et al. "Precise Relic WIMP Abundance and Its Impact on Searches for Dark Matter Annihilation." *Physical Review D*, vol. 86, no. 2, 3 July 2012, https://doi.org/10.1103/physrevd.86.023506. Accessed 12 Nov. 2024.

[41] Feng, Jonathan L. "The WIMP Paradigm: Theme and Variations." *SciPost Physics Lecture Notes*, 13 June 2023, https://doi.org/10.21468/scipostphyslectnotes.71. Accessed 12 Nov. 2024.

[42] Arakawa, Jason, and Tim. "Is a Miracle-Less WIMP Ruled Out?" *SciPost Physics*, vol. 11, no. 2, 3 Aug. 2021, https://doi.org/10.21468/scipostphys.11.2.019. Accessed 12 Nov. 2024.

[43] "Quest for Dark Matter - Lux Zeplin Experiment - Rau's IAS." *Compass by Rau's IAS*, 30 Sept. 2024, compass.rauias.com/current-affairs/quest-for-dark-matter-lux-zeplin-experiment/. Accessed 12 Nov. 2024.

would be established by a verified signal from direct detection experiments. A measurement of the WIMP mass, the shape of the interactions with normal matter, and even astrophysical data on the distribution of dark matter in our galaxy might all be obtained by examining the signal with a number of experimental targets. This knowledge complements that which may be gleaned via indirect dark matter detection or particle colliders. (Cushman et al.)[44]

As opposed to "direct" detection methods, which seek interactions between dark matter particles from the local halo and an appropriate target, "indirect" dark matter searches concentrate on identifying the byproducts of dark matter candidates' annihilation or decays that have gravitationally accumulated in cosmological objects. But both of these approaches rely on figuring out what dark matter surrounds us. The employment of early universe probes (cosmic microwave background power spectrum, 21-cm astronomy, and nucleosynthesis) to restrict the properties and composition of the dark matter is often absent from "indirect" investigations. Dark matter is predicted to build up in the halo surrounding galaxies like the Milky Way and in clusters of galaxies. The ability of the dark matter particles to decay or destroy one another is necessary for obtaining evidence from these areas with large concentrations of dark matter. (Pérez de los Heros).[45]

However, because "indirect" dark matter searches are primarily concerned with finding dark matter annihilation products, they usually overlook astrophysical processes in galactic centres that provide comparable signals, such as collisions of high-energy particles, cosmic ray interactions, and supernova remnants. The issue is that these processes result in very similar signs from particle creation, which makes it challenging to differentiate between astrophysical and genuine dark matter signals. Last but not least, significant background contaminations from such processes would preclude any conclusive detection of dark matter signals and necessitate extremely sensitive measurements and targeted observations in order to isolate and validate the emission of any features associated with dark matter. However, the potential for improved observational methods and data processing makes this an intriguing opportunity to enhance these searches and gain more knowledge about dark matter, leading to more definite separations between astrophysical noise and dark matter signatures (Balazs et al.).[46]

The lack of knowledge about cosmic backgrounds is a major problem that afflicts indirect searches for DM. There will undoubtedly be several tenable astrophysical explanations for a DM-like signal. However, indirect searches offer robust and somewhat model-independent limits on novel physics given established backgrounds. Some of the strongest constraints on WIMP dark matter are provided by low-energy (about 10 GeV) positron measurements by AMS-02, gamma-ray studies of the Milky Way's dwarf satellite galaxies, and CMB bounds from Planck. The best constraints on spin-dependent WIMP-nucleus scattering are found in solar neutrino measurements. (Algeri et al.)[47]

High energy colliders, such as the LHC, attempt to produce and detect Dark Matter like WIMPs. High energy colliders, such as the LHC, attempt to produce and detect Dark Matter like WIMPs. The LHC accelerates protons to 13 TeV. Two beams go in opposite directions around a 27-kilometer ring before coming into contact in many detectors. Two all-purpose detectors, ATLAS and CMS, were created to detect dark matter, SUSY, and the Higgs and to search for the unknown. As of July 2012, the first objective—the finding of the Higgs boson, the final component lacking from the standard model of particle physics—had

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[44] Cushman, P, et al. *WIMP Dark Matter Direct Detection.* 2013.
[45] Pérez de los Heros, Carlos. "Status, Challenges and Directions in Indirect Dark Matter Searches." *Symmetry*, vol. 12, no. 10, 8 Oct. 2020, p. 1648, https://doi.org/10.3390/sym12101648.
[46] Balazs, Csaba, et al. "A Primer on Dark Matter." *ArXiv.org*, 7 Nov. 2024, arxiv.org/abs/2411.05062. Accessed 14 Nov. 2024.
[47] Algeri, Sara, et al. *Statistical Challenges in the Search for Dark Matter.* 2018.

been accomplished, and Higgs and Englert were awarded the Nobel Prize right away. The remaining goals are yet unfulfilled. At the LHC, SUSY dark matter particles might appear in a variety of ways. In addition to jets of particles formed during the decay chain of SUSY particles ejected after the collision, missed transverse energy when the dark matter particle departs unnoticed might be a possible indication. The masses of SUSY particles are more constrained as a result of the absence of such a signature. The MSSM contains 105 free parameters. The resultant constrained minimum supersymmetric model (CMSSM, or MSUGRA) unifies all fermion masses $m_{1/2}$ and all scalar masses m_0 at large scale, leaving just five parameters under certain simplification assumptions. (Freese)[48]

However, while colliders detect missing energy, they are unable to determine with certainty if DM is present in a signal event. The existence of a neutral and "stable" particle—which may have even decayed outside the detector—can be verified with ease. (Arcadi et al.)[49]

Future Directions in Dark Matter Research

DARWIN is a detection technology being developed to improve the search for Dark Matter. According to the APPEC Roadmap, the DARWIN project seeks to establish a future astroparticle observatory in Europe. Using a multi-ton liquid xenon target for the direct detection of dark matter particles in a sensitive time projection chamber, the ultimate dark matter detector is intended to be designed and built. In order to finally cover the whole WIMP-parameter space before neutrino backgrounds take over, DARWIN seeks to increase sensitivity to unprecedented levels. In addition to having a reasonable possibility of identifying dark matter, such a detector would be able to investigate its characteristics, including mass, interaction strength, and local distribution within our galaxy. DARWIN will use a variety of potential couplings (spin-independent, spin-dependent, and inelastic) to search for WIMP dark matter across a broad mass range, from as low as 5 GeV/c^2 to above 10 TeV/c^2. It will also be perfectly suited for many other uncommon event searches due to its minimal backdrop. Axions and axion-like particles, neutrinos from supernovae, neutrinos from other uncommon nuclear processes, neutrinoless double beta-decay of 136Xe without isotopic enrichment, and solar neutrinos, particularly the low-energy pp-neutrinos, are prime examples. The low-threshold, low-background astroparticle physics observatory will be called DARWIN (“DARWIN - Dark Matter WIMP Search with Liquid Xenon”).[50]

Along with in-development detection technology, there are also numerous alternative Dark Matter candidates. Three of them are Sterile Neutrinos, Fuzzy Dark Matter, and Dark Photons. I will now discuss these three candidates in brief.

Sterile Neutrinos: Although they haven't been shown to exist, sterile neutrinos are a unique type of neutrino that has been suggested as an explanation for several surprising experimental findings. Researchers are actively searching for them in a variety of tests. There may be various sterile neutrinos at different energies, even though the short-baseline experiments search for light sterile neutrinos with comparatively low energy—at the electronvolt scale. Sterile neutrinos with an electron voltage of about 1,000 may be associated with dark matter or other cosmic problems. Additionally, the heavy seesaw neutrinos that help explain the tiny neutrino masses we observe in the known light neutrinos may be neutrinos with a mass of

[48] Freese, Katherine. “Status of Dark Matter in the Universe - Katherine Freese.” *Ned.ipac.caltech.edu*, 2017, ned.ipac.caltech.edu/level5/Sept17/Freese/Freese_contents.html. Accessed 12 Nov. 2024.
[49] Arcadi, Giorgio, et al. *The Waning of the WIMP? A Review of Models, Searches, and Constraints*. Vol. 78, no. 3, 10 Mar. 2018, https://doi.org/10.1140/epjc/s10052-018-5662-y. Accessed 12 Nov. 2024.
[50] “DARWIN - Dark Matter WIMP Search with Liquid Xenon.” *Darwin.physik.uzh.ch*, 2 July 2023, darwin.physik.uzh.ch/. Accessed 12 Nov. 2024.

about 10^{13} gigaelectronvolts. Just above this size, at 10^{15} gigaelectronvolts, physicists also begin discussing grand unified theories and the interrelationships between various forces. (“Sterile Neutrinos | All Things Neutrino”)[51]

Fuzzy Dark Matter: Non-interacting ultralight bosonic particles that behave like waves and have coherent dynamics on galactic scales make up fuzzy dark matter (FDM). FDM presents a unique phenomenology alternative to cold dark matter (CDM) on sub-galactic length scales. The amazing success of ΛCDM cosmology, however, favours FDM predictions, which on large scales are indistinguishable from those of CDM. The particle's mass, which ranges over three decades of energy, $10{-}24 \lesssim m/eV \lesssim 10{-}22$ eV, is the primary parameter controlling the two FDM regimes. In order to produce wave-like behaviour at galactic scales, particles with such minuscule masses and typical velocities v observed in haloes containing galaxies the size of the Milky Way acquire a very long de Broglie wavelength. FDM can operate as self-gravitating dark matter waves and have a high occupancy number in the galactic haloes. On macroscopic scales, this results in a pressure-like effect that causes galaxies to have a flat core at their centre and a reasonably noticeable transition to a less dense outer area that follows the normal CDM-like distribution. (Anchordoqui et al.)[52]

Dark Photons: There have been theories regarding the existence of a new gauge boson called the dark photon. Because it comes from a symmetry of a hypothetical dark sector composed of particles completely neutral to the Standard Model interactions, it is dark. It is possible to detect this new gauge boson despite its darkness due to its kinetic mixing with the regular visible photon. (Fabbrichesi et al.)[53] Despite its lack of understanding, dark matter is the most likely explanation for why galaxies revolve more quickly than they should, considering the amount of visible matter they contain. The mechanism behind these interactions is unknown, despite the fact that we can see dark matter interacting with the cosmos. Dark photons are one option, said Carlos Wagner, a particle physicist in Argonne National Laboratory's High Energy Physics (HEP) branch and a professor at the Enrico Fermi Institute and the University of Chicago. In reference to the photons, W and Z bosons that carry the electromagnetic and weak forces, Wagner states, "The story is something like this: there could be an additional dark sector, where dark matter resides, and that couples weakly to the ordinary sector – in this case, via the mixing of a gauge boson, the dark photon, with the ordinary neutral gauge bosons." "The dark matter and, more generally, a hypothetical dark sector may couple in a relevant way with such a gauge boson." (Jackson)[54]

This search for dark matter is fraught with important theoretical challenges and numerous unanswered questions. The first question focusses on the characteristics of the dark matter particles, such as their mass, interaction mechanism, and early universe formation. WIMPs are very hard to detect with current detection methods since they are believed to interact only gravitationally and weakly. Serious doubts are raised by this lack of empirical evidence regarding the viability of other hypotheses, such as fuzzy dark matter, sterile neutrinos, or axions, as explanations for the invisible mass that governs cosmic distribution

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[51] “Sterile Neutrinos | All Things Neutrino.” *All Things Neutrino*, Fermilab, neutrinos.fnal.gov/types/sterile-neutrinos/#evenmore.

[52] Anchordoqui, Luis A, et al. “Fuzzy Dark Matter and the Dark Dimension.” *European Physical Journal. C, Particles and Fields*, vol. 84, no. 3, 15 Mar. 2024, https://doi.org/10.1140/epjc/s10052-024-12622-y. Accessed 12 Nov. 2024.

[53] Fabbrichesi, Marco, et al. *The Physics of the Dark Photon*. SpringerBriefs in Physics, 4 May 2020. Accessed 17 May 2023.

[54] Jackson, Kevin. “Dark Photons Could Explain High-Energy Scattering Data – Physics World.” *Physics World*, 17 Oct. 2023, physicsworld.com/a/dark-photons-could-explain-high-energy-scattering-data/. Accessed 12 Nov. 2024.

and galaxy patterns. The persistence of these unknowns suggests that our current understanding may be constrained by both theoretical assumptions and experimental practices.

Another dark matter theory that does not suit the facts is the Standard Model of particle physics, which does not specifically address non-baryonic particles like WIMPs. This gap is filled by adding hypothetical particles to the scenario in SUSY and other forms of the Standard Model extension. However, as there is no evidence of SUSY's existence at the LHC, there is much scepticism about its relevance to dark matter research. Moreover, models for WIMP relic density include the assumption of thermal equilibrium in the early universe. It could be argued that this is not satisfied by some alternative cosmological theories. The detection is quite challenging because research like LUX-ZEPLIN and DARWIN has been aiming for higher sensitivity thresholds. The very low cross-section interaction between WIMPs makes direct detection very difficult. Furthermore, indirect detection methods are impacted by cosmic background noise, making it impossible to connect any detected signals to dark matter. New detection techniques, advancements in experimental physics, and perhaps even a reconsideration of the basic principles that underpin our reality are required to get past these challenges.

Conclusion

The search for dark matter is one of the most intriguing and challenging problems in modern physics. Among the candidates considered, the WIMPs are undoubtedly the most popular. The role of WIMPs in cosmic structure is explained by the theoretical model known as ΛCDM and the concept of supersymmetry, even if experiments cannot conclusively prove their existence. This gap between theory and observation necessitates the development of novel theoretical frameworks and cutting-edge detection techniques that could either validate the existence of WIMPs or uncover more dark matter candidates. More knowledge of the early cosmic environment and the creation of new, extremely sensitive detection methods are expected to be key to advancements in this field. In the end, solutions to these dark matter riddles could radically change physics and the structure and origin of the universe in new and bold ways. Even if Dark Matter may ultimately be elusive, the hunt for it is enlightening.

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