# Searching Dark Matter Candidate Based on the State-of-Art Facilities: Evidence from WIMPs and ALPs

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Keywords: Dark Matter Search, WIMPs, ALPs.

Abstract: In contemporary astrophysics and cosmology, dark matter (DM) remains one of the most fundamental mysteries, derived from its gravitational pull-on radiation, observable matter, and the universe's large-scale structure. This study explores recent advancements in detecting DM candidates, focusing on WIMPs and ALPs. Significant progress in WIMP detection is highlighted by the TREX-DM detector achieving a low energy threshold and background level, enabling the exploration of sub-GeV WIMPs. Similarly, advancements in ALP detection have been marked by innovative experiments leveraging strong magnetic fields and novel techniques like nuclear magnetic resonance. These methods have improved sensitivity limits and explored previously uncharted mass ranges and coupling constants. The continual refinement in detection technologies and methodologies drives deeper investigations into DM properties. These advancements not only set stringent limits on DM interaction cross-sections but also open new avenues for exploration in the search for elusive DM candidates. This research is important because it can unravel the characteristics of DM, advancing a thorough knowledge of the genesis and development of the universe and directing upcoming astrophysical and cosmological research projects.

## 1 INTRODUCTION

Dark matter (DM) is one of the most profound mysteries in modern astrophysics and cosmology. Its gravitational pull-on radiation, observable matter, and the universe's large-scale structure suggests its existence. The concept of DM was first proposed by Fritz Zwicky in the 1930s, when he observed the peculiar motion of galaxies within the Coma Cluster, suggesting the presence of unseen mass to account for the observed gravitational effects (Zwicky, 1937). For decades, evidence for DM has cumulated through various astro observations, such as cosmic microwave background (CMB) radiation, gravitational lensing, and galaxy rotational curves (Rubin, 1970).

The significance of DM research is very crucial. It is estimated that DM makes up roughly 27% of the universe's total mass-energy content, this is in stark contrast to 5% baryons which is ordinary matter. For a complete picture of the creation and evolution of the universe, understanding DM is essential (Bertone, 2018). Its elusive nature challenges the current understanding of physics, pointing to potential new particles and interactions beyond the Standard Model.

Recent developments in WIMPs detection have been marked by the deployment of highly sensitive detectors designed to identify rare interactions between WIMPs and ordinary matter. The TREX-DM detector has shown promising results through reaching a background level of 80 counts $keV^{-1}kg^{-1}day^{-1}$ in the 1 to 7 keV range, and a low energy threshold of 1 keV. This sensitivity makes it possible to investigate WIMPs with masses smaller than 1 $GeV/c^2$, which is a breakthrough in the area (Castel, 2024). Ongoing improvements in reducing background noise and lowering energy thresholds are expected to further enhance the sensitivity of WIMP detection. Parallel to WIMP research, Considerable advancements have been achieved in the hunt for ALPs. Considerable advancements have been achieved in the hunt for ALPs, which are considered another well-motivated DM candidate (Castel, 2024). Current experiments have leveraged strong magnetic fields to detect the electromagnetic interactions of ALPs. A study using ferromagnets and SQUIDs

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Zhao, Y.
Searching Dark Matter Candidate Based on the State-of-Art Facilities: Evidence from WIMPs and ALPs.
DOI: 10.5220/0013074900004601

In *Proceedings of the 1st International Conference on Innovations in Applied Mathematics, Physics and Astronomy (IAMPA 2024)*, pages 276-281
ISBN: 978-989-758-722-1

(Superconducting Quantum Interference Devices) has pushed the boundaries of detection sensitivity, improving restrictions in specific mass ranges on the ALP-photon coupling constant (Gramolin, 2020). These experiments have begun to explore the mass and coupling regions where ALPs might explain anomalies in TeV gamma-ray transparency, thus opening new avenues in DM research. Previous studies have also employed novel techniques like nuclear magnetic resonance and spin-based amplifiers to detect ALPs, significantly improving the constraints on ALP-photon coupling. The NASDUCK collaboration has achieved unprecedented sensitivity in detecting the interactions of ALPs with nucleons, covering a previously unexplored mass range (Bloch, 2023).

The motivation for this research stems from the ongoing gaps in the knowledge of the composition and characteristics of DM. Despite extensive efforts, the identity of DM remains unknown. This research aims to contribute to the ongoing quest by exploring various detection methods and theoretical models. By synthesizing recent experimental results and theoretical developments, this study seeks to provide a comprehensive overview and propose new avenues for investigation. The rest part of the paper is organized as follows. The Sec. 2 introduces the definition and classification of DM, including potential candidates like WIMPs and axions, and their theoretical underpinnings. The Sec. 3 focuses on the theoretical description of axions, including Feynman diagrams and scattering cross-sections, detection methods, and typical instruments. It will present recent results and include figures from relevant studies. The Sec. 4 covers WIMPs, detailing their theoretical framework, detection principles, and key experiments. Recent findings will be discussed, with accompanying charts and graphs from recent literature. The Sec. 5 explores other DM candidates, their theoretical models, and detection techniques. Recent results will be illustrated with figures from studies conducted in the past few years. The Sec. 6 discusses the current limitations of DM research and outline potential future directions for overcoming these challenges. Eventually, a conclude remark is given in Sec. 7.

## 2 DESCRIPTIONS OF DM

Since DM doesn't emit, absorb, or reflect light, it is invisible to telescopic technology as they exist now. Even though its invisible, the gravitational pull of DM on observable matter, such galaxies and stars, suggests that DM exists. Fritz Zwicky first put up the concept of DM in the 1930s when he noticed that a galaxy's motion within clusters indicated the presence of unseen mass, significantly exceeding the mass of observable objects (Zwicky, 1937).

DM is broadly categorized into two types: cold DM (CDM) and hot DM (HDM). CDM consists of relatively massive particles that move slowly, while HDM includes lighter particles that travel at higher velocities (Press, 1990). For Cold Dark Matter (CDM):

- WIMPs. Among the most well-liked CDM contenders, WIMPs are hypothesized to interact only via gravity and the weak nuclear force. Their masses range from a few $GeV/c^2$ to a few $TeV/c^2$.
- Axions. Axions are hypothetical particles with extremely low masses, suggested as a solution to strong CP problem in QCD. If they exist, axions could also form part of the CDM (Peccei, 1977).

For Hot Dark Matter (HDM), there are some Light Neutrinos. Early cosmological models considered light neutrinos as potential HDM candidates. Neutrinos are very light, travel at relativistic speeds, and contribute minimally to the overall DM density (Press, 1990).

The most auspicious applicants for DM include WIMPs and axions. WIMPs are one of the leading contenders for DM. They exclusively interact through gravity and the weak nuclear force; neither the strong nuclear force nor the electromagnetic force is involved. WIMPs are classified as CDM due to their relatively large mass and slow movement compared to the speed of light. The "freeze-out" mechanism describes how WIMPs decoupled from the thermal equilibrium of the early cosmos, leading to the DM density observed today. The density parameter for WIMPs can be expressed as:

$$\Omega_X h^2 = \frac{m_X n_X}{\rho_c} \sim (3 \times \frac{10^{-27} cm^3 s^{-1}}{\langle \sigma_A v \rangle}) \qquad (1)$$

Here, $\Omega_x$ denotes the density parameter, h denotes the Hubble constant, $\langle \sigma_A v \rangle$ denotes the average interaction cross-section multiplied by the velocity (Press, 1990). Axions are lightweight hypothetical particles initially proposed to address the strong CP problem in QCD. It is anticipated that their masses will vary between $10^{-6}$ eV and $10^{-3}$ eV. Axions interact weakly with photons, which allows indirect detection methods. The density parameter for axions can be described by the equation:

$$\Omega_a = \frac{\rho_a}{\rho_c} = 10^7 (\frac{f_a}{m_p})(\frac{200MeV}{T_i})(\frac{A_i}{f_a})^2 h^{-2} \qquad (2)$$

Where Ωa is the density parameter, fa is the Peccei-Quinn symmetry-breaking scale (Peccei, 1977).

Despite the fact that DM cannot be seen directly, it is supported substantiated by cosmological observations and gravitational effects. Candidates such as WIMPs and axions offer plausible explanations for DM. Ongoing and future experiments aim to reveal more about the characteristics of DM, advancing the comprehension of the universe's composition and evolution.

## 3 SEARCHING FOR AXION

ALPs are hypothesized to address the strong CP problem in QCD. They are pseudoscalar bosons with no intrinsic spin. The axion-photon exchange is described by the Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F^{\mu\nu}} \tag{3}$$

where a denotes the axion field, gaγ γ denotes the axion-photon coupling constant, $F_{\mu\nu}$ denotes the electromagnetic field tensor, and $\widetilde{F^{\mu\nu}}$ is its dual. Feynman diagrams depict axion interactions, like the conversion of photons to axions in a magnetic field (Preskill, 1983).

A number of experimental strategies designed in order to identify ALPs and axions., mainly relying on their weak coupling to photons. Common methods include:

- Haloscope Searches. In these studies, axions are converted into observable photons by use of high-quality-factor microwave cavities submerged in a strong magnetic field.
- Helioscope Searches. These involve telescopes intended to use a high magnetic field to transform axions created in the Sun into X-rays, which would then be detected.
- LSW Experiments. These experiments involve shining a laser beam at a wall where axions are expected to convert to photons, which can then be detected on the other side of the wall.
- Axion Interferometry. This method exploits the interference patterns produced by axion-modulated laser beams in optical cavities (Gramolin, 2020).

For typical detectors, there are several follows:

- ADMX. This haloscope experiment makes advantage of a microwave cavity inside a strong magnetic field to find axion-photon conversion at specific resonance frequencies corresponding to the axion mass range of interest.
- CAST. A helioscope that aims to find axions created in the Sun by their conversion to X-rays using a powerful magnet (Gramolin, 2020).
- ABRACADABRA. This experiment looks for axion DM by detecting the magnetic fields induced by axions in a toroidal magnet configuration.

The SHAFT experiment demonstrated significant improvements in response to DM that is axion-like. The experiment enhanced the static magnetic field by using toroidal magnets with ferromagnetic powder cores made of iron-nickel alloy. The setup involved two independent detection channels with stacked toroids, each magnetized to create an oscillating magnetic field detectable by SQUID magnetometers. Results showed improved limits on a wide mass range of the axion-photon coupling constant (Gramolin, 2020). The ADBC experiment proposed a novel approach to interferometry employing a birefringent cavity to detect axion-modulated laser light. Over a broad range of axion masses, this architecture improves sensitivity to the axion-photon coupling, Using a realistic bowtie cavity design with adjustable mirror angles. The expected limits on the axion coupling from this experiment indicate significant improvements over previous methods (Gramolin, 2020).

The results from these experiments typically include exclusion plots showing the limitations of the axion-photon coupling constant gaγγ in relation to the mass of the axion ma. These plots help illustrate the sensitivity improvements and the parameter space explored by each experiment. Fig. 1 is an example of a graphical representation from the SHAFT experiment. It shows the axion-photon coupling strength exclusion limits for various axion masses, demonstrating the enhanced sensitivity of the SHAFT experiment compared to previous limits set by the CAST helioscope and other experiments (Gramolin, 2020).

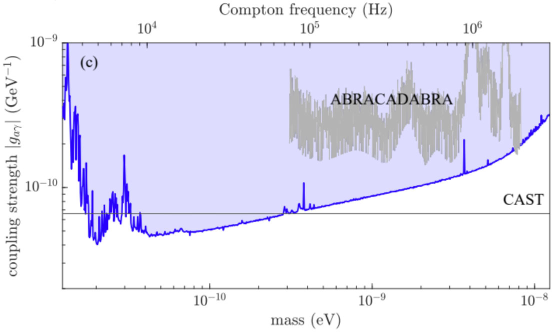

Figure 1: Graphical representation from the SHAFT experiment for searching cross sections (Gramolin, 2020).

# 4 SEARCHING FOR WIMPS

WIMPs are an ideal candidate for DM, arising naturally in supersymmetric models as the lightest supersymmetric particle. They communicate using gravity and the weak nuclear force, and their theoretical framework can be illustrated using Feynman diagrams. A common interaction is the destruction of WIMPs into particles in the Standard Model through intermediate states like the Z boson or the Higgs boson. The effective Lagrangian describing WIMP interactions includes terms such as:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C_{WW}}{4} W^{a}_{\mu\nu} \Pi \left(-\frac{D^2}{m^2}\right) W^{a\mu\nu} + \frac{C_{BB}}{4} B_{\mu\nu} \Pi \left(-\frac{\partial^2}{m^2}\right) B^{\mu\nu} + \ldots \qquad (4)$$

where LSM represents the standard model Lagrangian, $W^{a}_{\mu\nu}(B_{\mu\nu})$ represents the gauge group SU(2)L (U(1)Y) field strength tensor, D denotes the covariant derivative, while m represents the WIMP's mass. The scattering cross-section, crucial for detection, can be calculated using these interactions, often focusing on spin-independent or spin-dependent interactions depending on the experiment (Fukuda, 2024).

There are several methods for detection:

- Direct Detection. Measures the recoil energy of nuclei after scattering with WIMPs. Key principles include:
- Elastic Scattering. WIMPs elastically scatter off target nuclei, transferring kinetic energy.
- Threshold Energy. Detectors are sensitive to specific recoil energy thresholds to distinguish WIMP interactions from background noise (Fukuda, 2024).
- Indirect Detection. Searches for WIMP annihilation or decay products, such as neutrinos, gamma rays, or positrons.
- Cosmic Ray Observations. Observatories monitor excesses in cosmic rays which may indicate WIMP annihilation.
- Neutrino Telescopes. Detect neutrinos from the Sun's or Earth's WIMP annihilations (Fukuda, 2024).
- Collider Searches. Producing WIMPs in high-energy collisions, inferred by missing transverse energy (MET).
- Mono-jet and Mono-photon Channels. Characterized by a single high-energy jet or photon and large MET, indicative of WIMPs escaping detection (Fukuda, 2024).

Typical detectors are as follows:

TREX-DM. Using a high-pressure gas TPC with Micromegas readout for detecting low-mass WIMPs. Operated at the Canfranc Underground Laboratory, it aims to achieve low background levels and energy thresholds (Castel, 2024; Fukuda, 2024).

XENON1T. A liquid xenon detector designed for ultra-low background levels, searching for WIMP-induced nuclear recoils.

LUX-ZEPLIN (LZ). Another liquid xenon detector, an upgrade from LUX, with improved sensitivity to WIMP interactions (Fukuda, 2024).

The TREX-DM experiment has achieved significant milestones in WIMP detection. The detector, with an active volume filled with argon or neon mixtures, demonstrated the ability to attain an 80 counts ke $V^{-1}kg^{-1}day^{-1}$ background level and a low energy threshold of 1 keVee. Recent developments include a new readout plane integrating GEM and Micromegas technologies with the goal of achieve single-electron ionization energy thresholds. These developments set up TREX-DM to investigate WIMP masses lower than 1 GeV/c$^2$. Future muon colliders offer promising prospects for WIMP detection through both direct and indirect methods. Indirect detection benefits from analyzing the elastic μ+μ+ scattering's angular distribution, with beam polarization enhancing sensitivity. Studies indicate that with sufficient luminosity and beam polarization, these colliders could probe thermal WIMP masses, including the 2.7 TeV wino and 1 TeV Higgsino, highlighting their potential in improving the comprehension of DM (Fukuda, 2024). Fig. 2 demonstrates how the scattering cross-section's angular distribution is impacted by the WIMP, with polarization enhancing detection sensitivity.

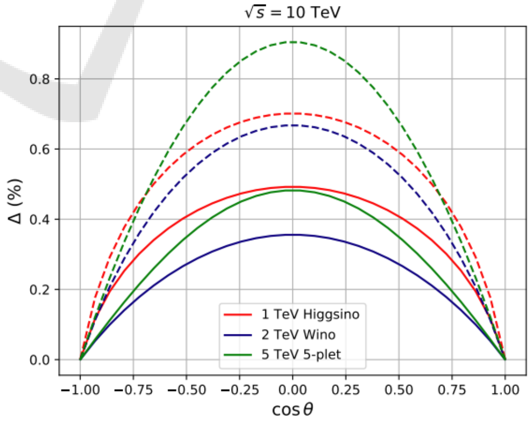

Figure 2: Δ(θ) for various WIMP candidates (Higgsino, Wino, 5-plet minimal dark matter) at sqrt(s) = 10 TeV. The solid and dashed lines represent unpolarized and polarized (Pμ+ = 0.8) initial muons, respectively (Fukuda, 2024).

## 5 SEARCHING FOR OTHER TYPES

Sterile neutrinos are hypothetical neutrinos that interact without using the weak force, making them hard to detect. They could have been created in the early universe by oscillations from active neutrinos. Their interactions can be represented by Feynman diagrams showing the transition from active to sterile neutrinos and vice versa (Akerib, 2020). The LZ experiment is a state-of-the-art direct detection search for WIMPs DM. It is a successor to the LUX and ZEPLIN-III experiments and is designed to explore WIMP-nucleon interactions with unprecedented sensitivity.

WIMPs are hypothesized to interact with ordinary matter through weak nuclear forces. These interactions can be described using Feynman diagrams, which depict the WIMP interacting with a nucleon through the mediator particle's exchange, such as a Z boson. The SI WIMP-nucleon cross-section is a crucial element for characterizing these interactions. The LZ experiment has set stringent limits on this cross-section, particularly rejecting values above $9.2 \times 10^{-48} cm^2$ at a 36GeV/cm$^2$ WIMP mass with 90% confidence (Aalbers, 2023). The LZ detector employs a dual-phase xenon TPC to search the characteristic low-energy nuclear recoils (NR) caused by WIMP interactions. The TPC is protected by a 4300-meter-water-equivalent overburden at the SURF in Lead, South Dakota (Aalbers, 2023). The detection process involves two primary signals:

- Scintillation Light (S1): Prompt photons produced by the interaction.
- Ionization Electrons (S2): Electrons freed from xenon atoms, which drift to the liquid-gas interface and generate secondary scintillation in the gas phase.

It is possible to distinguish between NR and ER using the ratio of S2 to S1, the latter being mainly due to background radiation (Aalbers,2023) (Akerib, 2020). The LZ TPC is a cylindrical chamber with a diameter and height of around 1.5 meters, filled by10 tonnes of liquid xenon. It is monitored by the top and bottom of the chamber are equipped with arrays of 494 PMTs to detect S1 and S2 signals (Aalbers, 2023). To reduce background noise, the TPC is encircled by two additional detectors. A liquid xenon "skin" detector between the cryostat wall and the TPC, comprising 38 2-inch and 93 1-inch PMTs. An outer detector comprising 17 tons of liquid scintillator filled with gadolinium to absorb neutrons (Aalbers, 2023; Akerib, 2020).

In its first 60 live days of operation, LZ's search data showed no significant WIMP signal, resulting in increased upper bounds on the cross-sections of WIMP-nucleon. The spin-independent WIMP-nucleon cross-section was given the strictest constraint, particularly for a WIMP mass of 36 GeV/$cm^2$ (Aalbers,2023). The following plot from the experiment illustrates the spin-independent WIMP cross-section vs WIMP mass with a 90% confidence level as depicted in Fig. 3. The LUX-ZEPLIN experiment signifies a significant milestone in DM research. By utilizing advanced detection methods and sophisticated instrumentation, it has achieved remarkable sensitivity in probing WIMP interactions, setting stringent limits on their possible cross-sections. These efforts contribute to narrowing down the parameter space for WIMPs and guide future explorations in the quest to understand DM.

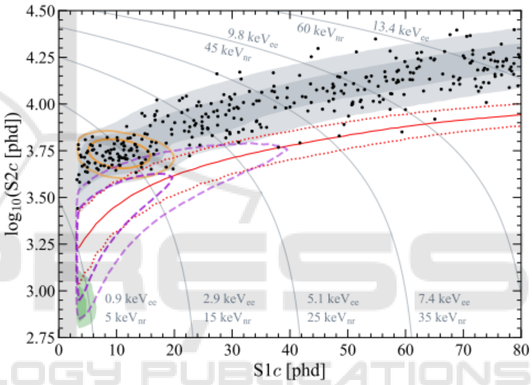

Figure 3: The WIMP cross-section's upper limit (black line), where the 1σ and 2σ sensitivity bands are indicated, respectively, by the green and yellow bands. (Aalbers, 2023).

## 6 LIMITATIONS AND PROSPECTS

Despite significant advances, DM research faces several limitations. One primary challenge is the absence of direct detection, even with highly sensitive experiments such as TREX-DM and LUX-ZEPLIN. These experiments have only been able to set upper limits on interaction cross-sections, indicating the need for even more sensitive detectors and innovative techniques to reduce background noise and lower energy thresholds. Theoretical uncertainties further complicate the search for DM. The vast parameter space of potential DM particle masses and interaction strengths means that current experiments may not be probing the correct ranges. This ambiguity makes it challenging to design experiments that are both comprehensive and sufficiently sensitive.

Despite these challenges, the prospects for DM research are promising. Future experiments, such as upgrades to existing detectors like LUX-ZEPLIN and ADMX, aim to enhance sensitivity and explore new parameter spaces. Innovations in detector technology, including novel materials and quantum sensing techniques, hold potential for breakthroughs in both WIMP and axion searches. Interdisciplinary collaborations and the integration of theoretical and experimental efforts are expected to accelerate progress. Advances in computational techniques, particularly machine learning, can help analyze vast datasets to identify potential DM signals amidst background noise. Theoretical advancements in understanding particle interactions and cosmological implications will guide future experimental designs. International collaborations will be crucial in overcoming financial and technological barriers. Projects like the Large Hadron Collider (LHC) and future muon colliders offer complementary approaches to DM research, potentially providing indirect evidence through particle collisions and decay signatures.

In summary, while DM research faces significant limitations, ongoing technological advancements, interdisciplinary efforts, and international collaborations provide a hopeful outlook for future discoveries. By continuing to push the frontiers of detection capabilities and exploring novel theoretical models, the scientific community is poised to make significant strides in comprehending DM.

## 7 CONCLUSIONS

In summary, DM remains one of the biggest puzzles in contemporary cosmology and astrophysics. This study has provided a comprehensive overview of DM research, concentrating on the leading candidates, WIMPs and axions. It detailed their theoretical underpinnings, detection methods, and recent experimental advancements. Despite extensive efforts, direct detection has not been achieved, underscoring the challenges posed by DM's elusive nature. However, significant progress has been made in setting stringent limits on interaction cross-sections and improving detection sensitivity. Looking forward, the prospects for DM research are promising. Future experiments, technological innovations, and interdisciplinary collaborations are expected to enhance sensitivity and explore new parameter spaces, bringing us closer to a potential breakthrough. The research's significance rests in its capacity to reveal fundamental aspects of the universe's composition and evolution. A thorough understanding of DM is essential to understanding cosmic history, making this research essential for advancing the knowledge of the universe and guiding future explorations in the quest to comprehend DM.

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