Analysis of the State-of-Art Dark Matter Candidate Search: Evidence from Wimps and Axion

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Abstract: Contemporarily, searching dark matter candidate remain a hot topic for physics and cosmology society. This study discusses the recent progress of detection for dark matter particles in this paper. Particularly, this research focuses on the efforts devoted to detecting WIMP and axion, including improvements in both theoretical frameworks and experimental techniques. According to the discussions, although many questions about dark matter candidates still don't have a clear answer, refinement in experimental methodology leads to more precise measurements. Benefiting by extension of the Standard Model, theory of dark matter also develops rapidly and provides a deeper understanding of this field to the astrophysics community. However, one notable point is that there are still many constrains in further detect efforts. The theoretical explanation develops to be complicated while today technology is insufficient to verify such results derived from the theory. The analysis provides a detail description about these limitations in the last few sections and also discusses the possible developments of dark matter detection in the future. These results aim to summarize the efforts particularly in the last five to ten years and offer a guideline for searching dark matter.

1 INTRODUCTION

The conceptual trajectory of dark matter reflects a shift from gravitational anomalies to a cornerstone of modern cosmology. Initially, postulated to account for galactic rotation curves and cluster dynamics, its theoretical status evolved through successive observational milestones and theoretical refinements. As detailed by Bertone and Hooper, the emergence of particle dark matter candidates coincided with the rise of precision cosmology, catalysing interdisciplinary inquiry spanning astrophysics and high-energy physics (Bertone & Hooper, 2018). Their historical synthesis underscores not only the empirical motivations but also the conceptual adaptability of dark matter frameworks across decades of evolving theoretical paradigms.

Understanding dark matter is pivotal to resolving foundational discrepancies in cosmology and high-energy physics. Its gravitational influence shape's galactic structure, yet its non-luminous nature evades direct detection, suggesting physics beyond the Standard Model (Bertone & Tait, 2018). Probing dark matter aids in constraining cosmological parameters, refining models of galaxy formation, and potentially unveiling new particles (Lisanti, 2017). Moreover, insights from dark matter dynamics could inform quantum gravity and unify theoretical frameworks across particle physics and cosmology (Ferreira, 2021). Thus, dark matter research serves as a crucible for testing the limits of modern physics and rethinking cosmic evolution.

In recent years, the field of dark matter detection has experienced a significant evolution, characterized by both technological advancements and theoretical refinements that have expanded experimental sensitivity. A fundamental shift has been the diversification of detection methodologies, extending beyond traditional Weakly Interacting Massive Particles (WIMPs) to explore a wider spectrum of possibilities, including ultralight candidates and axion-like particles. A notable development involves the LUX-ZEPLIN (LZ) experiment, which represents a substantial achievement in direct detection utilizing dual-phase xenon time projection chambers. The results published in 2023 establish the most stringent constraints globally on spin-independent WIMP-nucleon cross-sections at that time, reaching sensitivities below 10^{47} cm² for a WIMP mass of approximately 30 GeV/c² (Aalbers, et al., 2023).

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These findings effectively exclude substantial portions of previously viable parameter space.

Concurrently, innovative methodologies have been established to complement conventional detection techniques. For instance, research has proposed utilizing anisotropic Dirac materials to enable directional sensitivity to dark matter particles, employing the momentum-dependent anisotropy of electron recoil patterns (Coskuner, et al., 2021). These approaches are particularly valuable for distinguishing dark matter signals from background interference. The theoretical progression of axion dark matter models has additionally stimulated experimental innovation. Specifically, axion quasiparticles within condensed matter systems—such as topological insulators—have been proposed as a medium to amplify axion-photon coupling, presenting novel detection possibilities for sub-eV dark matter particles (Schütte-Engel, et al., 2021). In summary, the discipline has progressed toward a more holistic approach. As elucidated in recent literature, direct detection initiatives now incorporate comprehensive evaluation of both signal reliability and material limitations, while innovative detection frameworks are rapidly acquiring theoretical and experimental validation (Misiaszek & Rossi, 2024; Hochberg, et al., 2022). These collaborative endeavours underscore a fundamental transformation in how physicists conceptualize and investigate the enigmatic nature of dark matter.

This paper aims to overview the studies about dark matter candidates during the recent years and provide a rigorous discussion of dark matter candidates based on recent experimental constraints. The second section gives some brief information about the dark matter, including the classification of dark matter and so on. The third section focuses on one of the most promising dark matter candidates, i.e., WIMP. This section overviews the recent detective methodologies and experimental results of WIMP. Axion is another highly favoured and extensively studied dark matter candidate. Recent studies of Axion will be discussed in the fourth section. The paper also discussed limitations of recent studies on dark matter candidates at the fifth section and offers prospects for future research on this field.

2 DESCRIPTIONS OF DARK MATTER

Dark matter, an enigmatic, non-luminous component of the universe, exerts gravitational influence while mysteriously evading direct detection through electromagnetic interactions. Scientists infer its presence through various astrophysical and cosmological observations—galactic rotation curves, gravitational lensing, and patterns in the cosmic microwave background. Physically speaking, dark matter is thought to consist of particles that are stable, massive, and either weakly interacting or completely unresponsive to Standard Model gauge forces.

A crucial element in comprehending dark matter is its classification. It is generally divided into three main categories based on particle velocities during structure formation: cold, warm, and hot dark matter. Cold dark matter (CDM), comprising heavy, slow-moving particles like the hypothetical WIMPs (Weakly Interacting Massive Particles), remains the prevailing paradigm owing to its effectiveness in explaining the Universe's large-scale structure. CDM facilitates hierarchical structure formation, where small-scale structures emerge first before merging into larger entities. Warm dark matter (WDM), characterized by intermediate-mass particles with non-relativistic velocities, addresses certain small-scale inconsistencies in CDM models, such as the "missing satellites" problem, without significantly altering large-scale predictions. Hot dark matter (HDM), primarily associated with light neutrinos, moves at relativistic speeds during structure formation, thereby smoothing density fluctuations and contradicting the observed clumsiness of matter at small scales.

Beyond this thermal categorization, dark matter candidates are further diversified by their theoretical origins. These include axions, sterile neutrinos, gravitinos, and other particles arising from extensions of the Standard Model, including super-symmetry and string theory frameworks. Axions have garnered particular interest due to their dual capacity to resolve the strong CP problem while functioning as ultralight dark matter. Non-thermal production mechanisms, such as misalignment during the early Universe or the decay of topological defects, render axions plausible cold dark matter candidates. Though the fundamental properties of dark matter (i.e., its mass range, self-interaction cross-section, and potential couplings to visible matter) remain elusive, theoretical studies increasingly suggest its nature may be multifaceted. Some models propose a multi-component dark sector, consisting of particles with distinct masses and interaction strengths, a notion supported by precision cosmological simulations and phenomenological modelling (Franceschini & Zhao, 2023).

3 EXPERIMENTAL EXPLORATION OF WIMPS AS DARK MATTER CANDIDATES

Over the past few years, the search for Weakly Interacting Massive Particles (WIMPs) has entered a more sophisticated and challenging phase. Once the cornerstone of dark matter hypotheses, WIMPs are now tested across a broader landscape of experiments and theoretical models than ever before. As detection technologies mature and sensitivities reach unprecedented thresholds, both new opportunities and limits have emerged in the hunt for these elusive particles. This section offers a closer look at some of the key efforts from the astrophysical community to identify WIMPs.

A particularly significant contribution comes from the DarkSide-50 collaboration, whose recent study focused on probing low-mass WIMPs using a 12 ton-day dataset collected by the dual-phase liquid argon time projection chamber (TPC) (Agnes, et al., 2023). What sets this experiment apart is its use of underground-sourced argon, which contains vastly lower levels of radioactive ^{39}Ar compared to atmospheric argon, thus minimizing background interference. The detector's architecture enables fine-grained spatial and timing information, and it employs pulse shape discrimination (PSD) to distinguish between nuclear and electronic recoils. With these techniques, DarkSide-50 achieved sensitivity to WIMP masses as low as 1.8 GeV/c^2. The experiment scanned a broad energy range (approximately 0.1 to 200 keV) and reported no detection signal, but succeeded in pushing the exclusion limits for spin-independent cross sections down to 1.1×10^{43} cm^2 at 46 GeV/c^2, consolidating its position at the forefront of low-threshold dark matter experiments. The expected results and some collected data are shown in Fig. 1 (Agnes, et al., 2023).

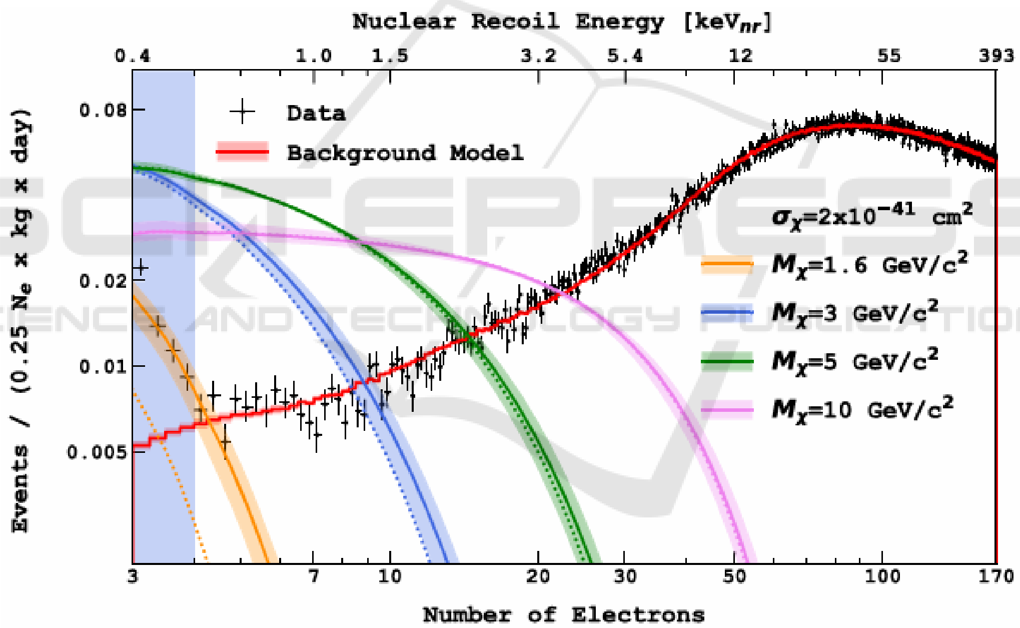

Figure 1: Data and background model compared to expected WIMP spectra (Agnes, et al., 2023).

While direct detection efforts like DarkSide-50 continue refining their methods, there is growing momentum in high-energy physics to explore WIMPs through precision measurement strategies. Franceschini and Zhao examined the potential of future muon colliders to reveal WIMP signatures through electroweak precision observable (Arbey & Mahmoudi, 2021). The logic here is not to spot WIMPs directly, but to infer their presence via quantum corrections to processes involving the Higgs boson and electroweak gauge bosons. Their simulations considered models in which WIMPs are embedded within SU(2)L multiples, such as pure Higgsions or winos, which subtly affect loop-level observables like the S, T, and U parameters. Assuming a 10 TeV muon collider, they estimated sensitivity to WIMP masses up to 1.5 TeV. Unlike direct detection, this approach is not limited by recoil energy thresholds or background radioactivity, and thus provides crucial complementary reach into the parameter space.

Theoretical and cosmological tools have also joined the fray, expanding the toolkit available to researchers. Borah et al. proposed a connection between WIMP dark matter models and gravitational wave spectra generated during first-order phase transitions in the early universe (Borah, et al., 2022). Their framework is grounded in scenarios where dark sector symmetries--responsible for stabilizing WIMPs, i.e., break spontaneously, releasing gravitational radiation. These signals, if observed by upcoming detectors such as LISA or DECIGO, could indirectly trace the thermal history and couplings of WIMP-like particles. In particular, the gravitational wave spectral shape, including the peak frequency and energy density, becomes a probe for underlying dark sector parameters. This line of research underscores the increasingly interdisciplinary nature of dark matter studies, bridging high-energy theory, cosmology, and observational astrophysics.

At the same time, the absence of conclusive detection across decades of experimentation has led some researchers to re-evaluate the WIMP paradigm altogether. Bottaro et al. offered a comprehensive review of the narrowing phase space for conventional thermal WIMP models in light of the latest null results from major detectors like LUX, XENON1T, and PandaX (Bottaro, et al., 2022). Their analysis synthesizes experimental constraints with relic abundance calculations, revealing that many minimal WIMP scenarios are now strongly disfavoured. For instance, scalar or vector WIMPs with standard electroweak interactions and masses between 10 and 1000 GeV are largely excluded by a combination of direct detection and collider data. The author advocates for a pivot toward less traditional frameworks--such as feebly interacting particles, inelastic dark matter, or multi-component models--that may better accommodate the observed null results without abandoning the WIMP concept entirely.

Taken together, these developments paint a picture of a field in transition. Direct detection experiments like DarkSide-50 continue to refine background suppression and extend sensitivity to previously inaccessible low-mass regimes. Simultaneously, high-energy physics offers an alternative route through indirect observables and precision measurements. Theoretical models are increasingly being designed with a broader cosmological perspective, recognizing that gravitational waves or early-universe signals might be just as important as nuclear recoil tracks in understanding dark matter. Meanwhile, the critical reassessment by Bottaro and colleagues injects a note of caution and suggests that the community may need to broaden its conception of what counts as a viable WIMP. Ultimately, the search for WIMPs exemplifies the evolving nature of scientific inquiry. It is no longer confined to one experimental avenue or theoretical model, but rather encompasses a spectrum of ideas and technologies--each with their own strengths and limitations. Whether WIMPs will eventually be detected or ruled out remains to be seen, but the sophistication and diversity of recent efforts ensure that human beings are closing in on a more definitive understanding of their role, or lack thereof, in the cosmos.

4 AXIONS AS VIABLE DARK MATTER CANDIDATES

Among the many candidates proposed to explain the nature of dark matter, axions have gained renewed attention in the last several years, not just for their theoretical elegance but for the increasingly precise methods developed to look for them. Born from the Peccei-Quinn solution to the strong CP problem in quantum chromodynamics, axions--if they exist--could also fill the role of cold dark matter, provided they were produced non-thermally in the early universe. What makes them especially intriguing is their unique signature: a weak coupling to photons in the presence of magnetic fields, a property that can be exploited in highly specialized laboratory settings.

An impressive example of this approach is found, which demonstrated how the limits imposed by quantum measurement noise could be circumvented through the use of squeezed-vacuum states in a resonant microwave cavity (Backes, et al., 2021). In this setup, axions would convert into single photons within a narrow frequency band around 5.7 GHz, corresponding to axion masses close to 23.7 μeV. Rather than relying on brute-force signal amplification, the researchers enhanced sensitivity by injecting engineered quantum noise into the cavity, suppressing unwanted fluctuations and increasing signal fidelity. Their measurements achieved around a 37% noise reduction below the standard quantum limit. Although this experiment covered a relatively confined spectral region, it pushed the boundary of what was previously considered experimentally possible and provided a proof-of-concept that future axion searches could benefit from quantum metrology.

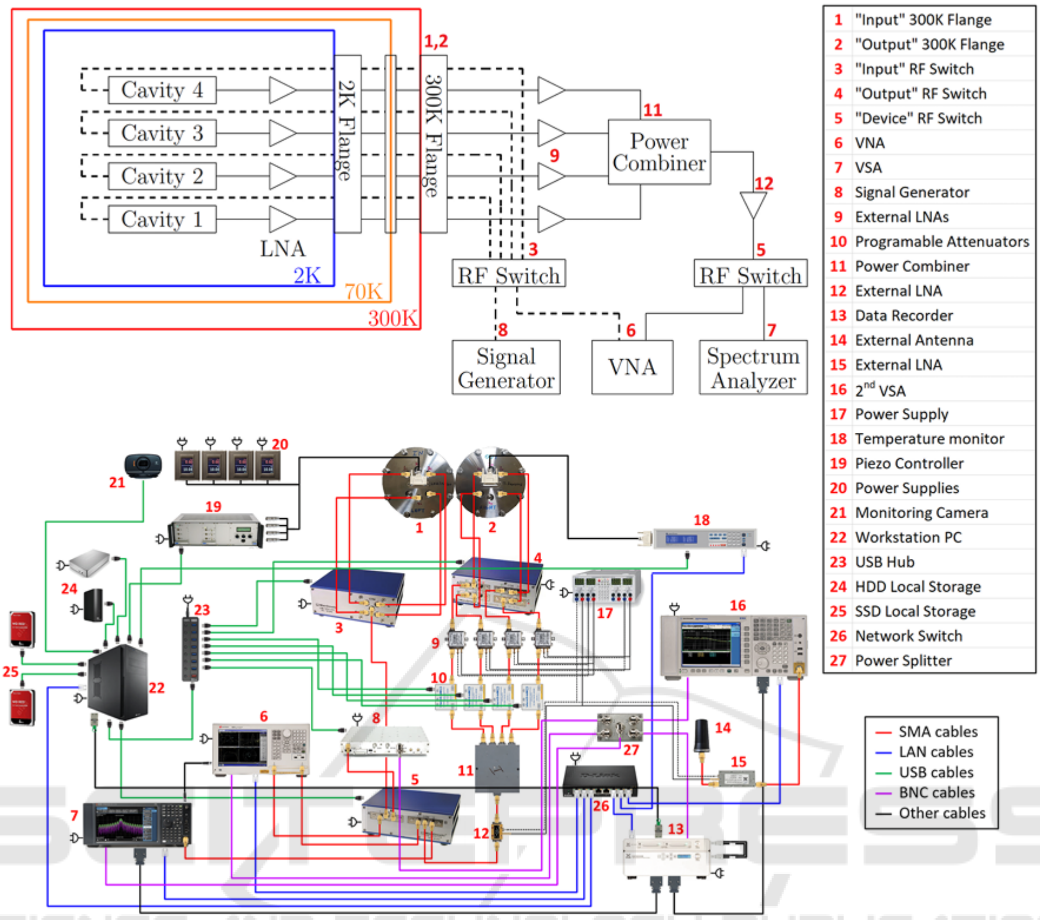

Figure 2: Simplified outline of the CAST-CAPP setup (Adair et al., 2022).

Equally noteworthy is the CAST-CAPP collaboration's hybrid solar axion search, which combined the infrastructure of the CERN Axion Solar Telescope with high-sensitivity cavity systems from CAPP as shown in Fig. 2 (Adair et al., 2022). In this configuration, axions hypothetically produced in the Sun's core would convert into microwave photons when encountering a strong transverse magnetic field. The experimental setup featured a copper cavity operating at cryogenic temperatures (about 2 K), nested within a 9 T magnetic dipole, and tuned to scan frequencies corresponding to axion masses between roughly 20 and 24 μeV. The team achieved sub-100 Hz frequency resolution over more than 100 MHz of bandwidth, which was an impressive technical feat, considering the thermal and vibrational noise challenges of such an arrangement. Although no signal was observed, the experiment set stringent upper bounds on the axion-photon coupling constant, reaching sensitivity levels on the order of 10^{-14}/GeV, further narrowing the range of viable QCD axion models. Turning to searches for invisible axions, hypothetical particles that interact primarily through gravity and extremely weak electromagnetic couplings, Kim et al. designed a low-noise haloscope targeting the 22 μeV mass range, approximately matching a 5.3 GHz resonance (Kim, et al., 2024). Their experimental platform employed a dilution refrigerator to chill the apparatus to millikelvin temperatures, a high-Q tuneable microwave cavity, and a phase-sensitive detection circuit optimized for narrowband scanning. Over a 500 kHz spectral window, they achieved sensitivity down to $g_{a\gamma\gamma}\sim 1.2\times10^{-15}$/GeV, placing one of the tightest constraints to date on axions in this mass range. This experiment is particularly notable for combining fine frequency resolution with long integration times in a compact apparatus, a strategy increasingly favoured for probing high-mass axion regions where signal-to-noise ratios are expected to be especially low.

Meanwhile, the HAYSTAC Phase II experiment, as reported by Bartram et al., pursued a broader-band approach, covering the 3.3-4.2 μeV mass range, corresponding to frequencies between 0.8 and 1.0 GHz (Bartram, et al., 2021). This setup implemented a squeezed-state receiver chain similar to Palken's but operated over a much larger scanning range and longer data collection period--more than three weeks of continuous runtime. The experiment ruled out axion-photon couplings stronger than 2×10^{-14}/GeV across the entire mass window probed, extending the exclusion zone for conventional QCD axion models. What distinguishes HAYSTAC in this landscape is the balance it strikes between spectral coverage and quantum noise suppression, offering a viable path forward for future large-scale searches.

Collectively, these experiments show a field that is no longer speculative, but increasingly guided by technological refinement. Microwave haloscopes, once considered niche instruments, are now enhanced by techniques from quantum information science, such as parametric squeezing and ultralow-noise detection chains. Moreover, collaborations like CAST-CAPP illustrate the value of merging astrophysical infrastructure with high-precision laboratory components, offering hybrid approaches that can tackle previously untouched regions of the axion parameter space.

Another common theme is a shift toward modularity and tunability: detectors now target mass ranges in a more flexible and frequency-resolved manner, allowing experimentalists to move from deep-narrow to wide-shallow scans depending on the physics targets. Cryogenic engineering, frequency synthesis, and digital signal processing are becoming just as important to axion searches as theoretical modelling. Importantly, no confirmed detection has been made, but the pace at which parameter space is being excluded has accelerated significantly. What was once an open field having, in just a few years, become a dense network of constraints and possibilities.

Looking ahead, upcoming experiments like ADMX-G2 and MADMAX are expected to further capitalize on these trends, scaling up cavity volume and magnetic field strength while maintaining fine control over noise. At the same time, newer approaches involving dielectric haloscopes, broadband photon counting, and cavity arrays promise to further broaden the toolkit available to experimental physicists.

In essence, axion dark matter searches have transitioned from isolated laboratory curiosities into a coordinated and multi-institutional scientific campaign. The progress since 2020 illustrates how creative experimental design informed by careful theory is beginning to encroach on what was once considered a vast and elusive space. Whether or not axions turn out to be the key to dark matter, the strategies developed in their pursuit are likely to influence experimental physics for years to come.

5 LIMITATIONS AND PROSPECTS

Despite the increasing technical sophistication of current dark matter detection efforts, the search remains deeply constrained by both fundamental and practical limitations. One of the clearest challenges lies in the sheer breadth of possible parameter space. For both WIMPs and axions, viable mass ranges span several orders of magnitude and couplings to ordinary matter may be so weak as to elude even the most sensitive instruments. In many cases, experiments are only capable of probing narrow slices of this space at any one time, which makes comprehensive coverage a slow and often painstaking process.

Another issue that continues to hamper progress is the complexity of background noise mitigation. As detectors grow more sensitive, they inevitably become more susceptible to spurious signals including cosmic rays, ambient radioactivity, and even mechanical vibrations. The painstaking process of discriminating potential signals from background events often dominates the analysis effort. For example, the techniques required to isolate potential axion-induced microwave photons or rare nuclear recoil events are both hardware-intensive and computationally demanding. Even when statistical anomalies appear, they are rarely sufficient to constitute a convincing detection, requiring months or years of follow-up just to rule out false positives.

Theoretical ambiguity further complicates the picture. While both WIMPs and axions arise naturally in well-motivated extensions of the Standard Model, neither is uniquely predicted. In practice, this means that every null result leaves open dozens of alternative interpretations. Adjusting model parameters, introducing new symmetries, or assuming non-standard cosmological histories can shift the expectations just enough to put the signal out of reach again. This moving target quality makes long-term experimental planning difficult and often forces researchers to hedge between different design strategies rather than focus resources narrowly. In other words, the outlook for dark matter research is far from bleak. What has changed, especially in the last five years, is the growing interdependence between experiment and theory. Instead of blindly surveying massive swaths of parameter space, future programs are expected to rely more heavily on model-informed strategies. Experiments are becoming modular, tunable, and more sharply focused on specific interaction mechanisms. Quantum technologies, once considered peripheral, are now central tools for overcoming the fundamental noise barriers of traditional detection systems.

Another reason for optimism lies in the diversification of experimental platforms. From microwave cavities and dielectric haloscopes to muon colliders and gravitational wave observatories, the range of techniques available to probe dark matter has never been broader. This redundancy is not merely a luxury; it is becoming a necessity. Given how elusive dark matter appears to be, having multiple, orthogonal approaches may be the only reliable path toward confirmation. Moreover, the overlap between cosmology, astrophysics, and particle physics is finally beginning to feel less like an interdisciplinary ambition and more like a working reality. It is now common for a single research program to draw on tools and insights from all three domains.

In the end, the most promising feature of the current landscape may be its adaptability. Researchers have shown that they are willing to pivot, both conceptually and technologically, as new data or constraints emerge. While no discovery has yet been made, the combined pressure from theory, computation, and precision measurement continues to narrow the options. This convergence, even in the absence of direct evidence, is itself a measure of progress. The search for dark matter may still be one of physics' most difficult pursuits, but it is no longer a shot in the dark. Instead, it is an increasingly focused campaign.

6 CONCLUSIONS

To sum up, detection of dark matter candidates is presently highly active while many efforts have been dedicated, leading to various creative detect methods emerging. The recent detect works include direct detection and indirect detection. With theoretical framework from string theory and super-symmetry joining, some indirect detections are able to minimize the interference from background radioactivity and recoil energy thresholds. The second and third sections respectively provide analytical discussions of efforts dedicated to detection of WIMPs and axions by the astrophysics community. Though the final concrete answer to the dark matter particles is not yet clear, these methods developed to refine and increase precision of previous measurements, have gained great attention and provide the community a further understanding of dark matter. Nevertheless, the recently detection efforts are still limited by insufficiency of experimental techniques, which constrain the search in an extremely narrow range. It is emphasized that the theoretical explanation has already developed to a pretty in-depth and highly precise level while the experimental techniques are not enough to verify the theoretical results. The future study is promising to adjust and enhance the theoretical works through more precise experimental data. This paper offers a comprehensive overview of dark matter candidates' detection with particularly focusing on WIMPs and axions, which is so important in today's understanding of the dark matter.

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