Searching for Dark Matter: Evidence from WIMPs, Axions, and Primordial Black Holes

Tianjiao Kang
Abbey College Cambridge, Cambridge, U.K.

Keywords: Axions, Dark Matter, Primordial Black Holes, Standard Model, WIMPs.

Abstract: As a matter of fact, dark matter remains one of the most profound mysteries in modern astrophysics and cosmology. Though it does not emit, absorb, or reflect light, its presence is inferred from its gravitational effects on visible matter, radiation, and the large-scale structure of the universe. This study explores the historical development of dark matter thesis, the various lines of observational evidence supporting its existence, e.g., galactic rotation curves, gravitational lensing, and cosmic microwave background radiation and the leading theoretical models proposed to explain its nature. Particular attention is given to WIMPs, Axions, and Primordial black holes, the top three practical candidates of dark matter. Additionally, the paper reviews current and future experimental efforts aimed at direct and indirect detection of dark matter. By synthesising contemporary findings, this work aims to provide a comprehensive overview of the dark matter problem and highlight the challenges and prospects in uncovering its true identity.

1 INTRODUCTION

The first thing that may spring to mind while discussing dark matter is that it is “dark”. The idea of dark matter emerged in the early 20th century when astronomers were attempting to figure out the universe’s total mass density from stellar masses in galaxies. It became evident that non-stellar baryonic matter existed in a gaseous phase within the vacuum of space (Gordon, 2020; Strumia, 2023). The abundance of deuterium and other light elements in primordial gas clouds suggested that the density parameter for baryonic matter was much lower than the value required by cosmic observations, implying that a significant portion of mass must consist of non-baryonic matter, namely dark matter (Gordon, 2020).

In 1930, Swiss American astronomer Fritz Zwicky made the prediction that the Coma Cluster's galaxies would be destroyed because the cluster's galaxies' radial velocities were dispersed at a rate of about 1000 km/s (Dutta, 2018; CERN, 2021). The stars and gas clouds did not provide enough gravitational attraction to hold the cluster together. The same issue was faced by American astronomer Vera Rubin later in the 1970s: stars at the galaxy's margins were travelling too quickly to be embedded in the luminous matter of the galaxy; therefore, there must be another force in the universe that is invisible to the naked eye that keeps the stars in orbit (Gordon, 2020). According to the most recent observation, dark matter has an abundance of 26.4% of the whole universe (Workman et al., 2024).

The dark matter field has been continuously explored over the last ten years as its discovery will solve the most significant physics puzzles and advance the attempts to unify the laws of physics (Harigaya & Lou, 2023). Following the discovery of the Higgs Boson in 2012, scholars have been focussing more on the quantum side of physics, employing known particles from the Standard Model (CERN, 2022; Luo, 2024). Dark matter is non-interactive with ordinary baryonic matter and radiation, but it does exhibit minimal interactions with gravity, hence, dark matter’s gravitational pull-on galaxies is one of the traditional methods of detecting it.

Researchers are now delving further into the micro-scale thanks to the 2012 discovery of the Higgs Boson, which had a major influence on particle physics and helped uncover other dark matter candidates such as sterile neutrinos (Ahmed, et al., 2022). The primordial black holes, for instance, are one theory on dark matter (Workman et al., 2024). Furthermore, scientists are now examining the anti-matter side of the search for dark matter after the LHC

Kang, T.
Searching for Dark Matter: Evidence from WIMPs, Axions, and Primordial Black Holes.
DOI: 10.5220/0013823100004708

In *Proceedings of the 2nd International Conference on Innovations in Applied Mathematics, Physics, and Astronomy (IAMPA 2025)*, pages 252-257
ISBN: 978-989-758-774-0

at CERN revealed the presence of anti-matter. On the other hand, hypothesis is also put out to refute the presence of dark matter by modifying the gravity models that allows the anomalous measurements of galaxies.

Dark matter's considerable influence on the composition and development of the universe serves as the driving force behind research into it (CERN, 2022). Observable and detected evidence, such as gravitational lensing, galaxy rotation curves, and fluctuations in the cosmic microwave background, all points to the presence of a form of non-baryonic matter that does not interact with light (Irastorza, 2021). Dark matter contributes significantly to the mass-energy content of the universe while being invisible (Luo, 2024). Understanding its nature could unlock answers to some of the most sophisticated questions in cosmology and particle physics, potentially revealing physics beyond the Standard Model (Queiroz, 2017).

This essay will explore three major theoretical candidates for dark matter, i.e., Weakly Interacting Massive Particles (WIMPs), axions, and primordial black holes, examining their theoretical foundations, physical characteristics, and current detection strategies (Alonso-Álvarez & Tait, 2023). A comparative analysis will then summarize the strengths and limitations of each model using contemporary data. Finally, the essay will conclude by highlighting the ongoing relevance of dark matter research and its broader implications for cosmology and particle physics (CERN, 2022).

2 DEFINITIONS OF DARK MATTER

Dark matter is an invisible and hypothetical form of matter that neither emits, absorbs, nor reflects electromagnetic radiation, which makes it fundamentally different from ordinary (baryonic) matter (Dutta, 2018; CERN, 2022). Its elusive nature renders it undetectable through conventional electromagnetic observational methods, such as telescopes or radiation detectors (Primack & Gross, 2000). Nevertheless, dark matter reveals its presence indirectly through gravitational interactions, influencing the motion of galaxies, gravitational lensing, and the large-scale structure of the universe (CERN, 2022; Workman et al., 2024).

General relativity alone cannot account for the observed gravitational effects in galactic rotations and cosmic expansion unless an added source of unseen mass is assumed (Gordon, 2020). This discrepancy has led to the conclusion that a substantial amount of matter, dark matter, must exist beyond what can be seen directly. As such, dark matter plays a vital role in cosmological models and the formation of large-scale cosmic structures (Primack & Gross, 2000).

Dark matter is typically categorized as "cold," "warm," or "hot," depending on its free-streaming length, which refers to the typical distance a particle travels without scattering (Workman et al., 2024). Hot dark matter consists of fast-moving, low-mass particles, such as relic neutrinos. Warm dark matter particles, such as sterile neutrinos, are intermediate in mass and speed, while cold dark matter, including Weakly Interacting Massive Particles (WIMPs), is composed of heavy, slow-moving particles that are highly favoured in theoretical models for structure formation (Feng & Zhang, 2024; Kumar, 2024). Despite the name, dark matter is not necessarily "dark" but is better described as "transparent," as it does not interact with light at all (Dutta, 2018).

Among the leading candidates for dark matter are WIMPs, axions, and even primordial black holes (Lu, 2022). WIMPs are particularly attractive due to their predicted stability over cosmic timescales and their compatibility with cold dark matter models (Dey, 2023). These particles are thought to interact only via gravity and the weak nuclear force, making them detectable in principle through nuclear recoil events in underground detectors or indirectly through their annihilation products (Fox, 2018; Luo, 2024). Despite ongoing experimental efforts, the true appearance of dark matter remains one of the most significant open questions in modern astrophysics and particle physics.

3 WEAKLY INTERACTING MASSIVE PARTICLES

Weakly Interacting Massive Particles (WIMPs) are currently the most widely recognized candidates for dark matter, and it is predicted that it makes up most of the dark matter (Queiroz, 2017; O'Hare, 2017). These hypothetical subatomic particles are massive and electromagnetically neutral, meaning they do not emit, absorb, or reflect light, making them nearly impossible to detect using traditional methods (Dey, 2023). WIMPs are believed to be non-baryonic since they are not composed of quarks and interact primarily through gravity and potentially via other weak-scale forces (Gordon, 2020; Kumar, 2024).

In the early universe, when particles were in a state of thermal equilibrium and dark matter and its components existed in extra-dimensions, the majority of WIMP candidates are predicted to have been thermally created (Feng & Zhang, 2024; Queiroz, 2017). As the universe expanded and cooled, these particles fell out of equilibrium and their abundance "froze out", a process known as thermal freeze-out (Feng & Zhang, 2024). WIMPs would have stopped annihilating, and their abundance became fixed as the universe cooled (Feng & Zhang, 2024). For a particle with weak-scale mass and interaction strength, the calculated abundance from this freeze-out matches the dark matter density one observes today. Notably, WIMPs arise naturally in many supersymmetric extensions of the Standard Model, requiring no fine-tuning to match cosmological data (Lu, 2022; Strumia, 2023).

Efforts to detect WIMPs fall into three primary categories: direct detection, indirect detection, and collider production. Direct detection involves observing WIMPs interacting with atomic nuclei in laboratory settings, while indirect detection focuses on finding the secondary particles—such as gamma rays, cosmic rays, and neutrinos—resulting from WIMP annihilation or decay far from Earth (Gordon, 2020; Lu, 2022). Searches for WIMP annihilation, such as gamma rays, neutrinos, and cosmic rays in neighbouring galaxies and galaxy clusters, are part of experimental efforts to find WIMPs (Gordon, 2020; Workman et al., 2024). The Large Hadron Collider (LHC) is also being used in attempts to produce WIMPs directly through high-energy particle collisions (Workman et al., 2024).

Indirect detection methods focus on regions where dark matter is expected to accumulate, such as galactic centres and dwarf galaxies. These areas have low baryonic matter content, which minimizes interference from ordinary astrophysical processes (Lu, 2022). Telescopes like Fermi-LAT and VERITAS have placed constraints on WIMP models by failing to detect gamma rays that would result from annihilation events. While high-energy neutrinos are also predicted as annihilation products, their weak interaction makes detection extremely difficult. The ICECube neutrino observatory in Antarctica may eventually distinguish WIMP-produced neutrinos from background sources, though as of 2014, only 37 cosmic neutrinos had been recorded, making such analysis inconclusive. Another possible indirect signal may originate from the Sun. WIMPs interacting with solar protons or helium nuclei may lose energy and become gravitationally trapped if it drops below the local escape velocity, potentially contributing to a unique signal detectable by future solar observations (Gordon, 2020).

4 AXIONS

Axions were once thought to provide a dynamical solution to the Standard Model's strong CP problem (Preskill, 2023). These particles contribute to the cosmological constants, making them a practical candidate for dark matter (Rosenberg, 2024; Svrcek & Witten, 2023). Axion masses are typically extremely small, often well below 1 eV, which means they are unlikely to be produced in accelerators (Rosenberg, 2024). Nevertheless, researchers continue to experiment with innovative methods to detect axions. These methods include:

- Laboratory-based detection: This involves searching for axions or axion-induced effects within laboratory settings. Utilising advanced experimental setups, such as high-field magnets, superconductors, low-background detection systems, and low-radioactivity procedures is necessary to detect them. Direct detection methods are employed, where axions are produced naturally in the laboratory. One such method includes using high-density photon sources like lasers to generate axions in a magnetic field (Svrcek & Witten, 2023). Another technique involves examining changes in the polarization of laser beams passing through a magnetic field (Rosenberg, 2024).
- Axion halo experiments: These experiments aim to detect the axions thought to constitute the local galactic dark matter halo. If axions are the primary component of this halo, their number density would be significant (Svrcek & Witten, 2023). The virtual velocity of these particles within the galaxy is approximately 300 km/s, a value that is consistent with the properties of axions (Rosenberg, 2024). Axions are believed to gain their velocity by falling into the galactic potential well. If axions exist, they would be produced in substantial quantities within the solar interior (Svrcek & Witten, 2023).
- Axion helioscopes: These experiments search for axions emitted by the Sun, which are detected at terrestrial detectors. This involves the conversion of solar axions back into photons in a strong laboratory magnet. When the magnet is oriented toward the Sun, X-rays can be detected on the opposite side, as the resulting photons retain the same energy as the incoming axion. This phenomenon occurs through the

Primakoff axion-photon conversion, where axions transform into photons within the Coulomb fields of charged particles in the solar plasma (Rosenberg, 2024).

Axions can carry energy out of stars and are created in hot astrophysical plasmas. The coupling strength of these particles with normal matter and radiation is bounded by the constraint that stellar lifetimes or energy loss rates are not in conflict with observational data (Preskill, 2023). There are two main types of cosmic relic axion populations: a non-thermal population, which behaves as cold dark matter (CDM), and a thermal population, which behaves as a hot dark matter (HDM) component, similar to massive neutrinos. If axions were in thermal equilibrium during the early Universe, this would depend on the inflationary reheat temperature and assumptions about pre-BBN cosmology. The excess radiation generated in this process imposes additional constraints on the axion-photon coupling and on the mass of axions (Rosenberg, 2024; Svrcek & Witten, 2023). Fig 1 below gives an illustration of the Primarkoff axion-photon coupling (Irastorza, 2021).

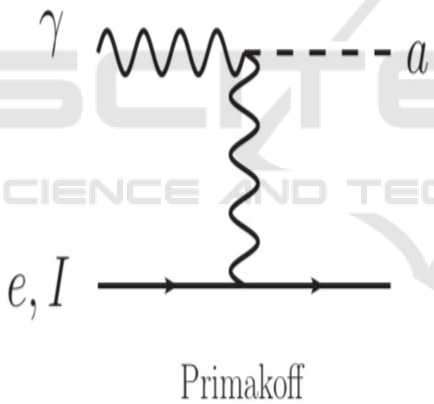

Figure 1: Showing the Primarkoff axion-photon coupling (Irastorza, 2021).

5 PRIMORDIAL BLACK HOLES

A type of hypothetical black holes, primordial black holes (PBHs), are believed to have formed in the early universe, shortly after the Big Bang, and they are a fascinating candidate for dark matter. Unlike stellar black holes that form from the gravitational collapse of massive stars, PBHs are theorized to originate from the direct collapse of high-density regions in the infant universe before any stars even existed (Gordon, 2020). This makes them unique among black hole classes and particularly interesting from a cosmological standpoint. PBHs may have formed during the radiation-dominated era, when the universe was filled with high-energy particles and extreme densities. During this time, quantum fluctuations produced during the inflationary epoch could have grown sufficiently large to cause localised regions of spacetime to undergo gravitational collapse once they re-entered the cosmological horizon (Primark & Gross, 2000; Fox, 2018). These regions, if spherically symmetric and dense enough, could bypass the need for stellar evolution and directly collapse into black holes of varying masses. The masses of PBHs could span a wide range, from sub-planetary scales to several hundred or even thousands of solar masses, depending on the horizon scale at the time of formation (Workman et al., 2024).

The collapse of super-horizon fluctuations, extreme perturbations generated during inflation, is believed to be the most probable origin of PBHs. These fluctuations could act as seeds for black hole formation in the early universe. PBHs could have formed during both the inflationary and radiation-dominated eras, particularly in regions where subatomic matter was so densely packed that gravitational collapse could, without the explosive stellar supernova events associated with ordinary black holes (Workman et al., 2024; Primack & Gross, 2000; Fox, 2018).

One feature that makes PBHs fit the primary characteristic of dark matter is that they do not emit light and are extremely difficult to detect via electromagnetic radiation, and most importantly they are non-luminous and interact predominantly through gravity. Due to its close alignment with what is expected from dark matter, PBHs are an attractive dark matter candidate (Particle Data Group, 2012).

PBHs are supported historically by the MACHO (Massive Astrophysical Compact Halo Object) project in the 1990s. During the experiment, more observed gravitational microlensing events were happening towards the Magellanic Clouds than could be explained by known stellar populations. This implies that there is a presence of compact, invisible objects in the galactic halo which have consistent mass range with PBHs.

Recent advances in gravitational wave detection have further revived interest in PBHs. NASA’s LIGO (Laser Interferometer Space Antenna) have detected many black hole mergers, some involving blackholes with masses and properties that do not align with standard stellar evolution models. These observations have prompted the hypothesis that at least some of these mergers could involve PBHs formed in the early universe (Workman et al., 2024; Dey, 2023). In addition, LISA is expected to detect the upcoming space-based gravitational wave detector and is predicted to provide crucial data on mergers involving lower mass blackholes. PBHs are a viable dark matter candidates for several reasons:

- No need for new particles: Unlike WIMPS or axions, PBHs do not require the introduction of any new fundamental particles beyond the standard model. Their formation is a natural phenomenon of general relativity applied to conditions in the early Universe.
- Gravitational dominant: PBHs interact via gravity, which is how dark matter influences large-scale structures like galaxies and galaxy clusters.
- Longevity: PBHs with masses above 10^{15} grams would not have evaporated due to Hawking radiation, making them stable on cosmological time scales (Workman et al., 2024).

However, PBHs are not without their challenges. So far, observational methods like microlensing surveys (e.g., EROS, OGLE), cosmic microwave background (CMB) distortion studies, and wide binary start constraints have not yet had much evidence of primordial black holes. Nevertheless, there remain several "mass windows" in which could still make up all or sizeable proportion of dark matter. For example, asteroid-mass PBHs (~10^{17} to 10^{23} grams) and intermediate-mass PBHs (~10-100 solar masses) remain less constrained as one does not yet have strong enough data in those ranges to refuse the existence of PBHs (Workman et al., 2024; Carr, n.d.).

Current and future observational programs such as the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST), the Square Kilometer Array (SKA), and space-based gravitational wave observatories like LISA, are expected to test these remaining possibilities more deeply. Improved stimulations of early-universe density fluctuations and more detailed modelling of PBH formation scenarios are also helping theorists narrow down workable models (Harigaya & Lou, 2023; Strumia, 2023). Some researchers have even proposed broader cosmological roles for PBHs. PBHs might explain the origin of supermassive black holes in galaxy centers, contribute to the reionisation of the universe, or even play a part in generating matter-antimatter asymmetry through Hawking radiation (Alonso-Álvarez & Tait, 2023).

In conclusion, while PBHs have not yet been detected, they are still a strong candidate for explaining dark matter due to their compatibility with existing cosmological theories, combined with their potential detectability through gravitational wave astronomy, ensuring that they will remain a focus of intense research in the years to come.

6 COMPARISON, LIMITATIONS AND PROSPECTS

Despite the abundant gravitational evidence in galaxies, the true nature of dark matter is still unknown (CERN, 2022). WIMPs, Axions, and Primordial black holes are currently the top competitors; each has its own advantages and emerges from different theoretical motivations. They interact with gravity and the weak nuclear force, and they are heavy. They are created in the early cosmos through thermal production, in which particles separate from the heated plasma of the early universe (Lu, 2022). Nevertheless, despite decades of searching via indirect detection (gamma rays, neutrinos), collider experiments (LHC), and underground detectors (LUX, XENON), WIMPs have not yet been found. In the future, more sensitive detectors and background investigations of gravitational waves will be used. In contrast, axions have a mass density spectrum that is 10^{-15} times that of WIMPs. They were first put forth to address the strong CP problem in quantum chromodynamics, but because of their similarities to the expected dark matter candidates, they gained popularity as dark matter candidates (Workman et al., 2024). However, so far there is not any evidence of WIMPs due to their substantially light mass and weak coupling interactions with photons and matter makes it significantly hard to detect in space. Active search ongoing and new techniques like halo scopes and quantum sensor are emerging. Finally, Primordial Blackholes (PBHs), although not the most widely accepted model, does not require new particles. They are formed from density fluctuations in the early universe with a mass of several solar masses and only interact gravitationally and it has the greatest number of detecting methods such as gravitational lensing, CMB effects, gravitational waves, dynamical tests. It is challenging to differentiate it from astrophysical black holes (Workman et al., 2024). Current blackhole detection techniques will continue to find primordial blackholes. WIMPs is the front-runner, even though each candidate addresses some important physics issues.

7 CONCLUSIONS

To sum up, this study examined three prominent dark matter candidates, i.e., WIMPs, axions, and PBHs, comparing their origins, physical properties, detection strategies, and current experimental constraints. WIMPs, while theoretically attractive due to the “WIMP miracle”, faces challenges from decades of blank results. Axions, although offers an elegant pair of solution to the strong CP problem and dark matter, their extraordinarily weak interactions make them almost impossible to detect. PBHs, offers a non-particle alternative tied to early-universe conditions, yet are increasingly constrained by observational data. Each candidate occupies a unique theory, highlighting the need for diverse approaches. This comparative study underscores the importance of pursing multiple approaches in the dark matter search. By mapping the strength and limitations of leading candidates, this work contributes to reminding future strategies in both theoretical modelling and experimental design. Looking forward, advances in detector sensitivity, gravitational wave astronomy, and cosmological observations will continue to experiment and refine the viable parameter space for each candidate. The harmony between theory, experiment, and astrophysical data will be key in guiding discovery.

REFERENCES

Ahmed, A., Grzadkowski, B., Socha, A., 2022. Implications of time-dependent inflaton decay on reheating and dark matter production. *Physics Letters B*, 831, 137201.

CERN., 2021. Search for dark matter in events with a Higgs boson and missing transverse momentum with the ATLAS detector. *Technical Report*, TS2021, 11.

CERN., 2022. Status report on dark matter searches Technical Report, TS2022, 13.

Dey, U., 2023. *Phenomenological studies of light dark matter at the LHC.* Deutsches Elektronen-Synchrotron (DESY).

Dutta, S., 2018. *A study on dark matter and dark energy*. Undergraduate thesis, St. Xavier’s College.

Fox, P. J., 2018. TASI lectures on dark matter. *TASI*, 2018.

Gordon, S., 2020. *Dark matter: A study into its possible constituents.* Master’s dissertation, Imperial College London.

Irastorza, I. G., 2021. *An introduction to axions and their detection*. Center for Astroparticle and High Energy Physics (CAPA), Universidad de Zaragoza.

Kumar, R., 2024. WIMP and unnaturalness. *ResearchGate*. 11.

Lu, Z., 2022. Comparison of the detection paradigms of axion and WIMPs. *Journal of Physics: Conference Series*, 2386, 012078.

Luo, L., 2024. Dark matter detection strategies: A comparative analysis. *International Journal of Astronomy and Astrophysics*, 14(3), 203–217.

O’Hare, C. A. J.,2017. *Detecting WIMPs, neutrinos and axions in the next generation of dark matter experiments.* Doctoral dissertation, University of Nottingham.

Particle Data Group, 2012. Review of particle physics. *Physical Review D*, 86(1), 010001.

Primack, J. R., Gross, M. A., 2001. Hot dark matter in cosmology. *Current aspects of neutrino physics*, 287-308.

Queiroz, F. S., 2017. WIMP theory review. *Proceedings of Science: EPS-HEP2017 – European Physical Society Conference on High Energy Physics*, EPS-HEP2017, 080.

Strumia, A., 2023. Dark Matter from freeze-in and its inhomogeneities. *Journal of High Energy Physics*, 2023(3), 1-8.