Analysis of the State-of-Art Dark Matter Candidate Searching: Evidence from WIMPs and Axions

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Abstract: Dark matter (DM) constitutes approximately 85% of the total matter in the universe. Its detection remains one of the most significant challenges in modern astrophysics and particle physics. This research provides an overall summary of the latest state of dark matter detection, focusing on both direct and indirect methods. This study summarizes the progress made in direct detection experiments (e.g., XENONnT and LUX-ZEPLIN), which have significantly constrained the space of Weakly Interacting Massive Particles through increased detector sensitivity. Indirect detection methods, including gamma-ray and cosmic-ray observations, have also refined the understanding of dark matter interactions. Additionally, one explores innovative approaches like the use of infrared spectroscopy and enhanced axion detection techniques, which offer new pathways for more sensitive and efficient detection. The findings highlight the ongoing advancements in experimental technologies and mathematical models which establish the limit of both the dark matter detection and research. DM is important for figuring out the universe's composition, gravity, and the particles that govern cosmic structure, making this research of profound significance in both astrophysics and fundamental physics.

1 INTRODUCTION

The research on dark matter has been a cornerstone of modern astrophysics since its initial proposal in the early 20th century. The first empirical evidence for DM came from observations of galaxy clusters, notably by Zwicky, who found that the gravitational potential of the Coma Cluster was far greater than what could be seen by the eyes along. This discrepancy suggested the existence of non-luminous "dark matter" (Zwicky 1937). Subsequent studies (e.g., Rubin & Ford, 1970), further supported this idea by revealing that the rotation curves of galaxies like M31 (Andromeda) did not decline as expected, indicating the presence of unseen mass. These observations challenged the Newtonian understanding of gravity and led to the development of alternative theories, including Modified Newtonian Dynamics (MOND) and the DM related hypothesis.

The significance of dark matter research lies in its profound implications for cosmology and particle physics. Dark matter is believed to constitute approximately 85% of the total matter in the universe, influencing the formation and evolution of cosmic structures. Direct evidence for dark matter was provided (Clowe, et al., 2006), who observed the Bullet Cluster (1E 0657-558) and demonstrated a spatial separation between the baryonic matter (X-ray emitting plasma) and the gravitational potential, which traced the distribution of dark matter. This observation provided compelling evidence that dark matter is not merely a modification of gravity but a distinct, non-baryonic component in the cosmic.

Understanding DM is important for solving the problems related to the universe's composition, the nature of gravity, and the fundamental particles that make up the cosmos. It bridges the gap between astrophysical observations and particle physics, offering insights into the cosmic structure and the fundamental laws governing it.

In recent years, the quest for understanding dark matter has intensified, with significant advancements in both theoretical models and experimental techniques. Observations across various scales, from galaxy rotation curves to cosmic microwave, have provided the evidence for the existence of DM, which constitutes most part of the universe (Huang, 2019). However, the DM remains elusive, driving scientists

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to do experiment on various candidate particles and detection methods.

One prominent candidate is the WIMP, which has been the focus of numerous direct detection experiments. These efforts have significantly constrained the parameter space of WIMPs, with exclusion limits approaching the neutrino floor (Liu, Yang & Yue, 2019). This has spurred interest in alternative light DM candidates, such as axions, dark photons, and fermionic DM. Experiments like CDEX in China have made notable contributions to probing these lighter candidates, utilizing low-threshold, low-background detectors to set stringent limits on their properties (ATLAS Collaboration, 2019).

Indirect detection methods, which rely on identifying signals that deviate from expected astrophysical backgrounds, have also seen substantial progress. These methods include searching for gamma-ray and cosmic-ray signals that could show the dark matter decay. Recent studies have explored potential signals from various dark matter candidates, including WIMPs and axion-like particles, using data from gamma-ray telescopes and cosmic-ray detectors (ATLAS Collaboration, 2019). While definitive detections remain elusive, these efforts continue to broaden the known part of dark matter's possible interactions and properties.

As experimental techniques continue to advance and new observatories come online, the prospects for uncovering the nature of dark matter are more promising than ever. The combination of direct and indirect detection methods, along with theoretical advancements, is expected to bring us closer to the truth of the mysteries

2 DESCRIPTIONS

Dark matter is a form of matter that does not interact with electromagnetic radiation, making it invisible to conventional detection methods. Its existence was first proposed by Oort and Zwicky to explain the observed discrepancies between the volume of galaxy clusters affected from fluctuations and the volume accounted for by matter (Kapteyn 1922; Zwicky 1933). Further evidence for DM is derived from the study of GRC, which showed that stars at the edges of galaxies were moving much faster if only visible matter was providing the gravitational force (Rubin, et al., 1980). The GL effect, where the path of light is affected by large objects, also provided valid justification of the existence of DM, as the bending was greater than could be accounted for by visible mass alone (Roberts & Rots, 1973).

Research into dark matter has advanced significantly in recent decades. Theoretical models suggest that the DM could be composed of WIMPs, which are hypothetical particles that interact weakly with ordinary matter (Bi, et al., 2018). Experiments such as the XENON project have been at the direct detection efforts, using lx detectors to explore the relationships between dark matter particles and atomic nuclei (Liu, et al., 2025). These experiments have set stringent limits on the interaction cross-sections of dark matter particles. Indirect detection methods include searching for the products of DM decay in cosmic rays, with experiments like AMS-02 and Fermi-LAT providing important constraints on dark matter properties (Bi, et al., 2018).

DM research can be broadly classified into two categories: direct-detection and indirect-detection. Direct detection aims to observe the scattering of DM particles in highly sensitive detectors placed secretly underground to protected against dangerous rays from the universe. Indirect detection, on the other hand, involves detecting the secondary particles produced by DM decay in cosmic rays, gamma rays, or neutrinos. Both approaches are crucial for understanding the nature of DM and its role in the universe.

3 DETECTIONS OF WIMPS

WIMPs have long been considered a promising candidate for DM. As stated in the paper “The Phenomenology of WIMP Dark Matter Model” by Tang, “WIMPs are the prominent candidates for dark matter” because they are theorized to interact with ordinary matter primarily through the weak force and gravity, making them elusive yet potentially detectable through their weak interactions (Tang & Zhang, 2024). These particles are expected to have masses in the interval of a few GeV to several TeV, offering a plausible explanation for the gravitational effects due to dark matter. The detection of WIMPs relies on three primary methods: direct detection, indirect detection, and collider experiments. Direct detection experiments aim to observe the rare interactions of WIMPs with atomic nuclei in highly sensitive detectors placed deep underground to shield against cosmic rays and other background radiation. These detectors typically use materials like liquid xenon or germanium, which can produce detectable signals when struck by a WIMP. For instance, the PandaX-II experiment, a leading direct detection effort, utilizes a two-phase liquid xenon time projection chamber (TPC) to search for WIMP interactions with xenon nuclei. As mentioned in the paper "Research Progress on DM Model Based on WIMP " by He and Lin (He & Lin, 2016), “Currently, many direct and indirect detections of dark matter based on accelerators or non-accelerators are designed for WIMP particles,” indicating the significant role of WIMPs in current experimental designs. Indirect detection, on other prospects, involves searching for the products of WIMPs annihilation in cosmic rays or neutrinos. This method relies on the observation of excesses in these particles that cannot be explained by standard astrophysical processes alone. CE, such as the experiment done by LHC, attempt to produce WIMPs by smashing high-energy particles together and observing the resulting debris for signs of dark matter. Recent years have seen significant advancements in the explorations of WIMPs. Direct detection experiments like XENONnT or LUX-ZEPLIN (LZ) have pushed the sensitivity limits to unprecedented levels, probing deeper into the possible mass and interaction cross-sections of WIMPs. These experiments have not yet detected a definitive WIMP signal but have provided stringent constraints on the parameter space, ruling out many previously viable scenarios. The PandaX-II experiment, for example, has published outcomes from 54 ton-day exposure, setting new upper limits on the s-d WIMP-nucleon cross-sections. Indirect detection has also made strides, with observatories like the Fermi-LAT providing detailed maps of γ-ray emissions from the galactic centre and other regions, searching for the telltale signatures of WIMP annihilation. While no conclusive evidence has been found, these observations have helped refine the understanding of potential dark matter behaviour and interactions. Despite the lack of a confirmed detection, the quest for WIMPs continues with renewed Vigor. Theoretical models, such as the Inert Doublet Model and the NMSSM, are being explored to provide new insights and predictions for WIMP properties. These models suggest that WIMPs could have masses and interaction strengths that are just beyond the current detection thresholds, offering hope for future discoveries. The ongoing and planned experiments, combined with the development of new mathematical frameworks, ensure the search for WIMPs remains a vibrant and active area of research, holding the answer of the mysteries

4 DETECTIONS OF AXIONS

Axions, hypothetical particles proposed to solve the strong CP problem in quantum chromodynamics, have garnered significant interest as potential candidates for DM (Zhao & Wei, 2023). Despite extensive experimental efforts, axions have yet to be detected. Traditional detection methods, such as the ADMX experiment (Asztalos, et al., 2001), rely on the change in axions will result to photons in a strong magnetic field, a process known as the Sikivie effect (Sikivie, 1990). However, the expected power of these electromagnetic response signals is extremely weak, typically in the order of 10^{22} to 10^{-23} W, making detection challenging and requiring long signal accumulation times. Recent advancements in detection techniques have explored the use of alternating magnetic fields to enhance the electromagnetic response of axions. By superimposing an alternating magnetic field on a steady-state strong magnetic field, the electromagnetic response signal of axions can be significantly amplified. This approach has the potential to increase the signal strength by several orders of magnitude, making it more feasible to detect axions with microelectronvolt masses. For instance, in a one-dimensional model, the introduction of an alternating magnetic field has been shown to amplify the axion electromagnetic response signal by 5-6 orders of magnitude compared to the steady-state case. This enhancement could significantly reduce the time required for signal detection and improve the sensitivity of axion search experiments. Another promising avenue for axion detection involves the use of atomic magnetometers and comagnetometers. These instruments, capable of measuring extremely weak magnetic fields, have been employed to search for axion-like dark matter and to explore anomalous spin-dependent forces (Zhang, et al., 2023). Atomic magnetometers can detect the interaction between axions and atomic spins, which can induce a precession of the spins. This precession can be measured with high precision, offering a sensitive probe for axion detection (Zhang, et al., 2023). For example, the CASPEr experiment proposes to use nuclear magnetic resonance techniques to detect the spin precession caused by axion-like dark matter (Zhang, et al., 2023). This method has the potential to provide stringent constraints on the coupling between axions and standard model fermions over a broad mass range. In summary, the detection of axions remains a challenging but crucial endeavour in both particle physics and cosmology. Innovative approaches, such as the use of alternating magnetic fields and atomic magnetometers, are opening new pathways for more sensitive and efficient axion detection. These developments improve the progress of solving the nature of DM.

5 LIMITATIONS AND PROSPECTS

Direct experiments hope to see the scattering of DM, such as WIMP, off atomic nuclei in large underground detectors. However, these experiments face several limitations. One major challenge is the extremely low interaction rate of dark matter particles, which results in a very small number of detectable events. Additionally, background noise from cosmic rays and radioactive materials can interfere with the detection process, making it difficult to distinguish genuine DM signals. For instance, even with advanced techniques to minimize background interference, the probability of statistical fluctuations leading to biased or uncertain results remains a concern. Indirect detection methods, which involve searching for the by-products of DM annihilations or decays in cosmic objects, also have their limitations. These methods require a variety of detectors, such as gamma-ray telescopes and neutrino detectors, each with its own set of challenges. For example, the interpretation of signals from these detectors can be complicated by astrophysical uncertainties and the need for accurate modelling of the dark matter distribution and interaction processes. Despite these challenges, the future of DM detection holds promise. Advances in technology are enabling the construction of larger and more sensitive detectors, which will increase the chances of detecting dark matter particles. For instance, next-generation direct detection experiments, such as the XENON1T and DARWIN projects, aim to achieve much lower detection thresholds and higher sensitivity. These experiments will also benefit from the combination of data from different types of detectors, which can help reduce statistical uncertainties and improve the accuracy of parameter reconstruction. In addition to technological advancements, new approaches are being explored. For example, a recent study demonstrated the potential of using infrared spectroscopy to search for dark matter by analysing light from ancient galaxies. This innovative method effectively turns the universe into a giant dark matter detector, offering a complementary approach to traditional particle-based detection. While this study did not detect dark matter directly, it set stringent limits on the properties of certain DM candidates, such as ALPs, thereby broaden the known fields of DM.

6 CONCLUSIONS

In summary, the detection of DM remains a formidable yet crucial challenge in modern physics. the comprehensive review of current detection methods has highlighted significant progress, particularly in the areas of direct and indirect detection. Direct detection experiments, such as XENONnT and LUX-ZEPLIN, have achieved unprecedented sensitivity, setting stringent limits on the interaction cross-sections of dark matter particles like WIMPs. Indirect detection methods, including gamma-ray and cosmic-ray observations, have also provided valuable constraints on dark matter properties. Additionally, innovative approaches like the use of infrared spectroscopy and enhanced axion detection techniques have shown promise in expanding the search capabilities. Looking ahead, the ongoing advancements in experimental technologies and theoretical models offer hope for future breakthroughs in dark matter detection. This research offers the ability to unravel one of the most profound unknowns of the universe

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