A Comparative Framework for the Evaluation of Four Leading Dark Matter Candidates

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Dark matter constitutes $\sim 27\%$ of the entire universe and has a central influence on the formation and evolution of cosmic structure, yet its fundamental nature and identity remain unknown. This paper provides a narrative comparative review of the four leading dark matter candidates - Weakly Interacting Massive Particles (WIMPs), axions, sterile neutrinos, and primordial black holes (PBHs) - through the lens of a unified framework that evaluates each candidate's theoretical motivation, cosmological consistency, experimental compatibility, and detectability potential. We summarize the theoretical and observational evidence for each candidate, with particular attention given to how each proposal arises from extensions of Standard Model physics and how current experiments constrain its parameter space. Based on the established evaluation framework, axions emerge as the most theoretically well-motivated, cosmologically consistent, and experimentally promising candidate, followed by WIMPs, sterile neutrinos, and finally PBHs. This comparison provides an accessible and comprehensive overview of how each candidate theory compares, highlighting the strengths and limitations of each scenario while clarifying priorities for future experimental and theoretical investigations probing dark matter.

Keywords: Dark Matter, Weakly Interacting Massive Particles (WIMPs), Axions, Sterile Neutrinos, Primordial Black Holes (PBHs)

Introduction

Dark Matter

Dark matter remains one of the most prominent, unresolved mysteries in modern astrophysics. This elusive form of matter interacts only very weakly with ordinary matter and electromagnetic radiation, rendering it invisible to traditional detectors and laboratory probes. Nevertheless, the consequences of its gravitational interactions including unusual galaxy rotation curves, gravitational lensing of background light, and the large-scale clustering of galaxies[1], hint at its existence. Dark matter composes around 27% of the entire universe and the majority of the total matter content, making it one of the central topics of modern cosmology[1]. Early observational evidence for dark matter began with galaxy cluster studies. The term "dark matter" originated in the 1930s, when Fritz Zwicky observed that galaxies in the Coma Cluster moved at such high orbital velocities that the gravitational force of luminous matter could not explain them[2]. Subsequent observations of individual galaxies provided further support for these conclusions. In the 1970s, Vera Rubin and her collaborators observed that the rotational velocities of stars in spiral galaxies remain nearly constant ("static" or "flat") at large distances from the galactic center. This is a behavior that cannot be explained by the distribution of visible matter alone[3], thus suggesting the existence of a missing chunk of unseen matter. Each of these discoveries hinted at missing mass in the universe, solved by the introduction of dark matter.

Dark matter is the material theorized to be responsible for the structure of the universe, holding together a variety of cosmological structures, including galaxies, preventing their extensive drift. Additionally, dark matter doesn't interact with the electromagnetic (EM) force; methods of detection relying on emitted light interactions with EM detectors fail, but detection may be attempted through gravitational interactions. It is estimated that the halos of galaxies and globular clusters are the hiding places of dark matter, while dwarf galaxies contain most of the dark matter. To explain these observations, several theoretical dark matter candidates have been proposed. However, these potential cosmological sources, including primordial black holes, have yet to provide an answer. This creates consideration of alternative sources and dark matter candidates including WIMPs, axions, and sterile neutrinos. Each candidate's nature is encapsulated by a different theory, each explanation conflicting in some way with those of the other candidates. A great number of experiments have sought to detect these candidates either directly or indirectly, but at the

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moment, they have all failed to obtain any positive results. So, it is valuable to comparatively assess the theoretical motivations, cosmological consistency, experimental evidence, and detectability potential of the different dark matter candidates to determine which candidate is most likely and provide context to aid future experimental investigations.

Introducing the Four Dark Matter Candidates

Weakly Interacting Massive Particles (WIMPs)

Weakly Interacting Massive Particles (WIMPs) are a leading dark matter candidate: they lack electric charge, so they do not interact with light, but they do interact via the weak nuclear force and gravity. Therefore, WIMPs cannot be directly detected by virtue of their electromagnetic interactions. The WIMP miracle is one of the main reasons why WIMPs are so likely. WIMPs can be probed through a variety of experimental detection methods. It explains how particles with weak scale interactions can naturally account for the experimentally observed dark matter relic abundance through the mechanism of thermal freeze out in the early universe[4]. This theoretical attractiveness has turned WIMPs into a staple topic in particle physics as well as in cosmology.

WIMPs are believed to weigh between a few gigaelectronvolts (GeV) and several teraelectronvolts (TeV), corresponding to about a few to around a thousand times the proton mass[4]. Weak interactions in this particular mass window result in the expected relic dark matter density, leading to a wide range of theoretical and experimental investigations in this regime[4]. The majority of WIMP candidates considered as benchmarks in the most common particle physics models, especially supersymmetric (SUSY) theories predicting the existence of stable particles (e.g. the neutralino), lie in the GeV-TeV mass range[4].

The three main experimental techniques used to find WIMPs include direct detection, indirect detection, and collider production. Direct detection experiments try to register rare WIMP-nucleus scattering events. Indirect detection looks for annihilation or decay products, such as high energy photons or neutrinos, in areas of high dark matter density. Collider experiments, like those at the Large Hadron Collider, attempt to generate WIMPs through high energy collisions, flagging missing energy signatures as evidence. Direct detection experiments are especially effective in searching for traditional 10–100 GeV WIMPs[5]. Several astrophysical and solar investigations have also been carried out to probe light 5-50 GeV WIMPs. However, finding such light particles is difficult and the experiments must have extremely low energy thresholds[6]. Similarly, at the high mass end, theoretical and cosmological arguments confirm that thermal WIMPs cannot have masses with no limits at all. In fact, their masses have been limited by the calculations to $<\sim$ 100 TeV if 5-50 GeV WIMPs originated from the early universe. Nevertheless, the upper limit is still debated, and WIMPs with masses several tens to hundreds of times heavier than a TeV might still be possible[7]. Despite no clear WIMP signal being found within the 10 GeV-1 TeV mass range so far, experiments employing a wide range of detection methods set tighter and tighter limits on the characteristics and interaction strengths of WIMPs[4]. These negative findings gradually limit the allowed WIMP parameter space with future searches focusing on the light and heavy mass regions.

Recap

Weakly Interacting Massive Particles (WIMPs) are heavy and electrically neutral entities, which means that apart from their gravitational interactions, they mostly behave like ”ghosts” to us since they are capable of escape detection by our current electromagnetic instruments. What makes WIMPs very attractive candidates for dark matter is the so-called ”WIMP miracle.” This refers to the fact that particles interacting at the weak scale would naturally lead to the amount of dark matter observed by us today as a result of the thermal freeze-out of the early Universe. On the one hand, scientists look for WIMPs by nuclear recoil; on the other, they examine annihilation products such as gamma rays; and finally, the collider production of these particles is searched for through missing energy signatures. During the last decades, despite great efforts being put into the search for WIMPs, nothing has been confirmed yet, and at present, this field of study is gradually turning its attention to interactions of even weaker nature and mass ranges which remain uncharted.

Axions

Axions are a class of very light particles with a mass range approximated by the formula: $m_a \approx 5.7 \times 10^{-6}$ eV $\times$ $(10^{12}\ \text{GeV}/f_a)$[8], where f_a is the unknown axion decay constant; although a variety of experimental/observational constraints imply $f_a > 10^9$ GeV[9]. The anticipated mass of the QCD axion lies between $10^{-6} - 10^{-3}$ eV, although the exact mass range is not known[10]. Axions were initially proposed as a solution to the strong CP problem[11] and subsequently grew as compelling cold dark matter candidates[8]. Due to their extremely weak interactions with standard particles through the gravitational, electromagnetic, strong, and weak forces, axions escape detection by traditional telescopes and detectors. If axions exist in sufficient abundance, their collective mass could make them a viable dark matter candidate. In order to detect axion dark matter, traditional haloscope experiments in this area place strong magnetic fields in resonant cavities or electromagnetic circuits, and watch for axion transformation into photons at a frequency determined by the axion mass. By frequency tuning and reducing noise to extremely low levels, these haloscope experiments scan and place limits on the possible axion mass ranges and couplings[12]. For example, the

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ADMX (Axion Dark Matter eXperiment) scanned for axions in a 2.66 to 3.1 μeV mass range, but other tests could use different ranges[13].

Limitations on axion masses are also set by astrophysical observations, and the most significant of these come from the star cooling measurements that do not allow axions to be heavier than about 10^{-2} eV[14]. At the lowermost side, several theories posit 'ultralight axions' with masses as low as 10^{-12}eV or less[15]. The main feature of a very low-mass axion is its wave-like behavior over the extent of a whole galaxy. These axions do not behave as small particles, but rather as waves that can even affect the distribution inside galaxies. The wave characteristic can influence the formation and evolution of galaxies and thus can be the reason why some tiny galaxies have properties that do not comply with standard cold dark matter. Researchers are still exploring this by means of simulations and observations to confirm whether axions can be the constituents of dark matter[16]. Present studies keep on examining the viability of lighter as well as heavier candidates. Along with their works, the allowed axion mass ranges get more and more confined.

Recap

Axions are incredibly small, weakly interacting particles that were initially put forward to explain the strong CP problem in quantum chromodynamics. Their main advantage as a dark matter candidate is that they are very strongly theoretically motivated, as they naturally emerge from already existing physics rather than being added just to explain dark matter. Usually, they are searched for by detecting when they turn photons into magnetic fields, most notably in resonant cavity experiments like haloscopes. Although there hasn't been any conclusive discovery, a significant part of the theoretically favored parameter space is still unexplored, and experiments that are carried out are heading towards more sensitive detection, which makes axions one of the most promising candidates nowadays.

Sterile Neutrinos

Sterile neutrinos are also extensively considered as one of the dark matter candidates. These are right-handed neutrinos that, according to the Standard Model, do not participate in weak, electromagnetic, or strong interactions. They interact only by gravity and very small mixing with active (tau, muon, and electron) neutrinos. Current models project sterile neutrino masses in the MeV-keV range, and those in the keV mass range are popular warm dark matter candidates with potential to influence the formation of small-scale structures in the Universe. In contrast to WIMPs, sterile neutrinos are theorized to be produced non-thermally in the early Universe. For instance, by oscillation of active neutrinos in the Dodelson–Widrow mechanism or resonant production in the presence of lepton asymmetry[17]. Lepton asymmetry is the inequality of the number of leptons (axions or in our case, neutrinos) and antileptons (counterparts to leptons) in the early universe. As the free-streaming length (distance a particle can travel without slowing down) of sterile neutrinos is longer than that of cold dark matter, they are capable of diminishing small-scale clustering and thus solving the missing-satellite problem. This dilemma states that there are far too few dwarf galaxies rotating around larger galaxies, meaning there must be some sort of obstruction; that obstruction being sterile neutrino dark matter[18]. By suppressing the formation of small-scale subhalos, sterile neutrinos can bring theoretical predictions closer to reality. However, this creates a delicate balancing act. If the free-streaming length is too large, as is often the case with non-resonant DW production, it inhibits the formation of structures that are clearly observed in the Lyman-α Forest (patterns of hydrogen absorption in distant quasar light used to trace small-scale matter structure) and high redshift galaxy surveys[17]. Consequently, resonant production models are often favored, as they allow for a cooler momentum distribution that alleviates the missing-satellite problem without violating small-scale structuring constraints[18].

Due to their very weak mixing, sterile neutrinos can eventually decay, generating a narrow X-ray line from an X-ray photon with energy around $E \approx m_s/2$[19]. This X-ray signal may be searched for in galaxies and galaxy clusters, providing an important indirect detection method[17]. Several collaborations have undertaken the search for such a signal in various systems (e.g., galaxies and galaxy clusters.) The $\sim$3.5 keV X-ray line inferred for galaxy clusters and the Andromeda galaxy has been considered a potential signal of the decay of sterile neutrino dark matter[20]. In this decay, a sterile neutrino is split into a lighter active neutrino and a photon, whereby the photon energy is roughly half of the sterile neutrino mass energy. Thus, a 3.5 keV photon is indicative of a sterile neutrino mass of the order of 7 keV, given that the photon energy is approximately $(m_s)/2$. Follow-up observations have given inconsistent results, and many recent investigations created serious doubt on the 3.5 keV line being due to dark matter. Some explanations include emission lines, instrument systematics, or statistical changes. Overall, the 3.5 keV line is no longer seen as a leading dark matter signal.

Present X-ray and structure-formation limits severely constrain the allowed combinations of mass and mixing angle, but still, there is enough space in the parameter space so that keV sterile neutrinos can constitute some, or all of dark matter[17]. Some experiments have also been done to determine the truth about sterile neutrinos. The experiment is called a lab-scale keV sterile neutrino search using tritium beta decay in a LiF crystal read out by a magnetic microcalorimeter (MMC). The detailed description of their work is as follows: (1) they exposed a LiF crystal to a neutron field thus producing tritium

(^{3}H) inside it, (2) the crystal was cooled to 40 mK and a very sensitive MMC thermometer was attached, (3) the energies of the beta electrons from ^{3}H decays were recorded for about 10 hours, and (4) the measured beta spectrum was compared with the standard ^{3}H decay prediction. The measured spectrum was in very good agreement with the expected one, thus confirming that this small LiF+MMC setup is operational and can be utilized for the sterile neutrino search at the keV scale in the future[21].

Recap

Sterile neutrinos are a sort of right-handed neutrinos that are practically invisible except for their interaction through gravity and a very slight mixing with regular neutrinos. They are appealing because they require only a slight change of the Standard Model and at the same time can explain the neutrino masses as well as being potential dark matter particles. The main method of scientists to find these particles is through indirect detection by means of looking at the X-ray photons that are produced by the slow decay of these particles in galaxies and clusters. Despite the fact that some potential signals like the 3.5 keV X-ray line have been reported from time to time, no detection has been confirmed so far and the present studies are still examining their possibility in the parameter space which is getting more and more limited.

Primordial Black Holes

Primordial black holes (PBHs) are black holes that potentially originated from the large density fluctuations in the nascent Universe. They are considered an attractive dark matter candidate since they are cold, non-baryonic, stable, and, theoretically, can be generated in a quantity that may roughly account for the total dark matter[22]. Typically, the conception of PBHs is that they arise during the radiation-dominated epoch when an overdense area exceeding a critical threshold recollapses upon horizon entry. In terms of observations, PBHs are constrained through their astrophysical and cosmological effects. This yields a PBH mass determined by the horizon mass at that time and makes the final abundance extremely dependent on the amplitude of small-scale primordial curvature perturbations, which have to be substantially higher than those observed on CMB (Cosmic Microwave Background) scales to have any effect[22].

Many inflationary scenarios, such as those with features in the potential, are taken into consideration as possible means of power enhancement on PBH-forming scales while still being in agreement with large-scale cosmological data[22]. On the one hand, PBHs of any mass over many decades can be constrained; on the other hand, they are limited to a few “windows” in mass where, indeed, they could make up most of the dark matter. These mass ranges are investigated through Hawking radiation, microlensing, accretion, and CMB bounds, structure formation, and gravitational waves[22].

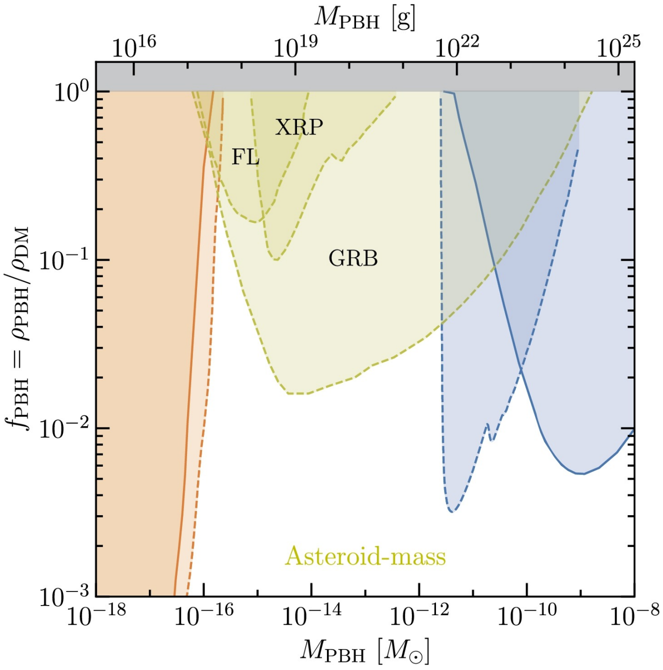

Fig. 1 Constraints on the fraction of dark matter that can be in the form of primordial black holes as a function of PBH mass, where the horizontal axis shows PBH mass and the vertical axis shows the fraction of dark matter in PBHs. With this, $f(PBH) = 1$ meaning PBHs could make up all dark matter, with colored excluded regions from evaporation, microlensing, gravitational wave, accretion, and dynamical limits. Optical microlensing is blue, gamma ray bursts are yellow, and evaporation is orange[22]. To read the figure, choose a PBH mass on the x-axis and move upward: shaded regions are ruled out, while unshaded regions remain allowed. The remaining gaps are the surviving mass windows where PBHs may still account for some, or in limited cases most, of the dark matter. Primordial black hole observational constraints highlight how gravitational and astrophysical effects link their signatures to the detectability criterion in the framework.

Recap

Primordial black holes (PBHs) are one of the non-particle dark matter candidates which could have been created from fluctuations of the density field in the early Universe. In contrast to particle dark matter candidates, PBHs interact only via gravity, so they can only be detected through their gravitational effects such as microlensing, accretion signals, and gravitational waves emitted from mergers. The big advantage of PBHs is that they do not call for new particle physics but merely depend on the early-Universe conditions to produce a large enough number. However, several observational constraints have excluded almost all the mass ranges, leaving just a few tiny windows where PBHs may still be the dark matter, and the research is ongoing to check these possibilities.

Methods

In order to determine the most likely dark matter candidates, a narrative comparative literature review was conducted. The candidates specifically looked at include axions, Weakly Interacting Massive Particles (WIMPs), sterile neutrinos, and primordial black holes (PBHs). In addition to major databases like Google Scholar, Harvard ADS, and arXiv, sources were also obtained from reputable journals such as Physical Review, Physics Reports, and Annual Review of Nuclear and Particle Science. Search words combined candidate, specific terms with generic terms, the latter being related to dark matter theory, cosmological constraints, and experimental detection. Review articles, as well as highly cited seminal papers, were given priority and their references were checked for further studies. Studies and papers were chosen by the dates they were published. Most papers selected were published after 2005, and only a few exceptions have been made. These exceptions were created just to explain the background of the candidates. Not every paper or study was kept. A couple of them were left out of the review. Studies were chosen if they helped shed light on one or more candidates and their theoretical justification, cosmological consistency, experimental constraints, or detection potential, while those studies that were irrelevant were rejected. Some papers did conflict with one another. Conflicts were solved by listing both paper's thoughts throughout the candidate's sections, and by cross referencing papers for factual checking. Some of the extracted data were the authorship, publication year, candidate, theoretical framework, cosmological implications, and the main experimental or observational results which were then organized for a direct comparison. The research was assessed via a narrative comparative approach that was structured around theoretical motivation, cosmological consistency, experimental evidence, and detectability potential. Also, the quality of the studies was evaluated based on the journal's reputation, citations, methodological robustness, and agreement with established observations, with contradicting results being clearly noted. This approach follows a narrative comparative literature review that establishes a quantitative evaluation framework and ranking system to compare theoretical and experimental perspectives on the identity of dark matter.

Dark Matter Candidate Evaluation Framework

A critical evaluation of the four dark matter candidates requires assessing key factors such as theoretical motivation, cosmological consistency, experimental or observational evidence, and detectability potential. The ranking order embodies the degree to which each one is a natural consequence of fundamental physics, how well it agrees with Universe simulations, and how feasible the detection attempts in the future look. Based on the evaluation framework and weighting scheme criteria, axions rank first, then WIMPs, next sterile neutrinos, and lastly primordial black holes.

When these standards are implemented, cosmological consistency is the baseline needed for differentiation, as a dark matter candidate that would not reproduce large-scale structure and cosmic microwave background observations would be immediately discarded. Theoretical motivation then becomes the major separating factor, favoring candidates that emerge naturally from known physics and disfavoring those that require a finely tuned early-Universe situation. Experimental and observational results are used only for comparison and not in absolute terms: candidates that are still allowed but have increasingly stringent exclusion limits placed on them are ranked lower than those whose parameter space is under active exploration. In this paper, Experimental Evidence refers to current data and existing constraints, while Detectability Potential refers to how effectively future experiments may test the remaining viable parameter space. Detectability potential is a future-oriented criterion and indicates whether current or near-future experiments can realistically test the most well-motivated regions of parameter space. The structured use of these criteria enables the ranking to incorporate both past results and future prospects without being dependent on a single factor. The evaluation criteria, along with their assigned weights and justifications, are summarized in the table below.

One of the crucial experimental handles comes from the LIGO/Virgo/KAGRA observations of approximately 10–100 solar mass black hole mergers. These experiments test the hypothesis that such binaries are PBHs making up all of the dark matter. The results indicate that although PBHs may have some role in this stellar-mass range, they cannot be the main contributors without the effect of a higher than observed merger rate and conflicts with other constraints[22].

Axions

Theoretical Motivation

In the discussion below, the axion category mainly refers to QCD-like axions. The existence of axions as dark matter candidates is supported by strong theoretical evidence, as on several occasions their existence has been implied by the need to explain the strong CP problem in quantum chromodynamics. This means axions are not an idea only invented to explain dark matter, but a phenomenon occurring naturally in the framework of a well-motivated theory. Axions are expected to be extremely light, safe from decay, and feebly interact-

Criterion	Weight	Why
Theoretical Motivation	0.30	Measures how naturally a candidate arises from established physics. Candidates that solve independent theoretical problems or are predicted by well-motivated frameworks are favored over ad hoc constructions.
Cosmological Consistency	0.35	Evaluates how well the candidate reproduces key observational features of the universe, including the cosmic microwave background and large-scale structure. This is the most critical requirement for viability.
Experimental Evidence	0.20	Reflects how constrained a candidate is by current experimental and observational data. While no candidate is confirmed, experimental limits help assess plausibility.
Detectability Potential	0.15	Assesses the feasibility of probing the candidate with current or near-future experiments. This is considered less important than theoretical and cosmological consistency but relevant for guiding future searches.

ing, thus having the exact characteristics exhibited by dark matter[10]. Moreover, their mass and interactions are directly linked to fundamental physics and not just taken as free parameters. Axions are considered to be among the most theoretically well-grounded dark matter candidates due to their connection to the strong CP problem and their suitable dark matter properties.

Cosmological Consistency

Cosmological studies of axions do not contradict cosmological observational data either. For the most part, axions can be regarded as cold dark matter throughout their entire mass range, thus enabling the formation of galaxies and galaxy clusters[23]. Vacuum misalignment, a possible early universe origin for axions, could naturally account for the correct relic abundance while not disturbing the cosmic microwave background[10]. Vacuum misalignment is when axions in the early universe start off at high energy states and then later go into the minimum state. This creates particles that may possibly make up dark matter. Hence, in the standard cosmological model, axion dark matter has a convincing fit and is not at odds with the results of precision measurements obtained by missions like Planck.

Experimental Evidence

On the other hand, the axion remains undetected in experiments but is still consistent with all the observational constraints that have been made so far. At the same time, these constraints have already excluded parts of the traditional axion parameter space. Observations of stars and supernovae, among other things, provide a limit on the axion interaction parameter, although a great deal of parameter space is still unexplored[14]. These astrophysical bounds restrict how strongly axions can interact with normal matter. Laboratory tests, like ADMX[13], have been performed to seek axions, which use the conversion of axions into photons in magnetic fields, thereby establishing the upper limit of the axion coupling to light[23]. To date, no definite signal has been recorded, but no experiment has disqualified axions as a component of dark matter due to how well they fit the strong CP problem. As a result, the allowed parameter space is becoming more limited over time.

Detectability Potential

Detecting axions continues to be considered promising, partly due to their traceable and predictable weak interactions. Agencies like ADMX are continuously pushing their limits by noise reduction and broader mass coverage[24]. A new round of experiments, such as dielectric haloscopes and precision quantum sensors, targets the axion mass region that has not been previously explored[25]. By the time technology is ready, axion hunts will have already plumbed the depths of theoretically favored territories, thus making axions one of the most testable dark matter candidates in the coming decades.

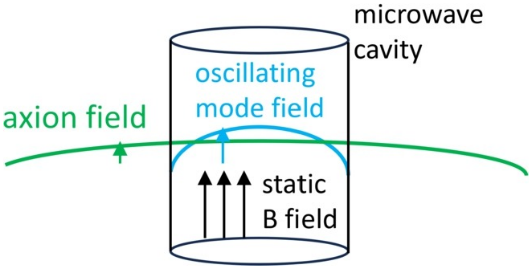

Fig. 2 An axion haloscope uses a strong magnetic field in a resonant cavity to convert dark matter axions into detectable microwave photons through the inverse Primakoff effect. The inverse Primakoff effect describes the scattering of axions off the electromagnetic field of an atom, turning it into a photon. Diagram showing how an axion haloscope detector uses a strong magnetic field and resonant cavity to convert axion dark matter into microwave photons that can be measured in the laboratory[26]. This setup shows why axions are considered experimentally testable.

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WIMPs

Theoretical Motivation

WIMPs are theoretically acceptable entities because they are inherent in various popular extensions of the Standard Model of particle physics, mainly the theory of supersymmetry. Supersymmetry is a theory that suggests that every known matter particle has a force carrier superpartner with a different spin. Supersymmetry also introduces the Lightest Supersymmetric Particle (LSP), which is the lightest, stable particle predicted by supersymmetric theories. If this theory were to be true, WIMPs would fit perfectly into the dark matter problem of the universe because the LSP would be neutral, weakly interacting, and stable[27]. The "WIMP miracle" is one of the most compelling arguments for WIMP, which demonstrates that a particle with weak-scale interactions and a mass in the GeV–TeV range very naturally gives a relic density that corresponds to the density of dark matter as it is observed. Since WIMPs fit naturally into multiple major particle physics models, they were historically one of the most studied dark matter candidates for years. However, over time, repeated null results from experiments have reduced confidence in the simplest WIMP models.

Cosmological Consistency

WIMPs do not contradict large-scale cosmological structures either. Given in the scenario that they move slowly as compared to the speed of light, they would act as cold dark matter, which is a must for explaining the formation of galaxies and galaxy clusters[28]. Cold dark matter is able to create halos around existing matter, creating gravitational pieces of scaffolding that can attract more matter, altering how galaxies form. WIMP-like behavior is backed by simulations with cold dark matter that can predict the distribution of galaxies today. Furthermore, the WIMPs do not have an adverse effect on light or normal matter in such a way that will hinder the development of the microwave background; thus, they are still in line with accurate cosmological measurements[29]. Hence, these particles are in agreement with spacetime's entire history from the Big Bang to today.

Experimental Evidence

Until now, no conclusive evidence of WIMPs exists in any single experiment, and many searches have placed strong limits on their interaction strength with ordinary matter[30]. Underground detectors, such as LUX-ZEPLIN[31], XENONnT[32], and PandaX[33], aim at the detection of the minute nuclear recoils caused by WIMP-atom collisional interactions. These experiments have ruled out large regions of the parameter space that were once considered the most likely. Indirect signals such as gamma rays released when WIMPs annihilate each other are also detected by the Fermi Large Area Telescope (Fermi-LAT), sensitive to WIMP energies ranging from 20 MeV to > 300 GeV[34]. However, none of these searches have produced a confirmed signal so far. Over the years, a few possible excess signals have been reported; however, none have been recognized as definitive WIMP detections. Since the criteria defining WIMPs are so specific, and they persistently evade experimental detection, they remain purely theoretical candidates requiring very narrow, sensitive experimental searches to validate their existence.

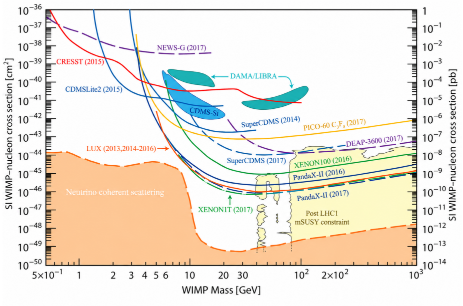

Fig. 3 Exclusion limits on the spin-independent WIMP–nucleon cross section versus WIMP mass from a multitude of WIMP searches, illustrating how a large portion of WIMP parameter space is ruled out by direct detection experiments[35]. Progressively narrowing constraints set by a broad range of WIMP-detection experiments motivate the WIMP detectability criterion within this paper's framework.

Detectability Potential

Although WIMPs still evade direct detection, future experiments will have much higher sensitivity. Plans for new detectors with bigger target masses and lower background noise (ex. XENONnT[32] will allow scientists to test WIMP interactions that are significantly weaker than what has been possible so far. Researchers are also upgrading detector materials and constraints, hoping to minimize false signals due to cosmic rays or natural radiation. What is more, the collaboration among underground detectors, space telescopes, and particle accelerators like the Large Hadron Collider enhances the possibility of detection. In the case that WIMPs are there within the allowed mass and interaction ranges, next-generation detectors are well-suited to find them.

Sterile Neutrinos

Theoretical Motivation

Sterile neutrinos are one of the theoretically possible dark matter candidates since they only slightly extend the laws of the Standard Model of particle physics. Unlike ordinary neutrinos, sterile neutrinos do not interact through the weak nuclear force and instead interact only through gravity and a very small mixing with active neutrinos. Many particle physics models that explain the origin of neutrino mass also predict the existence of sterile neutrinos; they are not introduced only for the purpose of dark matter explanation[36]. As a result of this link to neutrino physics, sterile neutrinos might be considered a very minimal and well-motivated addition to the already known theory.

Cosmological Consistency

Cosmologically, sterile neutrinos might agree with early Universe observations if their production is taken into account. In a typical non-resonant production scenario, sterile neutrinos are produced through mixing with active neutrinos in the early Universe, as suggested by Dodelson and Widrow[19]. Another production scenario includes lepton asymmetry, which can alter the momentum distribution and thus allow sterile neutrinos to act as cold dark matter. When generated correctly, sterile neutrinos can satisfy measurements of the cosmic microwave background and large-scale structure, meaning that they can be rated quite highly for cosmological consistency[17].

Experimental Evidence

Experimentally and observationally, the existence of sterile neutrinos has not yet been confirmed, but they are still allowed by present data. Scientists search for photons produced by the decay of sterile neutrinos, which occurs very slowly over cosmic timescales, using X-ray telescopes. For example, a tentative unexplained X-ray emission line near 3.5 keV has been identified in galaxy clusters and in nearby galaxies, which may be interpreted as a signal from sterile neutrino decay; however, this interpretation is still controversial[20]. While no detection has been confirmed, these findings continue to encourage further investigation.

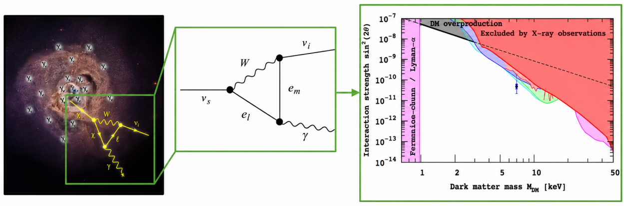

Fig. 4 A hypothetical sterile neutrino can decay into a lighter neutrino and an X-ray photon, creating an X-ray signal that telescopes can search for as indirect evidence of sterile neutrino dark matter[37–39]. Clear sterile neutrino decay signals bolster their experimental testability within this paper's framework.

Detectability Potential

In comparison to other dark matter candidates, sterile neutrinos can be detected to some extent, as their decay signatures provide a definite observational target. Next-generation X-ray instruments with higher energy resolution and sensitivity can either detect or exclude sterile neutrinos across most of their allowed mass range[17]. In addition, progress in cosmological observations and structure formation can still provide more constraints on sterile neutrinos as dark matter affects how likely they are to be detected.

Primordial Black Holes

Theoretical Motivation

PBH masses, unlike those of typical black holes, can vary by a factor of many millions, or even billions, ranging from less than a mountain to more than millions of the Sun's masses. A number of theoretical models put forward the idea of PBHs with masses as low as 10^{15} grams, while others permit masses even up to several thousand solar masses[40]. Due to the large variation in proposed mass range, PBHs are investigated as potential dark matter candidates in different mass windows in accordance with the selected formation scenarios[40].

Cosmological Consistency

Primordial black holes affect their environment in a similar way to how black holes do - almost solely through gravity. These objects (PBHs & standard black holes) can alter the path of light through gravitational lensing, influence star trajectories, and merge with other black holes, leading to the emission of gravitational waves which may be detected[41]. As PBHs move across galaxies, it is theorized that their gravitational interactions heat stars and disturb stellar systems. In addition, PBHs in some mass intervals might take in matter and release energy in the form of radiation, a process known as accretion, which helps astronomers to figure out their abundance in the Universe. Radiation released during accretion can be compared with theoretical predictions for PBH mass, allowing constraints to be placed on PBH abundance that remain consistent with established cosmological measurements (e.g., the Universe's thermal history, background radiation, the cosmic microwave background, and gravitational constraints)[40].

Experimental Evidence

Various experiments, by employing different methods and observations, have ruled out a large portion of the proposed PBH mass range outside of $1-10^3\ M_\odot$, although not all ranges in which PBHs might exist have been completely ruled out[40]. Several feasible mass windows still exist, like those around the mass of an asteroid or possibly at a few tens of solar masses, where the black hole merger gravitational-wave detections have led to a resurgence of the idea that PBHs may constitute dark matter[41].

Detectability Potential

Low mass PBHs have been ruled out since black holes that tiny (masses $< 5 \times 10^{14}$g or $2.5 \times 10^{-19}\ M_\odot$) would have

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evaporated due to Hawking radiation, although some recent work suggests a small mass window may remain under modified late-stage evaporation models[42]. Heavier mass ranges are also ruled out since scientists haven't detected signals from black holes that correspond to said mass ranges[43]. For these reasons, PBHs continue to be one of the most hotly debated issues in modern astrophysics and an important source of information in the field.

Ranking Discussion

The table below provides a comparison of how each candidate performs across the four evaluation criteria. The numbers in each box have been decided with the information presented throughout the paper. Within this framework, axions achieve the highest overall score, followed by WIMPs, sterile neutrinos, and primordial black holes. The following discussion and ranking explains how these scores arise by examining each criterion individually and comparing all candidates within that framework.

Side-By-Side Comparison

The four candidates can be mainly distinguished by how deeply they are based on current theory and how well they fit the usual cosmological picture. On the theoretical side, axions and WIMPs are top candidates because both arise from larger particle-physics ideas and were not independently postulated to explain dark matter. Axions are connected to the strong CP problem while WIMPs were found in many theories beyond the Standard Model and historically, a WIMP miracle has supported their existence. Sterile neutrinos are also a good fit to the theory because they relate to neutrino-mass physics but their modeling often requires additional assumptions. Primordial black holes are very different from the particle candidates which require a brand new particle, PBHs rely on special early-universe conditions leading to the right abundance. In terms of cosmological consistency, axions and WIMPs are the most similar to standard cold dark matter at large scales whereas sterile neutrinos can change the small-scale structure because of their free-streaming effects. PBHs can be cosmologically viable in some ranges but only if tighter conditions are met since many observations limit the allowed abundance of PBHs.

The candidates also differ when existing experimental evidence versus future detectability potential is compared. None of the four candidates has been experimentally confirmed so far. However, the present constraints vary in their range. Axions remain highly viable; although astrophysical data and laboratory experiments have excluded specific regions, a vast and favorable parameter space remains open. Decades of direct, indirect, and collider searches for WIMPs have, in fact, reduced the viable models to a very small number. Sterile neutrinos are limited by X-ray observations and structure-formation data, while contentious signals, for instance, the 3.5 keV line, are unfavored or yet to be verified. PBHs, over most of their mass range, are limited due to evaporation, microlensing, accretion, dynamical constraints, and gravitational-wave observations, which only give rise to a few windows where they could constitute the majority of dark matter. As to the future, Axions and WIMPs, according to this framework, retain the highest detectability potential mainly because a variety of experiments are still being upgraded in sensitivity. Sterile neutrinos also remain a possibility through enhanced X-ray and a growing number of precision laboratory searches, whereas the examination of PBHs is more limited by anticipated data from upcoming gravitational and astrophysical surveys scanning their remaining allowed regions.

Axions

Axions are the best overall performers as they obtain a high score in all four criteria and exceed the other candidates in theoretical motivation. According to the scoring table and the evaluation framework, axions receive scores of $TM = 5$, $CC = 5$, $EE = 4$, and $DP = 4$, leading to a total score of 4.65, which is the highest among all candidates. In contrast to the majority of dark matter candidates, axions were not conceived as the main contributors to dark matter but were rather developed as a solution to the strong CP problem in quantum chromodynamics, hence, giving them a quite unique and powerful theoretical ground[11]. From a cosmological point of view, axions are similar to cold dark matter, and so they do not contradict the formation of the large-scale structure, as evidenced by the simulations that not only reproduce galaxy clustering but also do not conflict with cosmic microwave background measurements[23]. On the experimental side, axions are still in line with all the present observational constraints, and even though they have not been detected so far, experiments like ADMX have attained the levels of sensitivity that they can be the first to discover axions in the regions most favored by theory[44]. In comparison with WIMPs, axions have been less excluded by experiments; as opposed to sterile neutrinos and PBHs, they are more compatible with cosmology. Their strong performance across all four criteria is what places them first within this framework. This section evaluates constraints already achieved by current observations and experiments.

This section focuses on future sensitivity improvements and upcoming searches rather than current limits. One of the criticisms raised against the hypothesis of axions constituting dark matter is their exceedingly weak interactions that make their detection and constraint a challenging task, thereby implying that they could remain experimentally inaccessible for a very long time[14]. Additionally, astrophysical constraints have already eliminated some axion models, thereby narrowing the

Each Section Is Ranked Out Of 5

	Theoretical Motivation	Cosmological Consistency	Experimental Evidence	Detectability Potential	Total
Axions	5	5	4	4	4.65
WIMPs	4	5	3	4	4.15
Sterile Neutrinos	4	3.5	3	3.5	3.40
PBHs	2	3	2	2	2.30

Total score per candidate = TM*0.3 + CC*0.35 + EE*0.2+ DP*0.15

Overview

A quick overview of all of the discussed information is provided below. This information can be used to easily understand the main points of the pages above.

Candidate	Theoretical Motivation	Cosmological Consistency	Experimental Evidence	Detectability Potential	Overall Summary
Axions	Strongly motivated through the strong CP problem and broader axion models.	Generally consistent with cold dark matter behavior across large scales.	No confirmed detection, but a large viable parameter space remains despite growing bounds.	Strong, with active haloscope and next-generation searches.	Strongest overall within this framework due to balanced performance across all criteria.
WIMPs	Strong motivation from beyond-Standard-Model physics and historical WIMP miracle arguments.	Consistent with standard cold dark matter and structure formation.	No confirmed signal after extensive searches; many classic models are now constrained.	Still strong because direct, indirect, and collider searches continue improving.	Strong candidate, but repeated null results lower its ranking in this framework.
Sterile Neutrinos	Motivated by neutrino-mass physics with some model dependence.	Can fit observations, but warm-dark-matter effects can create small-scale tensions.	No confirmed detection; X-ray and structure limits significantly restrict parameter space.	Moderate, through future X-ray and laboratory searches.	Viable but more constrained and model-dependent than axions or WIMPs.
PBHs	Do not require new particles, but depend on specific early-universe formation conditions.	Possible in limited cases, but many observations restrict abundance across mass ranges.	Strong constraints from lensing, evaporation, accretion, dynamics, and gravitational waves.	Limited to remaining mass windows testable by future surveys.	Lowest ranking in this framework because viable space is comparatively narrow.

parameter space that is still permissible. To this, a recent study states that axion interactions, which are exactly determined in the original hypothesis, inform the specific mass range experiments should target with experimental sensitivity being steadily improved[25]. Consequently, axions continue to be experimentally feasible, and the current and future experiments are actively probing the regions that are strongly theoretically motivated. This aligns with their high detectability potential ($DP = 4$) shown in the table, reinforcing their top overall ranking. However, this result is still framework-dependent. If more weight was given to current experimental exclusions, or if ultralight axion scenarios were more focused on instead of QCD-like axions, the comparison could become less straightforward.

Weakly Interacting Massive Particles (WIMPs)

WIMPs are ranked second because they perform excellently in terms of cosmological consistency and have strong theoretical motivation that depends on the model, but are behind axions in terms of experimental results. From the evaluation table, WIMPs are assigned $TM = 4$, $CC = 5$, $EE = 3$, and $DP = 4$, giving a total score of 4.15. This reflects their strong but not leading performance across the criteria. WIMPs, for instance, are natural byproducts in the minimal extensions of the Standard Model, like supersymmetry, and are additionally backed up by the WIMP miracle that provides the observed dark matter abundance through early Universe physics[27]. In cosmological simulations, WIMPs serve as cold dark matter, and thus, they are capable of reproducing the large-scale structure of the Universe perfectly well, which implies that they are equal to axions in this respect[28]. Yet from an experimental point of view, WIMPs bear the brunt: numerous direct, indirect, and collider searches over the last several decades have only led to exclusion limits, thus the parameter space that can accommodate WIMPs has been drastically reduced[32]. However, these strongest exclusions mainly apply to standard

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benchmark scenarios, while some nonstandard models such as inelastic, isospin-violating, or very weakly coupled WIMPs remain less constrained. While WIMPs are easier to search for than axions, their repeated non-detection lowers their detectability potential relative to axions. These points reflect present limits from completed or ongoing searches. This is reflected in their lower experimental evidence score ($EE = 3$), which pulls down their total relative to axions despite strong cosmological consistency.

A key point against WIMPs is that direct detection experiments aiming at increasing sensitivity, over decades, have not been able to unambiguously detect a WIMP signal; thus, large regions of the originally favored parameter space have been excluded[30]. The emphasis here is on next-generation detectors and future reach. The lack of detection has made some researchers doubt the classic WIMP paradigm. Nevertheless, this conclusion has yet to be finalized, as numerous well-motivated WIMP models anticipate interaction strengths that are too low for the current experiments to detect, or they may have nonstandard interactions which are more difficult to detect[4]. Thus, WIMPs cannot be ruled out, and they are still a possible solution to the dark matter problem as the experiments are progressively able to detect weaker couplings and wider mass ranges. This reduction in experimental confirmation lowers their overall score, preventing them from surpassing axions despite similar performance in other criteria.

Sterile Neutrinos

Sterile neutrinos carry third place because, on one hand, they are theoretically plausible and could be detected, but on the other hand, they have problems with cosmological consistency issues when compared to axions and WIMPs. In the evaluation table, sterile neutrinos are assigned $TM = 4$, $CC = 3.5$, $EE = 3$, and $DP = 3.5$, resulting in a total score of 3.4. This places them below WIMPs and axions due to weaker cosmological consistency and moderate detectability. Their theoretical motivation comes from neutrino mass models, so they represent the least radical extension of the Standard Model[36]. In fact, radiative decay is a way by which X-ray searches could detect sterile neutrinos, thus providing a potential detection method. However, signals like the 3.5 keV line that have been suggested are still under debate and have not been verified[20]. This criterion is based on current observations and present constraints. Although sterile neutrinos can be detected more easily than axions by decay signatures, their limited parameter space and less favorable cosmological agreement put them at a lower level than axions and WIMPs. This is reflected in their reduced cosmological consistency and detectability scores compared to the top two candidates.

One of the main points raised against the existence of sterile neutrinos is that their free, streaming nature might inhibit the formation of small-scale structures, thus leading to a discrepancy with galaxy formation observations[17]. Constraints also come from the Lyman-alpha forest, and different production models can weaken or strengthen this effect. Besides that, X-ray measurements impose very tight limits on their decay rates that rule out a large part of the parameter space. Nevertheless, it is possible that different production mechanisms, like resonant production due to the presence of a lepton asymmetry, generate momentum distributions that are colder and, therefore, not at odds with the constraints from structure formation[45]. Such models provide sterile neutrinos with the option of still being in agreement with cosmological and astrophysical data. However, the combination of moderate experimental constraints and only partial cosmological agreement explains their middle ranking relative to the other candidates in the framework.

Primordial Black Holes

This section considers existing observational bounds across different mass ranges. Primordial black holes are in the last position because they have the lowest theoretical motivation score, and they are the most strongly observationally constrained. In the evaluation framework and table, PBHs receive $TM = 2$, $CC = 3$, $EE = 2$, and $DP = 2$, leading to the lowest total score of 2.3 among all candidates. For instance, PBHs are not a consequence of particle physics, and thus they need large, finely tuned density fluctuations in the very early Universe, which makes their production less natural than that of particle-based candidates[22]. From the point of view of the Universe, computations indicate that making enough PBHs for dark matter would upset the cosmic microwave background measurements unless very particular conditions are met[46]. Regarding the observational side of the matter, a large variety of experiments are microlensing surveys, Hawking radiation upper limits, accretion constraints, and gravitational, wave observations that altogether exclude PBHs as a major dark matter constituent in most of the mass ranges[46]. The exact strength of some bounds remains actively debated because results can depend on astrophysical modeling assumptions and the details of PBH mass distributions. In principle, PBHs can be found by their gravitational impacts; nevertheless, the narrow ranges where they still exist make their detection potential very low. Hence, PBHs have the lowest chance of being dark matter within this framework. Their consistently low scores across all four criteria in the table explain their final position in the ranking.

One of the main arguments against primordial black holes as dark matter is that various observational constraints derived from microlensing, cosmic microwave background distortions, and Hawking evaporation exclude PBHs in a large part of the mass range[47]. As a result, the idea that PBHs can constitute the entirety of dark matter has been discarded for most masses. However, detailed analyses have identified several separate mass ranges in which PBHs are not ruled out and could still account for a substantial fraction of dark matter[40]. Hence, PBHs are still a possible, albeit limited, dark matter candidate.

Conclusion

Dark matter is one of the most prominent, unresolved puzzles in physics today. The four different dark matter candidates - axions, weakly interacting massive particles (WIMPs), sterile neutrinos, and primordial black holes (PBHs) - all weakly interacting, require a consistent framework for comparison based on their theoretical motivation, cosmological consistency, experimental compatibility, and detectability potential. Based on this ranking framework, axions rank strongest across the board with strong theoretical motivations, excellent cosmological consistency, great experimental compatibility, and promising detectability potential. WIMPS perform excellently in terms of cosmological consistency and have strong theoretical motivation, but suffer from uncertainty in their detectability potential. Sterile neutrinos align well with theory and offer promising detectability, but contradict certain small-scale cosmological structure formation theories. Finally, PBHs score lowest regarding theoretical motivation and detectability potential, although they are the most strongly observationally constrained candidates. The future of dark matter research is to a great extent dependent on improvements in detector sensitivity, which would increase the detectability potential of each candidate across the board.

Experimental results have already played a major role in changing how these candidates are viewed. Improvements would also affect the use of new observational techniques, and equally importantly, on continued theoretical work to sharpen and refine existing ideas. In fact, forthcoming experiments and surveys are generally seen as either a way to further constrain the dark matter field or to finally uncover its true nature. This review compares each candidate as an individual dark matter scenario. However, mixed dark matter models are also considered and tested in the dark matter community, and ranking systems could differ if multiple candidates contribute to the total dark matter abundance. This comparison shows that different scientific ideas can be evaluated by using shared criteria. It also highlights that both theoretical motivations and experimental evidence are important when weighing future research directions. As new observations and experiments continue to improve, the community will continue to explore the true nature of dark matter.

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