The State-of-art Searching Scenarios for Dark Matter Candidate: Evidence from Axion and WIMPs

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Abstract. In recent years, the dark matter still remains a mysterious in astrophysics and cosmology. So far, none of the candidate of dark matter is searched, even based on the state-of-art detection scenarios and facilities. With this in mind, this study comprehensively discusses dark matter's historical origins, research significance, and an overview of recent developments in this field. To be specific, the focus is placed on two candidate particles for dark matter: axions and Weakly Interacting Massive Particles (WIMPs). The ADMX project is discussed in detail concerning axions, emphasizing the utilization of susceptible detectors and instruments for large-scale searches across various mass ranges. Additionally, experiments such as XENON and LZ are examined to provide deeper insights into the existence of WIMPs. The article also addresses the limitations of current investigations and offers prospective directions for future research endeavors in dark matter. Overall, these results shed light on guiding further exploration of dark matter searching.

Keywords: Dark matter searching, Axion, WIMPs.

1. Introduction

Towards the conclusion of the 19th century, an intellectual discourse commenced within the astronomical community. Prompted by the advent of astrophotography, scientists discerned an uneven distribution of stars across the celestial sphere, along with the observation of darkened regions amidst densely populated star fields. This intriguing phenomenon posed an inquiry: were these dark regions attributable to a paucity of stars, or were they instead the consequence of obstructing material traversing the line of sight [1].

Fritz Zwicky, a renowned Swiss astronomer, is widely recognized as the dark matter pioneer. During the 1930s, while investigating the movements of galaxies within the Coma Cluster, Zwicky made a groundbreaking proposition. He observed that the visible mass within the cluster failed to account for the observed velocities of the galaxies, thereby prompting him to posit the existence of an imperceptible mass component [2].

During the groundbreaking astronomical research conducted in the 1970s, Vera Rubin and Kent Ford made significant contributions to our understanding of the structure and dynamics of spiral galaxies. Through their meticulous observations and analysis of rotation curves, they made a remarkable discovery that challenged our existing knowledge of the universe: stars at the outskirts of spiral galaxies were moving too quickly to be explained by the visible mass alone [3]. Furthermore, investigating dark matter emerges as a principal objective in our pursuit of scientific knowledge due to its pivotal significance in understanding the fundamental mechanisms underlying the universe. This study comprehensively discusses dark matter's historical origins, research significance, and an overview of recent developments in this field. To be specific, the focus is placed on two candidate particles for dark matter: axions and Weakly Interacting Massive Particles (WIMPs).

2. Candidates of Dark Matter

Despite the absence of direct empirical evidence supporting the existence of dark matter, the scientific community has identified several prospective candidates that could potentially constitute dark matter. WIMPs, which stands for Weakly Interacting Massive Particles, are one of the leading candidates for dark matter. They are hypothetical particles predicted by various theories beyond the

Standard Model of particle physics. WIMPs are characterized by their weak interactions with ordinary matter, meaning they interact with other particles primarily through weak nuclear force and gravity. This property makes them challenging to detect directly since they only leave subtle traces of their presence [4].

One of the critical reasons why WIMPs gained attention as potential dark matter candidates is their ability to explain the observed abundance of dark matter in the universe. According to theoretical models, if WIMPs exist, they will possess the suitable properties to account for the gravitational effects attributed to dark matter, which have been observed through their impact on galaxies and the universe's large-scale structure. Scientists have proposed various types of particles as potential WIMPs, such as the neutralino in supersymmetry theories or the sterile neutrino in some extensions of the Standard Model. If they exist, these particles will have masses ranging from several times the mass of a proton to several times the mass of an entire atom. Research on WIMPs plays a crucial role in comprehending the essence of dark matter and its significance in the universe. Despite numerous unresolved enigmas, the study of weakly interacting massive particles presents a captivating avenue to understand dark matter.

In the late 1970s, theoretical physicists Roberto Peccei and Helen Quinn originally proposed the concept of axions. However, at that time, axions garnered limited interest among particle physicists, who were primarily focused on high-energy collider physics [5]. Axions are hypothetical elementary particles that have attracted significant research interest due to their unique characteristics. They were initially proposed as an extension to the theory of strong interactions, known as quantum chromodynamics (QCD) [6]. Axions are characterized by their extremely low mass and weak interactions. They are thought to have been produced in the early stages of the universe, during the period of the Big Bang, and they are considered potential constituents of cold dark matter. Unlike other candidates for dark matter, axions typically have masses in the range of micro electron-volts (eV) or even lower, making them a lightweight candidate for dark matter.

One crucial feature of axions is their interaction with electromagnetic fields. Their interactions strongly depend on their mass and coupling constant. When exposed to a magnetic field, these interactions allow axions to convert into photons (electromagnetic waves). Similarly, photons can also convert into axions through a reverse process. Scholars have employed various experimental techniques and observations to search for axions. These include using strong magnetic fields, particle accelerators, and astronomical observations. Although direct detection of axions has yet to be achieved thus far, their existence is widely accepted, and researchers continue to explore experimental and observational avenues to gain a deeper understanding of their properties and search for potential evidence of their existence.

MACHO (Massive Astrophysical Compact Halo Object) is a massive interstellar compact object, a hypothesized component of dark matter in astronomy. MACHOs are considered dense objects that may have formed from celestial bodies such as stars or planets, with masses ranging from the mass of the Sun to tens of times the mass of the Sun. They play an essential role in explaining the composition of dark matter in the Milky Way [7]. According to the MACHO hypothesis, the Milky Way's dark matter can be composed of these compact objects that are difficult to detect directly. MACHOs do not emit or scatter large amounts of electromagnetic radiation, so conventional optical or electromagnetic observations cannot directly detect them. Instead, scientists rely on indirect observational means to study the existence and nature of MACHOs.

The existence of MACHOs can be inferred from the gravitational effects they cause. For example, by observing the gravitational lensing effect caused by the weak gravity around the star, it can be assumed that MACHOs may be behind it. In addition, by monitoring the light variation of background objects, that is, the brightness of light changes over time, scientists can also indirectly infer the presence of MACHOs behind it. However, with further study of dark matter, current evidence suggests that MACHOs may only explain a small fraction or no dark matter problem. Other dark matter candidates, such as WIMPs, are also being extensively studied and explored. So even if MACHOs exist in the Milky Way, they explain only a fraction of dark matter, not all of it.

Sterile neutrinos are hypothetical particles proposed as potential candidates for dark matter. Neutrinos themselves are neutral, weakly interacting particles that are included in the Standard Model of particle physics. However, sterile neutrinos differ from their active neutrino counterparts in not taking part in weak nuclear force interactions. The term "sterile" describes these neutrinos because they do not undergo interactions through the weak nuclear force, making them essentially "sterile" about such interactions. Consequently, sterile neutrinos do not experience the weak force processes that enable active neutrinos to participate in phenomena like beta decay.

Sterile neutrinos are especially intriguing as potential dark matter candidates because, much like active neutrinos, they interact extremely weakly with matter and can be produced in abundance during the early stages of the universe. If sterile neutrinos exist and possess suitable properties, they could have been generated in significant quantities during the intense heat of the Big Bang. They could contribute to the overall density of dark matter in the universe [8].

3. Searching for Axions

Several significant experiments have focused on the search for Axions in recent years. In this paper, our primary focus will be discussing the ADMX (Axion Dark Matter eXperiment). ADMX is an experimental project specifically created to detect axions, hypothetical particles that could exist within dark matter. The project is based in the United States and aims to search for these axion particles. ADMX employs a technique known as resonant cavity technology, which enhances its ability to detect axions with higher sensitivity. At the core of the ADMX is a high-precision resonator made of superconducting material and kept at extremely low temperatures. When axions interact with electromagnetic fields, they can be converted into photons, creating a resonance effect in the cavity. By adjusting the frequency of the resonant cavity, ADMX is designed to match the specific mass of the predicted axion particles, thereby increasing detection efficiency [9].

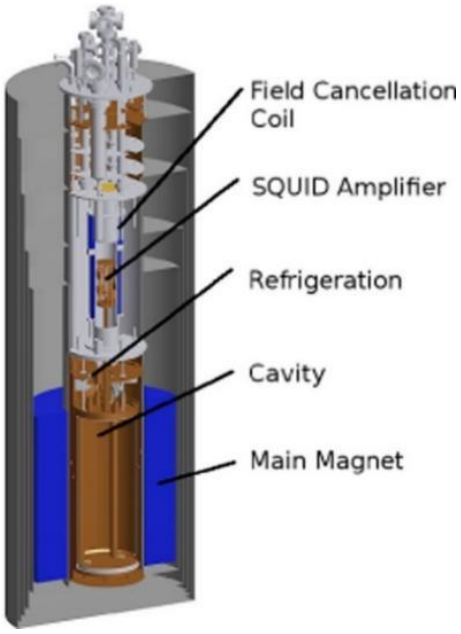


Fig. 1 Schematic layout of ADMX.

According to Fig. 1, there are specific components of the ADMX apparatus diagram:

- Field Cancellation Coil: used to reduce external magnetic field interference, maintain a stable and low noise environment, and improve the sensitivity of axion detection.
- SQUID amplifier: It is a high-sensitivity device used to amplify weak signals generated when interacting with axons, significantly improving the detection sensitivity of ADMX.
- Refrigeration: responsible for cooling the thermostat at different stages to maintain the ultra-low temperature environment required by ADMX, maintain the superconducting state, and reduce thermal noise.

- Cavity: It is the core part of ADMX and interacts with axions. Careful design and resonator optimization can achieve the best resonance and detection results.
- Main magnet: It is responsible for generating a strong and uniform magnetic field in the resonator, which is used to limit and control the axions and improve the sensitivity and accuracy of the detection.

In 2017, the Axion Dark Matter eXperiment (ADMX) searched axions within the 645-680 MHz frequency range. Axions are hypothetical particles considered to be potential candidates for dark matter. However, the investigation conducted by ADMX during that time did not yield any signals consistent with axions [10].

4. Searching for WIMPs

At present, XENON and LZ experiments are two experimental projects mainly used to detect WIMPs (Weakly Interacting Massive Particles). They use liquid xenon as a detection medium, taking advantage of xenon's sensitivity to WIMPs. XENON experiment is a series of projects, including XENON10, XENON100, XENON1T, and XENONnT. They use high-purity liquid xenon as a dark matter detection medium and build large liquid xenon detectors to detect WIMPs. The key to the XENON experiment is to reduce background noise to improve the detection sensitivity.

The LZ (LUX-ZEPLIN) experiment is the successor to the XENON experiment and is also based on liquid xenon detection technology. The LZ experiment is more extensive, uses more liquid xenon as the detection medium, and employs more advanced background noise suppression technology. The LZ experiment aims to improve the detection sensitivity of WIMP signals. It will be conducted underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA, at a depth of 4850 feet [11]. The detection scheme of these experiments is similar. They use large liquid xenon detection devices placed in a cold environment to increase detection sensitivity. When WIMPs and xenon atoms interact, weak light and electrical signals are generated in the detector. These signals are measured and recorded by photomultiplier tubes and electronics systems in the detector to look for signs of dark matter particles.

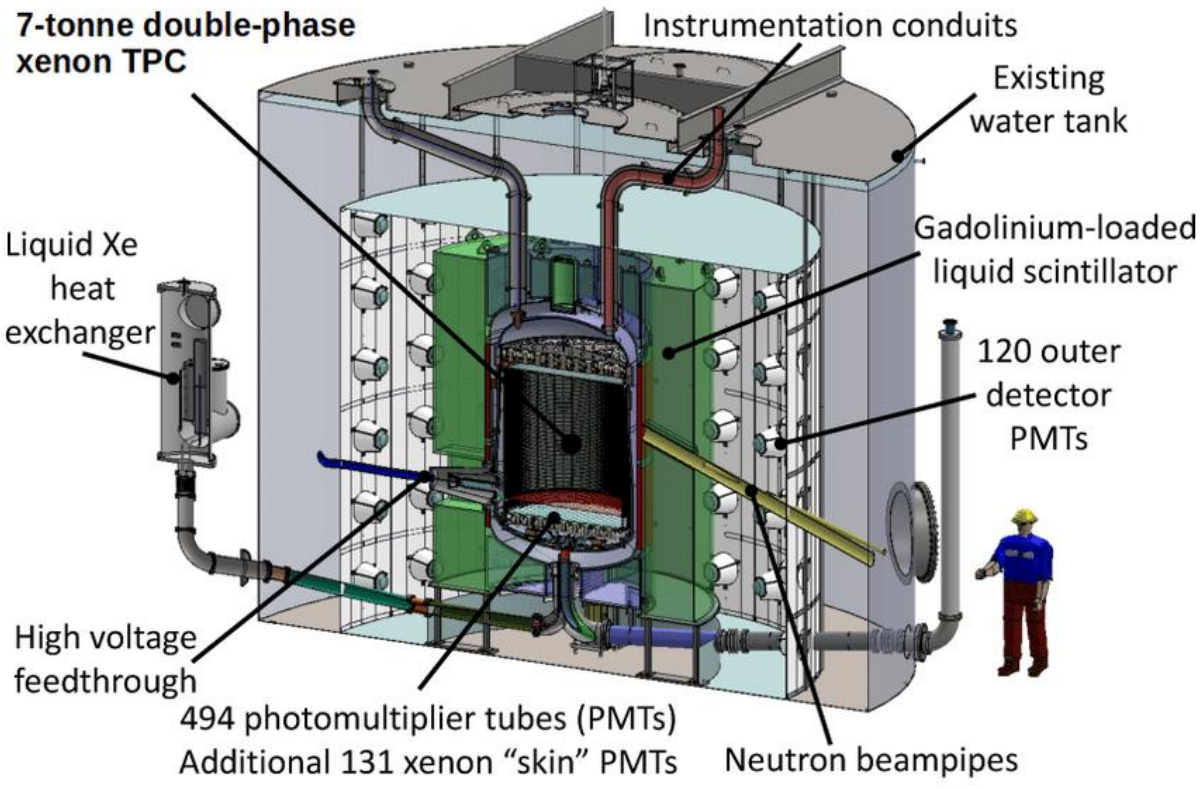


Fig. 2 Schematic layout of LZ experiment.

These are some essential components of the LZ experiment (seen from Fig. 2):

- 7-tonne double-phase TPC: As a core part of the experiment, the biphasic Xenon Time Projection Chamber (TPC) is filled with liquid xenon and is used to record and analyze particle interaction events in xenon.
- High voltage feedthrough: High voltage lead-out terminals charge liquid xenon, creating a high electric field strength to facilitate particle detection and measurement.
- Instrumentation conduit: The instrument conduit transmits signals and data, passing information from the detector to the data acquisition system for processing and analysis.
- Gadolinium-loaded liquid scintillator: In some configurations, the liquid scintillator is doped with radium (gadolinium) to detect neutron interactions and provide more information to distinguish between WIMP signals and background interference.
- Outer detector Photomultiplier tubes (PMTs): PMTs located outside the detector receive and amplify light signals generated in xenon gas to measure and analyze particle events.

XENON and LZ lack direct evidence of Weakly Interacting Massive Particles (WIMPs). Scientists plan to experiment using a fixed mass with an effective mass of 5.6 metric tons, exposed for 1000 days. At a 90% confidence level, LZ is expected to exclude weakly interacting particle-nucleon cross-sections of $1.4 \times 10^{\wedge}-48$ cm² and above. This corresponds to an improvement of an order of magnitude in sensitivity compared to recent liquid xenon (LXe) dark matter experiments, specifically for WIMPs with a mass of 40 GeV/c². The experiment was also planned to commence in 2020 [12].

5. Limitations and Prospects

Axions and WIMPs are exciting candidates for dark matter; no direct evidence has been observed. The search experiments of both candidates face a series of challenges and limitations. First, the mass of axions and the strength of their interactions with ordinary matter are unknown, which poses a challenge for experimental design and adjustment. Second, axion signals are weak, requiring susceptible detection techniques and a low background noise environment. In addition, the observed signal is also easily confused with other noise sources, further increasing the difficulty of finding axions.

Likewise, WIMPs, another promising dark matter candidate, face several limitations. First, WIMPs are very weak in mass and interaction with conventional matter, making it difficult to detect their signals directly. Second, the low interaction of WIMPs makes them more difficult to distinguish from other signs in the detector. In addition, the complexity of background interference (such as cosmic rays and background radiation) also increases the difficulty of WIMP detection.

However, the search for axions and WIMPs remains an active and compelling field, and the future outlook is full of opportunities. In the study of axions, through continuous improvement of technology and experimental design, we can further improve the limits on the mass of axions and the strength of interaction with ordinary matter. Developing a new generation of practical equipment and detection techniques, such as higher resolution resonators, amplifiers, and advanced dark energy resonators, will improve detection sensitivity and hopefully detect axion signals in a lower mass range.

In terms of WIMP, large-scale experimental equipment such as LZ and XENONnT are under active construction and will further improve the detection sensitivity of WIMP. Data collection from these experiments will provide additional limits and clues to studying WIMP interactions with ordinary matter. In addition to improving direct detection techniques, indirect detection methods are also being developed, such as indirectly searching for traces of WIMPs by detecting particles produced by cosmic rays.

Although no evidence of axions and WIMPs has been directly observed, searching for dark matter candidates is still actively underway. Improvements in technology and the development of a new generation of experiments offer great opportunities for further breakthroughs in this field in the future.

This will help reveal the nature and origin of dark matter in the universe, advancing our understanding of cosmology and fundamental physics.

6. Conclusion

Through analyzing axions and WIMPs, this study contributes to a better understanding these two candidate particles for dark matter. The ADMX project and experiments such as XENON and LZ have played pivotal roles in advancing our knowledge of dark matter; however, they also have certain limitations. Future research efforts should refine experimental techniques and methodologies to enhance detector sensitivity, enabling more accurate detection and confirmation of axions and WIMPs. Furthermore, exploring alternative dark matter candidate particles is crucial for gaining a more comprehensive understanding of the nature and properties of dark matter in the universe. With continued dedication and innovation, we are poised to unravel the mysteries of dark matter and elucidate its fundamental role in cosmological evolution and particle physics.

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