Current Searching and Future Prospects for Dark Matter: WIMPS, Axions and Sub-GeV

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Abstract: Dark matter remains a deeply unresolved and intriguing issue in contemporary physics era, containing approximately 25.9% energy density of the entire universe. While its gravitational effects are evident in galactic rotation curves and cosmic microwave background measurements, its composition and interactions beyond gravity are still unknown. This study summarizes the present theoretical landscape of dark matter and closely examines its leading candidate particles for example like Weakly Interacting Massive Particles (WIMPs), axions as well as sub-GeV particles. This research discusses the theoretical motivations, detection methods, recent experimental results, and future prospects for each candidate. The paper also addresses the challenges faced in dark matter detection, including background noise and energy thresholds, as well as explores upcoming experiments that aim to overcome these hurdles. According to the analysis, this study aims to provide insights into the ongoing efforts and future directions in the quest to unravel the fantastic truth of dark matter.

1 INTRODUCTION

Dark matter is believed to constitute approximately 25.9% to the universe's total energy matter content, vastly outweighing the ordinary baryonic matter, which accounts for a mere 4.9% (Ade, et al., 2016). Despite its dominant role in the universes mass-energy budget, dark matter has eluded direct detection due to its lack of electromagnetic interaction, rendering it invisible to conventional observational techniques.

The concept of dark matter was first induced by Swiss astronomer Fritz Zwicky during the early 1930s during his analysis of galaxy velocity dispersions, he found out this during his observation of the velocity dispersion of galaxy in the Coma Cluster (Zwicky, 1933). His measurements implied the existence of a significant amount of unseen mass. This notion was further reinforced in the 1970s by Vera Rubin's observations on galactic rotation curves, which revealed that the outer regions of spiral galaxies rotate at nearly constant speeds contradicting predictions made from visible matter alone (Rubin, et al., 1978).

In recent decades, dark matter has evolved into one of the most pressing unsolved problems in both astrophysics and particle physics and questioned numerous experts in related fields. Various theoretical models and experimental efforts have been developed to uncover its true nature. This paper presents a comprehensive review of the modern understanding of dark matter, including those leading candidates, detection techniques, experimental findings, and future prospects.

2 DESCRIPTIONS AND PROPERTIES OF DARK MATTER

Generally, dark matter is described as a non-luminous, non-baryonic form of matter which can interacts primarily under gravity and possibly via weak-scale forces, but not through electromagnetic or strong nuclear forces (Bertone & Hooper, 2018). Its gravitational effects are evident in galactic rotation curves, gravitational lensing, and cosmic microwave

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background (CMB) anisotropies, yet it has not been directly observed through electromagnetic means.

The Lambda Cold Dark Matter model outlines those essential properties that dark matter must exhibit:

- Cold: During the time of structure formation it must be Non-relativistic which allowing for the clumping of matter into galaxies and clusters.
- Collisionless: Not subject to self-interactions that would disrupt large-scale structure formation.
- Stable or Long-Lived: Persisting since the early universe to the present day.

Several theoretical candidates have been proposed based on these constraints. The three most studied types including WIMPs (Weakly Interacting Massive Particles), axions, and primordial black holes. Each possesses distinct theoretical motivations and implies different detection strategies (Abbott, et al., 2016; Nilles, 1984).

3 WIMPS

WIMPs (Weakly Interacting Massive Particles) have long dominated as primary candidates in dark matter research, due to their natural emergence in supersymmetric extensions of the Standard Model and their thermal production in the early universe. WIMPs are hypothesized to have masses between a few GeV and several TeV, interacting via weak-scale cross sections (10^{-4} to 10^{-41} cm) (Roszkowski, 2004).

This phenomenon is often termed the WIMP miracle. WIMPs thermally produced in the early universe would, through freeze-out, yield a relic abundance consistent with current observations of dark matter density. The aim of direct detection experiments is to measure nuclear recoils triggered by interaction with WIMPs which resulting from WIMP-nucleus elastic scattering. The differential recoil rate is typically given by:

$$\frac{dR}{dE_R} \propto \exp\left(-\frac{E_R}{E_0} \times \frac{4m_\chi m_N}{(m_\chi+m_N)^2}\right) \qquad (1)$$

where E_R is nuclear recoil energy, m_χ is WIMP mass, and mN: target nucleus mass, E_0 is a characteristic energy scale dependent on the local WIMP velocity distribution.

Several experiments have set stringent limits on WIMP-nucleon interactions (seen a typical facilitiy shown in Fig. 1 (Collaboration XENON, et al., 2018)), i.e., Liquid Xenon Time Projection Chambers (TPCs): Experiments like XENON1T (Collaboration XENON, et al., 2018), LUX (Akerib, et al., 2017), and PandaX-II (Cui, et al., 2017) use dual-phase xenon detectors that detect both scintillation (S1) and ionization (S2) signals; cryogenic detectors: SuperCDMS (Spooner, 2018) and CRESST-III (Abdelhameed, et al., 2019) use phonon and ionization measurements at millikelvin temperatures; bubble chambers: PICO-60 utilizes superheated liquids to detect WIMPinduced nucleation events (Amole, 2019). XENON1T currently sets the strongest constraints on spin-independent WIMP-nucleon cross sections, excluding values above 4.1 × 10^{-47} cm for WIMPs of 30 GeV/c mass.

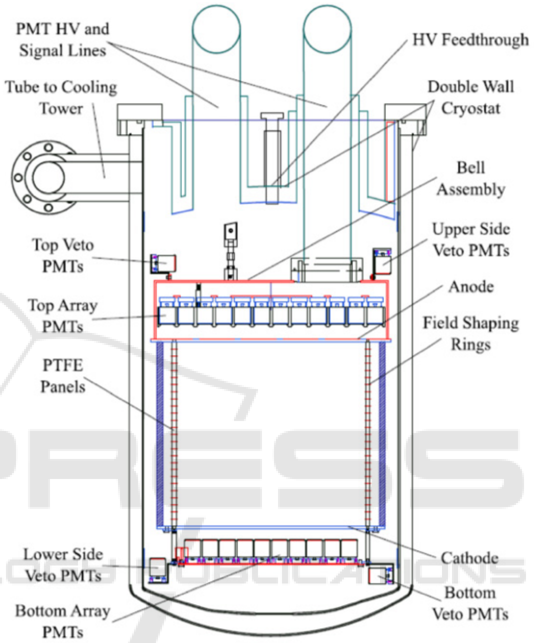

Figure 1: A typical facility for WIMPs detection (Collaboration XENON, et al., 2018).

4 AXIONS AND AXION-LIKE PARTICLES (ALPS)

Axions were initially introduced as a theoretical solution to the strong CP problem in quantum chromodynamics (QCD) through PecceiQuinn mechanism. As pseudo-Nambu-Goldstone bosons, axions are very light (eV to meV scale) and weakly coupled to standard particles.

In cosmology, axions produced through the misalignment mechanism can form a nonthermal cold dark matter component. Their mass and coupling are related via modelspecific parameters, often expressed in terms of the axion decay constant fa.

Because axions couple weakly to photons, Detection methods typically exploit the axion's ability to convert into photons under strong magnetic fields. The ADMX experiment [uses a microwave cavity inside a mag-netic field to detect axion-photon conversions (Ringwald, 2012). CAST looks for solar axions converting to X-rays. SLight-Shining-Through-Walls (LSW) is a facility that laboratory searches for regenerated photons behind a barrier. ADMX currently constrains QCD axions in the mass range of 2.663.31 eV. Future projects aim to explore a broader mass range using improved resonant cavities and quantum amplifiers.

5 SUB-GEV DARK MATTER

Recent advancements in theory have proposed the existence of dark matter particles with masses under 1 GeV , especially in hidden sector or dark photon models (Battaglieri, et al., 2017). Such particles often go undetected in traditional WIMP searches due to their minimal recoil signatures.

To probe such light particles, detectors must achieve extremely low energy thresholds:

- Semiconductor Detectors: SENSEI and SuperCDMS employ CCDs capable
- of detecting single-electron events from dark matter-electron scattering (Crisier, et al., 2018; Agnese, et al., 2017).
- Cryogenic Calorimeters: The CRESST-III experiment has achieved thresholds as low as 30 eV using CaWO crystals (Abdelhameed, et al., 2019).
- Ionization-only Noble Detectors: Xenon-based detectors like XENON10 and XENON1T have been repurposed to look for ionization-only signals (Essig, et al., 2012).

SENSEI currently leads the field in constraining dark matter-electron interactions for certain masses under 5 MeV/c.

6 CHALLENGES, COMPARISON, AND FUTURE PROSPECTS

Both WIMPs, axions, and sub-GeV particles each present unique challenges in terms of detection. Background radiation from natural and cosmic sources poses significant limitations on experimental sensitivity, especially as experiments reach unprecedented sensitivity. Coherent neutrino-nucleus scattering (CNNS) is anticipated to emerge as a major source of irreducible back ground noise (seen from Fig. 2) (Billard, et al., 2014).

In addition, many sub-GeV dark matter candidates deposit less than 1 keV of energy upon interaction. Reaching the necessary sub-keV or even sub-100 eV thresholds requires breakthroughs in sensor technology and noise reduction. To improve sensitivity, experiments must scale to multiton masses while maintaining ultra-low background conditions. This is especially true for WIMP searches, where signal rates are extremely low.

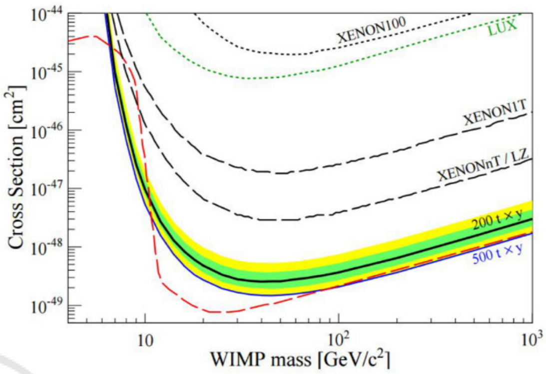

Figure 2: The cross section as a function of WIMPs mass.

Table 1: Comparison of Dark Matter Candidates.

Candidate	Mass Range	Main Interaction	Leading Experiments
WIMPs	GeVTeV	Weak nuclear	XENON1T, LUX, PandaX
Axions	eVmeV	Axion-photon coupling	ADMX, CAST
Sub-GeV Particles	MeVGeV	Electron recoils	SENSEI, SuperCDMS, CRESST

Table 1 presents a comparative overview of three major dark matter candidates including the most common one WIMPs (Weakly Interacting Massive Particles), axions, and sub-GeV particles —based on their characteristic mass ranges, primary interaction mechanisms, and leading experimental detection efforts. WIMPs, occupying the GeV to TeV mass scale, are primarily expected to interact via weak nuclear forces and have been extensively targeted by experiments such as XENON1T, LUX, and PandaX. Axions, which are ultra-light particles in the eV to meV mass range, interact through axion-photon coupling and are being probed by experiments like ADMX and CAST. Meanwhile, sub-GeV particles, ranging from MeV to GeV, are hypothesized to interact through electron recoils and are investigated using highly sensitive cryogenic and semiconductor detectors in experiments, e.g., SENSEI, SuperCDMS, and CRESST. This classification highlights the diverse theoretical landscape of dark matter candidates and illustrates how different detection strategies are tailored to their distinct physical properties.

In the coming years, a series of advanced and large scale experiments are expected to push the boundaries of dark matter detection to significantly advance the search for dark matter by exploring previously inaccessible regions of parameter space. The new generation time projection chambers (TPCs) such as XENONnT , LZ , and the future DARWIN detectors are being design to probe spin-independent WIMP-nucleon cross section to neutrino floor, where significant solar and atmospheric neutrinos built up backgrounds . This advancement method cellenge the traditional detection method (Aprile, et al., 2016; Akerib, et al., 2020; Aalbers, et al., 2016). Such detectors reflect the culmination of years of technological advancement in background reduction, target mass scaling, and signal discrimination. In parallel, the CYGNUS project proposes a novel approach using a gaseous detector array capable of directional detection, allowing it to measure the incoming direction of WIMPs. This directional sensitivity would provide a powerful tool for distinguishing potential dark matter signals from terrestrial and cosmogenic backgrounds, leveraging the Earth's motion through the galactic halo (Agnese, et al., 2018). Furthermore, rapid progress in quantum sensing technologies is opening new avenues for detecting ultra-light candidates mass under the eV interval. Techniques such as superconducting qubits, quantum calorimeters, and optomechanical devices may allow for the detection of tiny energy depositions previously thought to be undetectable. Together, these efforts promise a transformative leap in dark matter discovery potential.

7 CONCLUSIONS

Understanding the particle properties of dark matte continues to be a central challenge in modern physics. While extensive experimental campaigns have ruled out significant area of parameter space for WIMPs, the field is far from exhausted. Axions and sub-GeV particles provide theoretically motivated and experimentally accessible alternatives. The development of increasingly sensitive detection technologies has brought the field to a critical juncture. upcoming projects aim to explore interactions below the neutrino floor, employ directional sensitivity, and leverage quantum technologies. Regardless of the outcomediscovery or continued null resultsthe data gathered will be invaluable for constraining models and guiding theoretical developments. Delving the nature of dark matter would not just solve a central puzzle in cosmology but could also open a telescope to physics beyond the Standard Model, fundamentally altering the understanding of the enormou the universe.

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