Probing Candidates for Dark Matter: Evidence from WIMPs and Axions

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Abstract: As a matter of fact, dark matter makes a profound impact on the evolution and structure of the universe in recent years. However, the exact composition of dark matter is still unknown, which remains unsolved and puzzling issues for astrophysics and theoretical physics. To probe the components of dark matter, researchers suppose candidates for dark matter, such as WIMPs and axions, correspond with the features of dark matter. With this in mind, this study detailly analyze two most widely investigated dark natter candidates, i.e., WIMPs and axions. To be specific, the theoretical framework as well as state-of-art detections scenarios are demonstrated. According to the analysis and evaluations, detectors such as XENONnT for WIMPs as well as ADMX for axions can shrink the parameter space to recognize the particles' range and give further definitions. Overall, this analysis implicates the different probing circumstances and challenges in different particles, introducing their regularity and compatibility.

1 INTRODUCTION

As one of the most advanced science topics, the research for dark matter has experienced a process that abounds with various explorations and discoveries. From astronomical observations and theoretical simulations to high-energy physical experiments, all the stages have contributed valuable insights into the composition of the universe. The concept of dark matter dates back to the early 20th century, when astronomers looked at galaxies and star clusters and found inconsistencies between mass estimates based on visible stars and observed gravitational effects, suggesting an additional source of mass. Fritz Zwicky is the first scholar to propose that dark matter exists. In his in-depth study of the Coma cluster, he used Verrier's theorem to analyze the velocities of its members and found that the mass estimated by the light emitted by the visible galaxies alone was much lower than the actual mass needed to sustain its motion, suggesting indirectly that dark matter might exist. Specifically, he found that the visible matter constituted only about 1% of the required mass. Hence, Zwicky proposed a non-luminous form of matter that could provide the indispensable gravitational force to explain the high velocities. Overall, the ground-breaking discovery introduced that most of the universe's mass could be invisible, challenging the prevailing notions of cosmic structure (Fritz,1933). This breakthrough leads to the concept of a flat spin curve that challenges previous understanding that the distribution of galactic matter and its gravitational pull decrease with increasing radius. The unseen mass corresponded with Zwicky's concept of dark matter. Their work made a difference in providing robust and independent evidence for dark matter within individual galaxies, reinforcing the necessity for a new component in the cosmic mass inventory (Vera et al., 1970). After that, with the numerical simulations, Jerry Ostriker and Peebles studied the stability of disk galaxies. They demonstrated that disk galaxies without a meaningful number of non-luminous masses would be dynamically unstable and would not survive long without the gravitational support of a substantial figure for dark matter (Ostriker & Peebles, 1973).

Altogether, the early observations and hypotheses about dark matter had a profound impact on astronomy. They crucially influenced the cognition of cosmic structure, galaxy formation, and unified model, challenging existing models of the universe and setting the stage for subsequent researches. These pioneering efforts have revealed the limits of visible matter in interpreting cosmic

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phenomena, meaning that it needs to extend beyond visible entities to dark matter. These work challenges traditional physics and opens up new avenues for revealing the state and distribution of dark matter and its impact on the evolution of the universe.

The theory of dark matter, accompanied by technological advances, has moved from theoretical speculation to the cornerstone of physics with empirical support. After more than a century of development, the theory has achieved remarkable results and is seen as a central factor in explaining key problems, scientists have not only made breakthroughs in the proportion of dark matter, but also deepened their understanding of the properties of dark matter, further confirming the scientific and accurate theory of dark matter. Recent studies have mapped unprecedented precision for large-scale structures by leveraging advanced observational technologies. As data accumulate and analytical techniques continue to evolve, the understanding of dark matter will become more accurate. Power spectrum is a tool to quantitatively describe the intensity distribution of the density perturbation of matter in the universe with the change of spatial scale. In the dark matter power spectrum, oscillations at specific wave numbers are hallmarks of baryon acoustic oscillations (BAO). These sound waves originate from the energy released by the formation of hydrogen atoms in the early universe, and they drive patterns of sound waves in the cosmic background. As the universe expands, these sound waves stretch, but their amplitude and phase information is preserved. When these waves travel to the time of formation of the cosmic microwave background (CMB), they leave a unique mark in the plasma environment, forming the "Doppler peak" or "acoustic peak" in the CMB spectrum. This phenomenon is an important prediction of the standard cosmological model and has been verified by observational data. With the further evolution of the universe, these initial acoustic disturbances are amplified and reflected in large-scale structures.

Neutron stars also have emerged as critical natural laboratories for studying dark matter. A recent research by the University of Melbourne marks the importance of neutron stars in capturing and annihilation of dark matter. For the rapid energy transfer, dark matter annihilation in neutron stars can heat the stars rapidly, making the process remarkable within days. In addition, the heating effect brings both opportunities and challenges to the fields of astronomical observation and cosmic exploration. It bodes well for the discovery and confirmation of dark matter through observations of stars or the structure of the universe. Moreover, neutron stars also can efficiently capture dark matter due to their high density, accumulating these particles over time (Bell et al., 2024). The main goal of the BREAD experiment is to explore the dark matter in the universe, focusing specifically on the mysterious particle called the axion. The experiment uses a wideband reflector to capture the weak radiation signal generated by axion particles, thus effectively improving the detection efficiency. This innovative approach offers new opportunities to reveal the nature of dark matter, such as axions and dark photons, by using a broadband approach. This experiment employs a coaxial dish antenna to capture photons and improve the probability that axions change into photons (Wang & Christina, 2023).

In spite of extensive research, the exact composition of dark matter still needs to be discovered. To give insights into the frontier research and probe the composition, the paper elaborates on the candidates for dark matter, WIMPs, axions. Also, it provides compelling information about the other types. The structure of this article goes like this: The second part is about the details of dark matter, including definitions, categories, and a series of concepts and formulas. WIMPs and axions are separately introduced in terms of their principles, representative instruments, and current research in Sec. 3 and Sec. 4. It also mentions the other types of candidates in Sec. 5. The Sec. 6 is about the limitations and prospects. Ultimately, Sec. 7 contains a summary and conclusion.

2 DESCRIPTIONS OF DARK MATTER

Because of its inability to emit, absorb, or reflect light, dark matter cannot be detected by conventional optical detection. Invisible as it is, dark matter's influence in the universe is profound and significant, affecting the motion of ordinary matter and light, mainly through gravitational interaction. Scientists have used sophisticated astronomical observations and in-depth data analysis to confirm the existence of dark matter, which is estimated to account for about 27% of the total mass of the universe. Dark matter is a central topic in astronomy and cosmology, and its existence can be inferred from indirect evidence is mainly reflected in its significant gravitational effect. Specifically, when measuring the velocities of stars at the edges of galaxies, if dark matter does not contribute, the predicted rotation rate based on the distribution of visible matter will be lower than observed. It reveals that the actual mass distribution of galaxies is larger than the visible part, and this extra, invisible mass is considered dark matter:

$$v(r) = \sqrt{\frac{GM(r)}{r}} \quad (1)$$

Here, V (r) represents the velocity of rotation at a radius of r, which describes the linear velocity of a planet or satellite around a star; G is Newton's gravitational constant; and M (r) represents the total mass of all visible matter within the radius r from the center of the galaxy.

Based on Kepler's Third Law, when all the masses are centered in a galaxy and form a center of mass, objects in different orbits are gravitationally affected by the center of mass. As the distance from the center of the galaxy increases, the gravitational pull on the object weakens and its rotation rate changes, showing a decreasing trend with the increase of radius r:

$$v(r) \propto \frac{1}{\sqrt{r}} \quad (2)$$

In the 1970s, Vera Rubin and her partners succeeded in revealing the motion of gas layers in spiral galaxies by observing 21-centimeter radio emission from hydrogen atoms. At the time, it was widely believed that the material distribution at the galaxy's edge should decrease as the distance from the center increases, and its rotation speed should decrease accordingly. However, the actual observations were unexpected, and the speed at which spiral galaxies rotate did not follow this expected pattern. The researchers have constructed mathematical models. By doing so, scientists have successfully simulated a complex system of mass distributions involving both dark matter and ordinary matter, further confirming the key role played by dark matter in maintaining the stability of galaxy structure and determining its dynamic behavior:

$$\rho(r) = \frac{\rho_0}{1+\left(\frac{r}{r_0}\right)^2} \quad (3)$$

where ρ_0 and r_0 are constants. With the calculus proving, this model helps maintain the flat rotation curves that were observed at large radii by a consistent gravitational pull from the dark matter halo. Applying the galaxy rotation curves and dark matter models, researchers can better understand the mass distribution and dynamics of galaxies (Eistein, 1916).

Gravitational lensing plays an important role in exploring the universe and verifying dark matter. When a massive object is in the middle of a light path, it focuses the passing light gravitationally, bending or even magnifying or shrinking the light from a distant background. The gravitational field can change the path of light, which may lead to the reconstruction of distant galaxies, star clusters and even the structure of the universe. The principle of gravitational lens effect can be deduced and described by a set of precise mathematical formulas, among which the deflection angle formula is the most representative:

$$\alpha = \frac{4GM}{c^2 d} \quad (4)$$

where G is the gravitational constant proposed by Newton, which describes the gravitational force between objects; M is the mass of a lens object, which determines the degree of bending of the lens to light; c is the speed of light. The formula shows that the deflection angle of light passing through the lens is proportional to the lens mass and inversely proportional to the distance. The lens equation, combined with deflection angle, is widely used in physics and astronomy to explain optical phenomena.

$$\vec{\theta}S = \vec{\theta} - \frac{D_{LS}}{D_S}\vec{a} \quad (5)$$

where $\vec{\theta}S$ is the actual position of the source, $\vec{\theta}$ is the observed position, D_{LS} is the distance between the lens and the source, and D_s is the distance from the observer to the source. Moreover, the Einstein radius θ_E is also important to gravitational lensing. It is a characteristic angular radius of the ring-like image that is formed when the source, lens, and observers are perfectly aligned:

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}} \quad (6)$$

where D_L epresents the distance between the observer and the lens and affects the intensity of gravitational lens effect. When light passes near a massive object, it is bent by gravity, called gravitational lensing. Einstein's radius describes the degree of bending.

Based on the abovementioned principles, gravitational lensing has applications in mapping dark matter, estimating cosmological parameters, and detecting exoplanets and objects that do not emit light (Mohan & Goswami, 2024). Polarization is an attribute of electromagnetic wave, which describes the directivity of electric vector. In CMB, due to the fluctuation of density and the gravitational effect of dark matter, microwave photons will be scattered in the process of propagation, resulting in polarization effect (Eisenstein et al., 2005). By measuring and analyzing the CMB polarization accurately, researchers can get the information of the early universe, such as the distribution of matter, the density of dark matter and the evolution of the universe. Accurate measurement and analysis of CMBs are essential for revealing the composition and evolution of the universe. The researchers used radio telescope facilities to make high-precision observations of the CMB and constructed a temperature anisotropy and power spectrum. These spectra describe the fluctuation characteristics of CMB and can be transformed into cosmological model parameters. For anisotropies, it can be described by combining the Boltzmann equation with fluid dynamics. The evolution of perturbations reflects the influence of dark matter through the fluid equations (Komatsu et al., 2009):

$$\frac{d\delta}{dt} + \nabla \cdot \nu = 0 \quad (7)$$

$$\frac{d\nu}{dt} + \mathcal{H}\nu = -\nabla\Phi \quad (8)$$

where δ is the density perturbation, ν is the velocity field, $\mathcal{H}$ is the Hubble parameter, and Φ is the gravitational potential. For the CMB temperature power spectrum C_l, its relationship to cosmological parameters can be obtained through linear perturbation theory,

$$C_l = 4\pi \int k^2 P(k) [\Delta_l(k)]^2 \frac{dk}{k} \quad (9)$$

where $P(k)$ is the initial perturbation power spectrum, and $\Delta_l(k)$ is the multipole coefficient. This project intends to study the influence of microwave background radiation (CMB) on the origin of the universe by using the observed data of spectrum, energy spectrum and polarization. By continually improving observations and theoretical models, the knowledge about dark matter will be more deeply understood. The detailed cosmic composition charts collected by the Planck Co-op reveal the distribution of dark matter and dark energy in the universe. Fig. 1 shows the temperature power spectrum D_ℓ^{TI}, highlighting the peaks and troughs that correspond to different physical processes in the early universe. The first peak at $\ell \approx 200$ is influenced by the matter content, including dark matter. The subsequent peak reveals the abundance or ratio between dark matter and ordinary matter, often reflected in the power spectrum of cosmic microwave background radiation. These early density perturbations leave unique imprints on the CMB spectrum, containing information on the ratio of dark matter to ordinary matter (Planck Collaboration 2020).

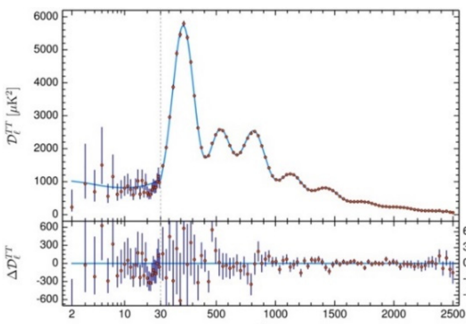

Figure 1: The temperature power spectrum D_ℓ^{TI} (Planck Collaboration 2020).

Combining the above-mentioned models and observations and other attributes of dark matter, researchers conclude three main properties of dark matter. The gravitational effect from dark matter, which is one of the main properties, has been mentioned frequently in this paper. Generally speaking, it provides gravitational forces to hold the stars at the same velocity, whatever the distance they are from the mass center, and helps the universe keep in balance (Vera & Kent, 1970). Dark matter also has a notable property of non-electromagnetic interaction. Dark matter affects the fate of the universe in its elusive form. It plays a transparent role in the universe because of its weak interaction with electromagnetic forces (Clowe, et al., 2006). Therefore, indirect methods should be used for detection and research. On the large scale, the distribution forms a network structure, which affects the formation and evolution of galaxies. It can be said that dark matter is an integral part of cosmological research, and its mysterious and unique nature provides us with space to explore. It seems that the dark form halos around galaxies to provide the necessary gravitational pull to hold them together (Navarro et al., 2016).

When discussing the evolution of the universe, dark matter as a key and difficult to detect form of matter, its classification and nature is particularly important. This process is based on an in-depth analysis of the velocity and interaction strength of the dark matter elementary particles. In the Cold Dark Matter (CDM) model, dark matter particles move very slowly, much slower than the speed of light (Navarro et al., 2016). In contrast, hot dark matter (HDM) particles move at speeds close to the speed of light, preventing them from coalescing rapidly and keeping them relatively evenly distributed. Because hot dark matter does not form density disturbances, it does not contribute to the formation of galaxies and clusters. However, they smooth the distribution of matter at large scales, thus maintaining the uniformity of the universe at large scales (White et al., 1983). Warm dark matter (WDM) has a velocity that is intermediate between those of CDM and HDM. The moderate speed allows the medium-scale structures to form, explaining some of the structural details that CDM models struggle with (Colín, et al., 2000).

Dark matter is an important unsolved mystery in cosmology and particle physics, and its exact properties and modes of existence remain at the forefront of scientific research. Although it cannot be directly observed, scientists speculate through indirect evidence such as gravitational effects that dark matter accounts for about 85% of the total material energy in the universe, and has a decisive impact on astronomical phenomena such as cosmic structure, galaxy evolution, and microwave background radiation. The following parts of the paper focus on the elaborations of the WIMPs, axions, and other types.

3 SEARCHING FOR WIMPS

Weak-interaction massive particles (WIMPs) are widely considered one of the main candidates for dark matter. Here are properties of WIMPs that correspond with the dark matter's characteristics. First, WIMPs are predicted to have masses in the range of giga-electron volts to tera-electron volts, making them significantly more massive than ordinary subatomic particles such as protons and electrons. As the name suggests, WIMPs interact primarily through the weak nuclear force, which is one of the four fundamental forces in nature, allowing WIMPs to pass through ordinary matter without significant interaction that makes them difficult to detect. Moreover, WIMPs are stable on cosmological timescale. Scattering cross section is a key physical quantity in particle physics and cosmology, which quantifies the possibility of interaction between WIMP and nucleon. It can be complex, but a simplified version for spin-independent interactions is:

$$\sigma \approx \frac{G_F^2 \mu^2}{\pi}[Z(1-4\sin^2\theta_W)+(A-Z)]^2 \quad (10)$$

where G_F is the Fermi constant that represents the strength of the weak force, μ is the reduced mass of the WIMP-nucleon system, given by $\mu = m_\chi m_N/(m_\chi + m_N)$, where m_χ is the WIMP mass and m_N is the nucleon mass, Z is the atomic number of the nucleus and A is the atomic mass number of the nucleus. θ_W is the weak mixing angle, a parameter in the electroweak theory (Lewin & Smith, 1996).

In addition to the scattering cross-section formula, other formulas also make a difference in explaining the principles of WIMPs. The thermal relic abundance of WIMPs in the early universe is determined by their interactions with Standard Model particles. A typical formula for the relic abundance of WIMPs is,

$$\Omega_\chi h^2 \approx \frac{1.07\times10^9\ GeV^{-1}}{M_{PI}\sqrt{g_*}\langle\sigma v\rangle} \quad (11)$$

where $\Omega_\chi h^2$ is the density parameter of WIMPs, and M_{PI} is the Planck mass. g_* is the adequate number of relativistic degrees of freedom at the time of WIMPs freeze-out, $\langle\sigma v\rangle$ is the thermal average of the WIMP annihilation cross-section times velocity (Griest & Seckel, 1991). The formula for the annihilation cross section describes WIMPs into Standard Model particles, typically assuming WIMPs are spin-1/2 particles, which is,

$$\langle\sigma v\rangle \approx \frac{g^4}{16\pi m_\chi^2} \quad (12)$$

where g is the coupling constant. m_χ is the mass of the WIMP (Bertone et al., 2024). Moreover, WIMPs can be produced in proton-proton collisions at high-energy accelerators. The production cross-section formula depends on the specific WIMPs model. In the Minimal Supersymmetric Standard Model (MSSM),

$$\sigma(pp \to \chi\chi + \mathrm{X}) \approx \frac{\alpha_S^2}{m_\chi^2} \quad (13)$$

where a_S is the strong interaction constant. m_χ is the mass of the WIMP (Baer et al., 2015). The detections of WIMPs can be categorized into three main methods which are based on the theoretical properties of WIMPs. Direct detection is one of the crucial methods that aims to observe the scattering of WIMPs off nuclei in a detector. When WIMP smashes into a nucleus, it transfers some energy to the nucleus, creating a backlash that can be detected and measured. Nonetheless, the background noise from cosmic rays and natural radioactivity can mimic WIMP signals. Therefore, experiments are often conducted deep underground to reduce these disturbs.

The liquid noble gas detector is a standard detector for probing WIMPs, such as XENONnT, LUX-ZEPLIN, and PandaX, using liquid xenon or argon to detect scintillation and ionization produced by nuclear recoils. XENONnT, as one of the frontier detectors, currently improves sensitivity to WIMPs-nucleon elastic scattering cross section to detect. The process of the XENONnT experiment includes a series of detections. Initially, when particles interact with the liquid xenon target, they cause a primary scintillation light (S1 signal). This light is detected by photomultiplier tubes (PMTs) within the liquid xenon. Simultaneously, the interaction also generates ionization electrons, which drift towards the gas phase above the liquid xenon due to the work of an electric field, creating a secondary scintillation light (S2 signal). Then, the S1 and S2 signals detected in the Time Project Chamber (TPC) are analyzed for their time distribution. The S1 signal occurs almost immediately, while the S2 signal is delayed as it involves the drift of electrons. Meanwhile, Cherenkov light signals detected in neutron veto (NV) are also analyzed. The NV detects signals with a typical delay of around 200 microseconds, which helps differentiate between neutron events and potential WIMP signals.

Subsequently, by analyzing the spatial and temporal distribution of the signals, the experiment can effectively suppress background noise, such as the noises from neutrons and γ photons, ensuring the accuracy of the detected signals. Ultimately, combining S1 and S2 signals allows for accurate three-dimensional reconstruction of events, with the potential signal regions hidden during initial analysis to maintain objectivity, determining their position and energy within the detector. Fig. 2 illustrates how the experiment distinguishes between different event types using time and spatial correlations, ultimately aiming to identify potential dark matter with high sensitivity. The top left graph shows the time distribution of S1 signals that are generated by scintillation light when particle deposits are detected in the TPC. As for the data, the peak amplitude is approximately 0.4 PE/ns, and most S1 signals fall within the first 100-150 ns, indicating the prompt scintillation light caused by the initial energy deposition. The bottom left graph describes the time distribution of S2 signals produced by ionization electrons drifting to the gas phase above the liquid xenon, generating a second scintillation light. According to the graph, the primary S2 signal appears around 5-6 μs with an amplitude of around 0.4 PE/ns, and the alternative S2 signals are visible at around 2-3 μs and 10-12 μs, representing secondary interactions or reflections. Seen from Fig. 2, all of the data is combined in the bottom graph. The right panel displays the spatial and temporal distribution of signals detected in both the NV and the TPC. The color scale presents the intensity and location of the signals (XENON Collaboration, 2024).

This study will focus on the generation rate of nuclear reactions for WIMP particles that do not depend on rotation, specifically in relation to the data shown in the black line and the results of the LZ experiment (preprint, in purple), the PandaX-4T experiment (in red) and the XENON1T experiment (in blue). Altogether, the result from XENONnT represents a significant step forward in the search for WIMPs. Seen from Fig. 3, the experiment improves sensitivity, particularly in the mid-mass range, positioning it as a leading project in the field of dark matter research (XENON Cillaboration, 2020).

An indirect detection experiment plays a vital role in detecting the WIMPs. It looks for the annihilation or decay products of WIMPs, such as high-energy gamma rays, antiprotons, antideuterons, and neutrinos. The principle is that WIMPs cluster in the galactic halo, annihilate or decay, and produce high-energy particles.

The Fermi LAT is a high-precision instrument designed to detect high-energy gamma rays. It observes high-energy gamma-ray radiation in areas such as the center of the Milky Way Galaxy and implements experimental restrictions on WIMP annihilation. The core component of the instrument is the LAT, which integrates a precision target chamber composed of a multilayer silicon strip detector and a tungsten layer. When gamma-ray photons interact with tungsten, electron-positron pairs are generated, and these secondary particles trigger a detector to record their trajectory as they travel through the zone. By accurately measuring the motion paths and energy losses of these secondary particles, scientists can accurately reconstruct the initial energy and direction of incident gamma rays.

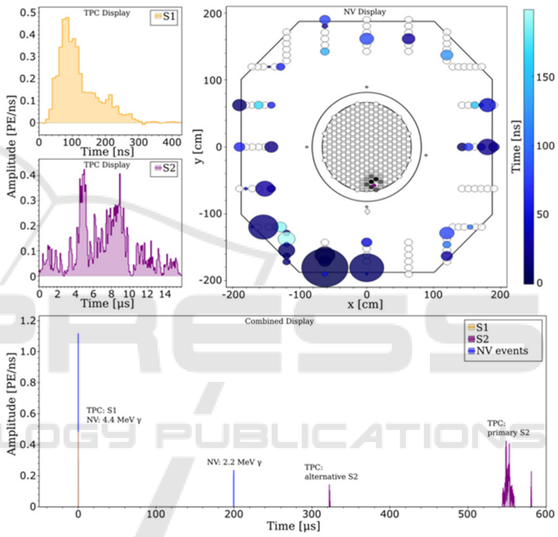

Figure 2: An overview of a signal detection and analysis process (XENON Collaboration, 2024).

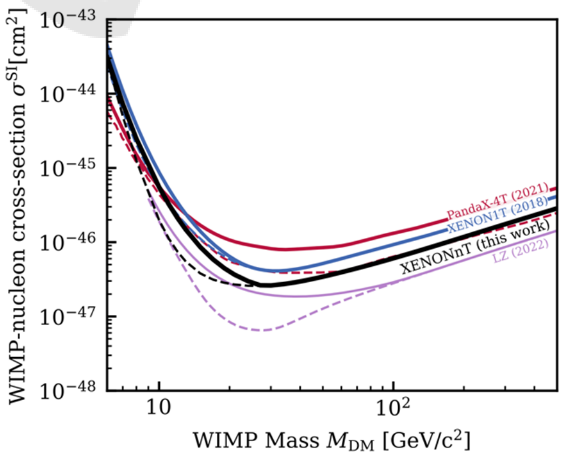

Figure 3: The cross-section of WIMPs (XENON Collaboration, 2024).

In terms of technical specifications, the Fermi LAT showed excellent performance indicators. It covers a wide range of energies, from 20 to 300 billion electron volts. In terms of field of view, the Fermi LAT has a wide field of view of about 2.4 spherical degrees, meaning it can scan and cover the entire sky every three hours. As the observed energy increases, the angular resolution is also excellent, at about 3.5 degrees at 100 megavolts and about 0.15 degrees at 10 billion. The telescope shown here is an exquisitely designed and massive telescope that measures 1.8 meters long, 1.8 meters wide and 0.72 meters high. The telescope was designed to operate at 650 watts, taking full account of the power requirements. In addition, the telescope weighs an astonishing 2,789 kilograms (Atwood et al., 2009).

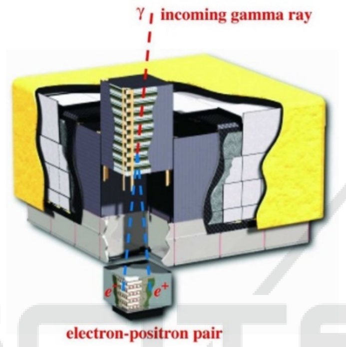

Figure 4: A sketch of the Fermi LAT (Atwood et al., 2009).

Recent observations by Fermi-LAT have focused on dwarf galaxies, which are considered ideal targets for dark matter searches due to their high dark matter content and low gamma-ray background. The latest analysis shows no significant gamma-ray signals by the 12 years of data, further constraining the parameter space for WIMP mass and interaction rates. This includes constraints that consider electromagnetic cascades (in solid blue lines) and not electromagnetic cascades (in dashed blue lines). For comparison, these constraints are also compared with the constraints of VERITAS (expressed in dotted lines), MAGIC (expressed in dotted lines) and HAWC (also expressed in dotted lines) and the correction of the J coefficient (see section 5 for details). In addition, the diagrams contain thermal cross-sections (up to m` 200 TeV, in red lines) and partial wave unity limits from nearby dSphs (in gray dotted lines) (Song et al., 2024). In the accelerator detection experiments, high-energy proton-proton collisions may produce WIMPs so detectors can identify WIMPs by observing missing energy and momentum. The paper just gives a brief about this detector (seen from Fig. 5).

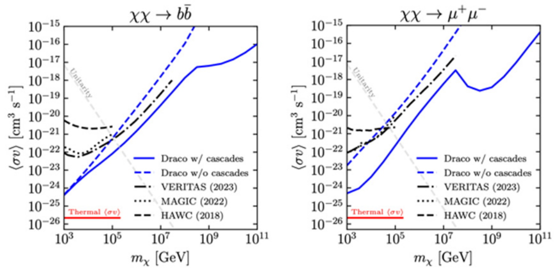

Figure 5: The upper 95% confidence level (CL) for the annihilation cross section of the $b\bar{b}$ (shown on the left) and $\mu^+\mu^-$ (shown on the right) channels of Draco is shown (Song et al., 2024).

4 SEARCHING FOR AXIONS

Axions is a hypothetical particle proposed in the theory of quantum color dynamics (QCD) to solve the problem of CP breaking. Axions are also considered an ideal candidate for dark matter, given their weak interaction and small mass. The interaction of axion with photons is the main task for axions to make a difference, according to which can be described by the effective Lagrangian,

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathrm{E} \cdot \mathrm{B} \quad (14)$$

where $g_{a\gamma\gamma}$ is the axion-photon coupling constant, a is the axion field, and E and B are the electric and magnetic fields. Understanding the mass formula and the axion-photon conversion rate is meaningful for both theoretical and experimental studies. For the axion mass formula, it relates the mass of the axion to fundamental constants and parameters in QCD,

$$m_a = \frac{\sqrt{z}}{1+z} \frac{f_\pi m_\pi}{f_a} \quad (15)$$

where m_a is the axion mass, z is the quark mass ratio, f_π is the pion decay constant, m_π is the pion mass, and f_a is the axion decay constant (Steven, 1978). The conversion rate of axions to photons in a magnetic field can be described by the Primakoff effect. The differential flux of axions converting into photons is given by:

$$\frac{d\Phi_a}{d\mathrm{E}} \propto g_{a\gamma\gamma}^2 \mathrm{B}^2 V \frac{\sin^2\left(\frac{qL}{2}\right)}{q^2} \quad (16)$$

where B is the magnetic field strength, V is the volume of the interaction region, q is the momentum transfer, and L is the path length of the magnetic field. The conversion rate formula is essential to calculate the expected signal in axion detection experiments. The experimenters can design setups such as magnetic field strength and cavity dimensions to maximize the chances of detecting axions. Besides, the formula also helps in setting limits on the axion-photon coupling constant from non-detections, thereby refining the parameter space for axion searches (Pierre, 1983).

Through persistent improvements in detection methods and equipment, researchers have made significant progress in detecting axions and exploring their potential as dark matter candidates. The resonant cavity is an important method to detect axions, such as ADMX, CAST, APLS II. It is a process that axions in a strong magnetic field convert into microwave photons that can be enhanced using a resonant cavity, providing signals for probes in the magnetic field. Axion dark matter experiment (ADMX) is a representation of resonant cavity experiments. The main equipment needed in the experiment are high-quality factor resonant cavities, strong magnets, and cryogenic detectors, which are composed together for measurements and detections. Seen from Fig. 6, the two primary measurements used in the ADMX are transmission measurement and reflection measurement, which are used to determine the resonant frequency ω_0 of the resonant cavity (ADMX Collaboration, 2024).

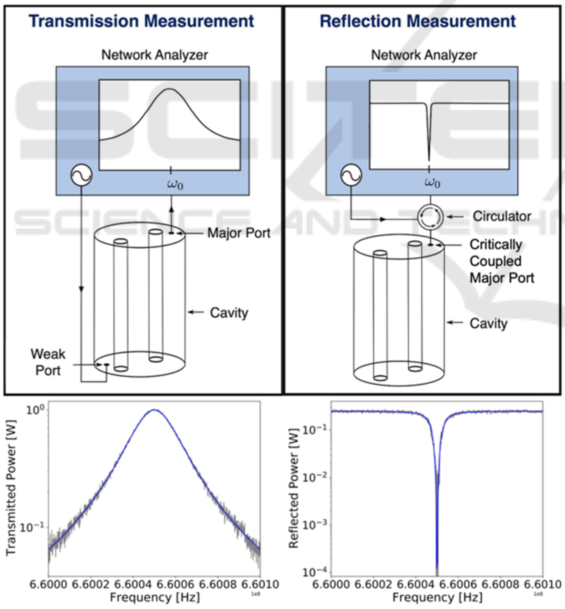

Figure 6: The transmission measurement detects the signal transmission from the weak port to the principal port of the cavity and then the data input in the network analyzer (left panel). The reflection measurement probes the signal reflected back from the major port of the cavity (right panel), and then the network analyzer displays the spectrum of the reflected signal, including the dip that also designates the cavity's resonant frequency ω_0.

The transmission measurement and reflection measurement can confirm the resonant frequency to maximize the sensitivity of the detection system to axion signals, probing the frequency at which axions exist. After the measurements and further amplications, the data can be analyzed and plotted to show the limits of axion-photon coupling constants at different axion masses. Fig. 7 includes the results from different models, such as Maxwellian and N-body models, as well as theoretical predictions (KSVZ and DFSZ models). According to the graph, the exclusion limits based on the Maxwellian model are higher than the ones based on the N-body model at the same axion mass, while the fluctuations are similar. Areas above the red and blue curves are parameter spaces where axions have not been detected, helping to define the mass and coupling ranges that are inconsistent with the presence of axions under current experimental conditions. Overall, the Fig. 7 provides a summary of current experimental capabilities and limitations

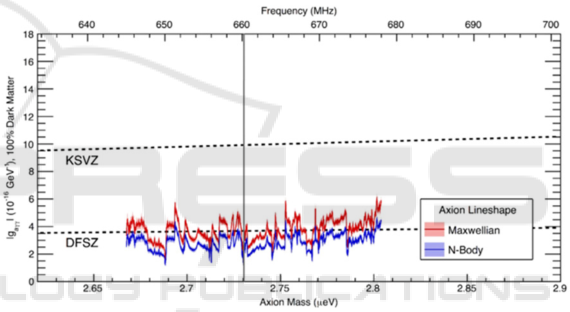

Figure 7: The chart shows the exclusion limits on the axion-photon coupling constant $g_{a\gamma\gamma}$ as a function of axion mass (ADMX Collaboration, 2024).

Solar axion telescopes such as the CERN axion solar telescope (CAST) also provide support for detecting axions. CAST uses strong magnets to capture and detect axions from the sun, which convert into X-rays. CAST uses a superconducting magnet to create a strong magnetic field through which solar axions can pass. The strong magnetic field also does convert work, and then specialized X-ray detectors at the ends of the magnets detect those photons. Moreover, the sunrise and sunset systems precisely align the magnet with the sun during sunrise and sunset, tracking it for about 1.5 hours each session. The converted X-ray photons are then detected by X-ray detectors, allowing researchers to analyze the data for axion signals as shown in Fig. 8 (CAST Collboration, 2017).

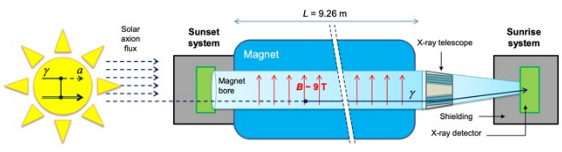

Figure 8: The flow chart for axions production. (CAST Collboration, 2017).

Based on the data collected from 2012 to 2015, CAST found no evidence of solar axion but set the most stringent limits yet on the axion-photon coupling constant $g_{a\gamma\gamma}$, which excludes a significant portion of the parameter space that is predicted by theoretical models. Seen from Fig. 9, the refined exclusion limits help narrow down the possible parameter space for axions (CAST Collboration, 2017).

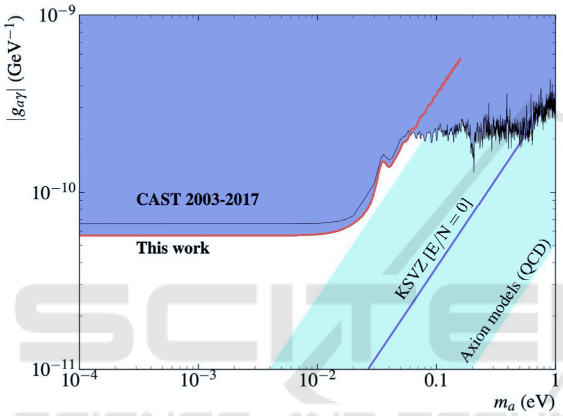

Figure 9: The parameter space for axions and axion-like particles (ALPs), showing the range of the latest constraints on the axion-photon coupling constant $g_{a\gamma\gamma}$.

Currently, optical cavities and lasers are used to detect axions. It probes the axion-photon conversion by applying intense lasers and high-reflectivity optical cavities. The Any Light Particle Search II experiment (ALPS II) is a representation of this kind of detection. ALPS II aims to achieve a sensitivity to the axion-photon coupling constant that is several orders of magnitude better than current limits. The experimental setups are superconducting dipole magnets to form the strong magnetic fields for the conversion, a high-power laser that generates the required input power, two 106-meter long optical cavities with a light-tight wall between them to block any direct light, a half-wave plate, and a detector, as presented in Fig. 10.

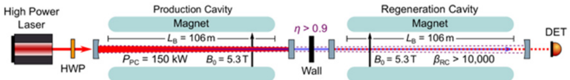

Figure 10: The flow chart illustrates the setups of the ALPS II experiment, which is designed to search for axion-like particles (ALPs) using a light-shining-through-a-wall (LSW) approach (Diaz et al., 2020).

During the detection, initially, the laser generates a high-intensity beam. Then, the half-wave plate adjusts the polarization of the laser beam to optimize the interaction within the magnetic field. For the most important part, the strong magnetic field in the production cavity prompts the photons from the laser beam to transfer into axion-like particles and facilitates ALPs conversion back into the regeneration cavity. Ultimately, the detector detects the regenerated photons, indicating the presence of ALPs (Diaz et al., 2020). The TES (Transition et al.) detection system, which is a highly sensitive calorimeter operated at cryogenic temperatures, plays a vital role in the ALPS II experiment by providing empathetic photon detection capabilities. The pulse exhibits a more profound and sharper voltage drop in 1.165 eV, and the pulse shows a shallower and broader voltage drop in 0.583 eV, meaning the detection captures a higher energy photon in 1.165 eV and a lower energy photon in 0.583 eV. Hence, to verify the linearity of the TES system, the pulse shapes maintain a positive correlation with the intensities. By comparing the detection results for photons of different energies, researchers can demonstrate that the TES system detects high-energy and has a higher sensitivity. Besides, researchers can optimize data analysis methods by analysing the data of the TES systems (Christina et al., 2024).

5 SEARCHING FOR OTHER TYPES

Besides WIMPs and axions, there are also some other competitive candidates for dark matter. Dark photons are hypothetical particles similar to photons but associated with dark matter, which interact weakly with ordinary photons through a mixing mechanism. The mixing term is,

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \quad (17)$$

where $F^{\mu\nu}$ is the electromagnetic field tensor of the ordinary photon, $F'_{\mu\nu}$ is the electromagnetic field tensor of the dark photon, and ϵ is the mixing parameter. Experiments look for weak interactions between ordinary matter and dark matter as detections

(Abazajian et al., 2012). Sterile neutrinos are also dark matter candidates assembled interacting only through gravity, not the weak nuclear force. The masses of sterile neutrinos are generally heavier than ordinary neutrinos. The mass term is,

$$\mathcal{L}_m = \frac{1}{2} m_S \bar{v}_S v_S \tag{18}$$

where m_S is the sterile neutrino mass, and v_S is the sterile neutrino field. Indirect detection through neutrino oscillation experiments and cosmic microwave background are used to analyze sterile neutrino experiments (Abazajian et al. 2012). Primordial black holes (PBHs) are black holes that formed in the early universe, shortly after the Big Bang, which are dark matter candidates. This study discusses the role of sterile neutrinos in cosmology and astrophysics, including their implications for dark matter and structure formation in the universe.

The mass of a single PBH is from less than a solar mass to several hundred times the solar mass. The mass can probably described as,

$$\beta(M) \sim \sqrt{\frac{2}{\pi}} \frac{\sigma(M)}{\delta_c} \exp\left(-\frac{\delta_c^2}{2\sigma^2(M)}\right) \tag{19}$$

where $\beta(M)$ is the probability of forming a PBH of mass M, $\sigma(M)$ is the density fluctuation at the mass scale, and δ_c is the critical density contrast. The experiments use gravitational wave observations and microlensing effects to detect (Carr, et al., 2016).

6 LIMITATIONS AND PROSPECTS

In spite of research such as WIMPs, axions, and sterile neutrinos have made significant progress in probing the dark matter candidates, they are still facing several challenges. For WIMPs, despite extensive searches, those experiments have yet to observe conclusive WIMP signals, so the interaction cross-sections they probed may still be above or below the sensitivity threshold. On the other hand, WIMPs span a broad range of possible masses and cross-sections, which makes it easier to rule out WIMPs entirely with significant experimental advancements. However, future experiments such as XENONnT aim to achieve greater sensitivity and lower background levels, potentially enabling the detection of lower interaction cross sections (XENON Collaboration, 2024).

Axions also face some limitations. For one thing, axions couple very weakly to photons and other particles, making them challenging to detect with existing technology. For another, the possible mass range for axions is vast, from micro-electron volts to millie-electron volts, which requires different detection strategies for different mass ranges. As the future prospects are high, haloscopes like ADMX are improving sensitivity to axions within specific mass ranges. The upgrades and new research also aim to cover broader mass ranges and increase detection potential. Moreover, laboratory searches are developing new techniques involving high-precision magnetometers and resonant cavities to detect axions (ADMX Collaboration, 2024).

Besides, sterile neutrinos cover a broad range of masses and mixing angles, but current experiments could be more extensive in their ability to explore the entire space, and it is indirect in obtaining the data. Thus, in future research, scientists expect they can explore the parameter space more comprehensively, and cosmological surveys can improve precision, which provides tighter constraints on sterile neutrino properties (Abazajian et al. 2012).

While the current research has faced several challenges, experimental sensitivity, technologies for observations, and theoretical modeling provide opportunities for overcoming this limitation. Probing for dark matter candidates is crucial for human beings to get insights into the truths of the universe.

7 CONCLUSIONS

Probing candidates for dark matter is the frontier mission for understanding the composition of dark matter. WIMPs and axions, as the most representative candidates for dark matter, lead researchers to focus on more specific data, aiming to correspond with the attributes of dark matter as the initial description in this paper. In spite of significant efforts, the detections of these candidates have been challenging due to their weak interactions or extensive parameter space. Advanced detection techniques and next-generation experiments such as XENONnT for WIMPs and ADMX for axions continue to push the boundaries of the knowledge. Further advancements in detector sensitivity, observational technology, and theoretical modeling will hold promise for overcoming current limitations. The continuing research not only deepens the understanding of dark matter but also propels the field of particle physics and cosmology forward, enhancing the grasp of the fundamental nature of the universe. By probing and understanding dark matter, one can obtain insights into the structure and evolution of the universe, agitating the study of dark matter to go ahead.

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