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Dissecting dark matter candidates: A comprehensive evaluation of axions, sterile neutrinos, and WIMPs

Xiaoxin Wang

Department of Physics, National University of Singapore, Singapore, 119077, Singapore

e0549005@u.nus.edu

Abstract. This article provides a comprehensive review of the three most popular candidates for dark matter: axions, sterile neutrinos, and WIMPs (Weakly Interacting Massive Particles). The article explores the theoretical origins of these candidates and their characteristic properties. It also examines the various observational constraints placed on them by different experiments, including direct and indirect detection experiments, as well as astrophysical and cosmological observations. The article also discusses the implications of these particle candidates on the development of cosmic structures, such as galaxies and galaxy clusters. This review aims to enhance comprehension of the present status in dark matter studies and the challenges faced in identifying the nature of dark matter. In summary, this comprehensive review provides a comparative analysis of the most promising dark matter candidates, shedding light on the latest developments in this exciting field of research.

Keywords: WIMPs, axions, sterile neutrinos, dark matter

1. Introduction

Dark matter, first proposed approximately a century ago, was introduced to explain the peculiarities seen in galaxy rotation curves. Since then, its existence has been substantiated by numerous observations spanning from galactic to cosmic scales. This review begins by presenting various proposed theories of dark matter, including both non-particle and particle dark matter. In this review, the emphasis is on particle dark matter contenders like Axions, Sterile Neutrinos, and Weakly Interacting Massive Particles (WIMPs). The three prominent candidates have emerged to address the dark matter conundrum. Each of these particle candidates originates from a distinct theoretical framework, and they possess unique properties that could possibly account for the elusive nature of dark matter. Axions, first proposed to solve the strong CP problem in quantum chromodynamics, could be produced in the early Universe in sufficient abundance to account for dark matter. Sterile neutrinos, an extension of the neutrino sector of the standard model, could have unique keV-scale masses, making them a viable warm dark matter candidate. On the other hand, WIMPs naturally arise in many theories beyond the standard model and offer an excellent candidate for cold dark matter due to their heavy masses and weak-scale interactions. Additionally, we will explore the experimental signatures and astrophysical implications and the role these particle candidates play in as dark matter. Finally, recent developments and future prospects in dark matter research will be highlighted. This review endeavors to fill a distinctive gap in the current literature, with a distinct focus on the comparison of the three leading dark matter candidates - axions, sterile neutrinos, and WIMPs. While many existing publications offer valuable insights into individual candidates, they often don't compare these contenders or explore their unique implications in the broader context of cosmic structure formation. This review, however, is designed to provide a comparative analysis, examining each candidate's theoretical origins, characteristic properties, and observational constraints. By offering a broader perspective that interlinks the separate discussions, this review contributes a fresh viewpoint to the dynamic and ever-evolving discourse on dark matter. It is our aspiration that this comprehensive comparison will aid in enriching our understanding of the dark matter conundrum and provide further momentum to this exciting area of research.

2. Non-particle dark matter

Dark matter hypotheses basically fall into two categories. In the Non-particle dark matter category, we do not need to nominate or invent new particles, but using other explanations to account for the influences caused by dark matter. While in another category (particle dark matter), dark matter is proposed to be some particle. Eugene Oks has reviewed some recent theories for non-particle dark matter candidates in [1], and included the relevant references. Some of the theories are summarized in the following subsections.

2.1. Exotic compact objects

Exotic compact objects, a collection of theoretical compact stars, are believed to contribute to dark matter's mass. These celestial entities distinguish themselves by the absence of electrons, neutrons, and protons. Instead, their unique quantum characteristics offer them resistance against gravitational collapse into black holes.

Exotic compact objects represent an array of intriguing hypothetical celestial bodies, including quark stars, fuzzballs, gravastars, boson stars, Q stars, and electroweak stars. Quark stars, potentially formed under immense pressure and temperature causing neutrons to disintegrate into quarks, are kept from further collapse by degeneracy pressure. Fuzzballs, similar to black holes yet lacking a well defined event horizon, are characterized by their unique, nebulous geometry owing to a superposition of microstates. Gravastars, or gravitational-vacuum stars, share exterior properties with black holes, but internally they exhibit a gravitational Bose-Einstein condensate-like state. Other intriguing concepts extend to boson stars, composed largely of bosons, Q stars which are highly dense and massive neutron stars, and electroweak stars where gravitational contraction is balanced by energy from the conversion of quarks into leptons. Each of these exotic compact objects presents unique characteristics and theories, eagerly awaiting observational confirmation, thereby enriching the captivating field of dark matter research.

2.2. Primordial black holes

Black holes from the early universe are not originated through gravitational contraction like conventional black holes. One recent idea suggests that quantum tunneling inside vacuum bubbles could produce them. This idea also says that ‘baby Universes’ split from our Universe and form primordial black holes. Should light primordial black holes be present, they could potentially serve as viable dark matter contenders.

2.3. Modified gravity

Modified gravity initially means ‘modified Newtonian dynamics’, which alters the equations of Newtonian mechanics to explain the observed rotation curves. Later versions have modification of Newtonian dynamics and general theory of relativity, including the strong equivalence principle.

A limitation of this modified theory arises from its performance in addressing galaxy clusters and dwarf galaxies. A recent research analyzed 175 galaxies and found that the modified gravity theory agreed with the observations of galaxies in the strongest external field. But the theory does not agree with the observations of galaxies experiencing a weaker external field. This research favoured dark matter over the modified theory.

3. Particle dark matter

Commonly proposed particle dark matter candidates include axions, sterile neutrinos and WIMPs. Each candidate has unique properties and is subject to different detection methods, such as direct detection experiments, indirect detection through cosmic signals, or collider experiments at particle accelerators. The properties and some detection methods of each particle are reviewed in this section.

3.1. Axions

The origin of Axions is the Strong CP problem, which has been reviewed in [2]. In short, an effective interaction term $\mathcal{L}_\theta$ can be derived from the Quantum Chromodynamics (QCD) Lagrangian density, as in equation (1).

$$\mathcal{L}_\theta = \theta q = \frac{\theta}{32\pi^2} F^a{}_{\mu\nu} \tilde{F}^{a\mu\nu} \equiv \theta \left\{ F\tilde{F} \right\} \tag{1}$$

The $F\tilde{F}$ term is charge conjugation even and parity odd hence CP violating. The θ term will contribute to the Neutron electric dipole moment (NEDM), which introduces observable effects. The early estimation of NEDM with respect to θ is $2.7 \times 10^{-16}\theta e$ cm. And more recently, it has estimated values $1.08 \times 10^{-16}\theta e$ cm and $4.5 \times 10^{-15}\theta e$ cm [3].

From a recent experiment, the NEDM is bounded above as $|d_n| < 2.9 \times 10^{-26} e$ cm [4]. Therefore, θ need to be smaller than a certain number, as in equation (2).

$$|\theta| < 0.7 \times 10^{-11} \tag{2}$$

This brings us the strong CP problem. Theoretically, $|\theta|$ value can take anything between 0 and π. The remarkably minuscule nature of the parameter θ cannot be explained naturally, this is a fine-tuning problem.

An early solution to the problem is to introduce a massless up quark, where a shift symmetry of $\theta \to \theta - 2\alpha$ would be an exact symmetry. Then θ is not observable, and the issue is settled. However, due to the Weinberg's up-down quark mass ratio [5], as in equation (3), the possibility of existence of massless quark has been ruled out.

$$Z = \frac{m_u}{m_d} = \frac{5}{9} \tag{3}$$

The Axion model is another solution, first introduced by Peccei and Quinn [6]. Peccei and Quinn considered the electroweak full Lagrangian and tried to find a symmetry like the massless quark case, $\theta \to \theta - 2\alpha$. They were able to obtain one such symmetry when H_u is connected to up-type quarks only, and quarks that are down-type are connected to H_d, as in equation (4).

$$\mathcal{L} = -\overline{q}_L u_R H_u - \overline{q}_L d_R H_d - V(H_u, H_d) + \text{H.c.} - \theta \left\{ F\tilde{F} \right\} \tag{4}$$

As the complete Lagrangian has global symmetry, those potential terms are not supposed to have $H_u H_d$ or $(H_u H_d)^2$. We will have the same type of θ shifts as seen from massless quark situation, this is the PQ global symmetry $\mathrm{U(1)_{PQ}}$. A Higgs field under such symmetry transformation is the axion a, with transformation $a \to a +$constant, like a Goldston boson with spontaneous breaking of the PQ symmetry. Such axion has the name PQWW axion, short term for Peccei-Quinn-Weinberg-Wilczek. Peccei and Quinn suggests that, for any θ, the vacuum expectation value $<a>$ can be chosen such that the resulting θ is zero, hence resolving the problem. In contrast to the massless quark scenario, this situation results in interactions and allows for the production within stars.

Furthermore, there are alternative axion models besides PQWW axion. One simple model is called Kim-Shifman-Vainstein-Zakharov (KSVZ) axion [7], the axion is very light due to the σ phase, and includes a high mass quark Q in the chiral symmetry. The Lagrangian density is in equation (5).

$$\mathcal{L} = -\overline{Q}_L Q_R \sigma + \text{H.c.} - V(|\sigma|^2) - \theta \left\{ F\tilde{F} \right\} \tag{5}$$

Regarding the σ field which is SU(2) ×U(1) singlet, shown in equation (6), the axion a can be treated as the phase of the field, with $a \equiv a + 2\pi N_{DW} f_a$, and axion period $2\pi N_{DW} f_a$, where N_{DW} is the domain wall number. f_S cannot be greater than v due to the periodicity (2π) of θ, we have $f_a = f_S/N_{DW}$. And the coefficient of the $F\tilde{F}$ term defines f_a as $\theta = a/f_a$.

$$\sigma = \left[\frac{v+\rho}{\sqrt{2}}\right] e^{\frac{ia}{fs}} \tag{6}$$

Essentially, the fundamental behavior of an axion is determined by the uncertain f_a scale. And the axion mass can be obtained as in equation (7) [8].

$$\mathrm{m_a} \approx 6\ \mathrm{eV}\left(\frac{10^6\mathrm{GeV}}{f_a}\right) \tag{7}$$

The PQ symmetry-breaking scale firstly implies that the axions are very heavy (~100 keV), which was ruled out by experiments. The other models constructed then have higher f_a value and lower $\mathrm{m_a}$ value.

The coupling between axion and matter radiation typically exhibit an inverse proportionality to the energy scale f_a. Researchers hold considerable interest in the axion two-photon coupling, as represented by Equation (8), where $\mathrm{g_\gamma}$ is dimensionless, and equal to -0.97 in the KSVZ model [7].

$$\mathrm{g_{a\gamma\gamma}} = \frac{\alpha\, \mathrm{g_\gamma}}{\pi\, \mathrm{f_a}} \tag{8}$$

The axion production rate in many experiments can be estimated, and it bounds the axion decay constant from below, $f_a \geq 10^4\mathrm{GeV}$. Astrophysics (mainly solar luminosity) constraints f_a window approximately as: $10^9 \leq f_a \leq 10^{12} GeV$ [3]. Figure 1 shows a schematic for the bounds on f_a.

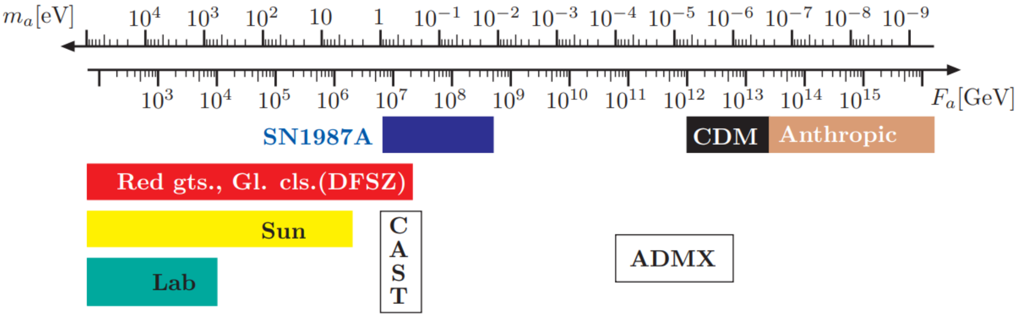

Figure 1. A schematic for the f_a bounds [3].

3.2. *Axion detection*

In the preceding section, we have explored the origin of axions. Consequently, it is essential to highlight that an ultra-light axion constitutes a promising dark matter candidate [9], because of the critical density shown in equation (9). An axion with mass about 20 μeV could potentially explain the density of dark matter observed throughout the Universe, where the value of Ω_m is about 0.27. For $\mathrm{m_a}$ lighter than 1 μeV, axions would result in an overclosed Universe, thereby establishing a lower boundary for their mass.

$$\Omega_a \approx \left(\frac{6\ \mu eV}{m_a}\right)^{\frac{7}{6}} \tag{9}$$

In the subsequent subsection of Section 3.2, we present an overview of some experimental approaches for cosmological axion detection. It should be noted that the mentioned techniques represent only a fraction of the experimental approaches currently under investigation in the scientific community.

As research progresses, it is anticipated that additional innovative methodologies will be proposed and explored, further expanding our understanding of this field.

3.2.1. Microwave cavity detectors. It is showed in [10] that axions present within the galaxy halo could potentially transform into photons when exposed to a highly intense magnetic field, and the power of conversion is shown in equation (10). Where ρ_a is the axion density in the halo, B_0 the strength of magnetic field, V the cavity volume, and C the factor depending on mode. Q_L is the factor of loaded quality. η is the power fraction from probe, η is generally tuned approaching or achieving a state of critical coupling.

$$P_{SIG} = \eta\, g_{a\gamma\gamma}{}^2 \left(\frac{\rho_a}{m_a}\right) B_0{}^2 V C Q_L \tag{10}$$

As the resonant conversion happens if the cavity's frequency matches the axion's mass, the search is conducted by adjusting the frequency incrementally step by step. Idea of the experiment is illustrated in figure 2. Axions undergo resonant conversion into nearly monochromatic signals which are captured using an antenna. Subsequently, a fast Fourier transform (FFT) is employed to determine the power spectrum. The detection of potential subtle variations in the thermalized axion spectrum could provide significant insights into the mechanisms behind the formation of our Galaxy [11]. A notable characteristic of the microwave cavity-based investigation is that the whole axion energy (mass and kinetic) is measured.

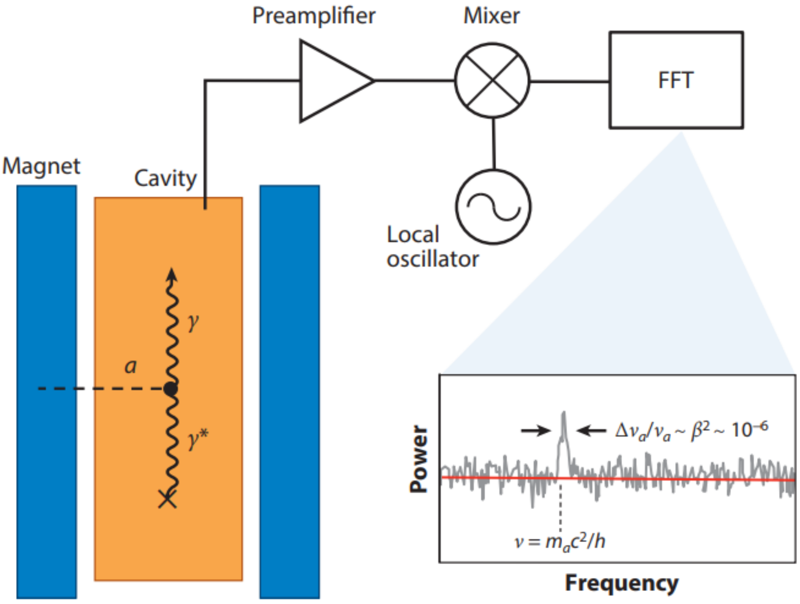

Figure 2. Diagram illustrating the microwave cavity approach to seeking dark matter axions [11].

3.2.2. ADMX (Axion Dark Matter eXperiment) and ADMX-HF (high-frequency). The ADMX experiment [11] was designed to reach KSVZ axion occupying the galactic halo, where the local density of the axion is $\rho_a \sim 0.45\ \mathrm{GeV\ cm^{-3}}$. The ADMX layout is illustrated in figure 3. The NbTi superconducting magnet used has dimensions 60cm × 110cm, and can sustain a central field of 8T. The experiment is also cooled to ~1.5K. The first operation period of ADMX (1995-2004) reaches a system noise temperature (T_{SYS}) at about 3K. After that, more advanced technologies consisting superconductors were employed. The level of noise produced by the MSAs is heavily influenced by changes in temperature and they are not performing better than the transistor based amplifiers. The ADMX experiment covers the energy range (1.9-3.65 μeV).

At Yale University, ADMX-HF was constructed with the aim of developing new methods and approaches for the next-generation detection [11]. The goal is to achieve a level of sensitivity in the detection of the coupling constant (axion and photon) up to ~ 2 ×KSVZ. Dilution refrigerators will be used to get a base temperature of ~25mK, which is a big improvement from ADMX.

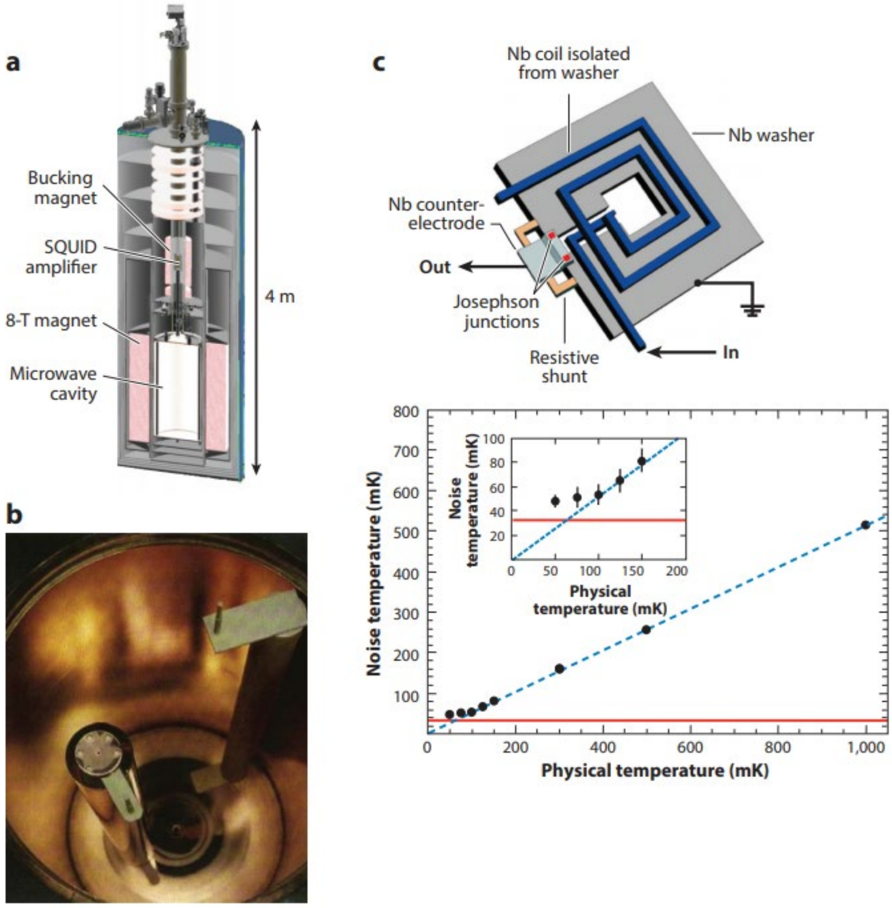

Figure 3. ADMX layout. (a) Arrangement; (b) Cavity; (c) SQUID (superconducting quantum interference device) amplifier [11].

3.2.3. Cosmic Axion Spin Precession Experiment (CASPEr). The CASPEr experiment will detect axions by NMR(Nuclear magnetic resonance) techniques [11]. It aims to cover the energy range of about 10^{15} to 10^{19} GeV-1. The central concept involves utilizing either the electric dipole moment or air currents to prompt the nuclear spin precession, and then measuring the resulting Larmor frequency related to the spins of the nucleus. If the frequency matches the axion mass, an NMR signal can be detected. In particular, CASPEr is sensitive enough to detect axions over a wide mass range: ~ 10^{-9} to 10^{-12} eV.

3.2.4. The KAGRA (Kamioka Gravitational Wave Detector) project. Michimura et al. [12] illustrates a new technique for dark matter axion search, using the KAGRA gravitational wave telescope. The KAGRA gravitational wave telescope is like an usual gravitational wave telescope mainly consisting of a Michelson interferometer, which is highly sensitive to small oscillations and small distance change. Figure 4 shows the schematic of the apparatus. There are three kinds of particles which can be detected in the following ways: Axion-like particles (ALPs) involves observing laser polarization, while scalar fields that cause variations in particle masses or the fine structure constant will be detected by observing changes of the path length of light. Additionally, vector fields can be identified by detecting unconventional fluctuating forces applied to reflective surfaces.

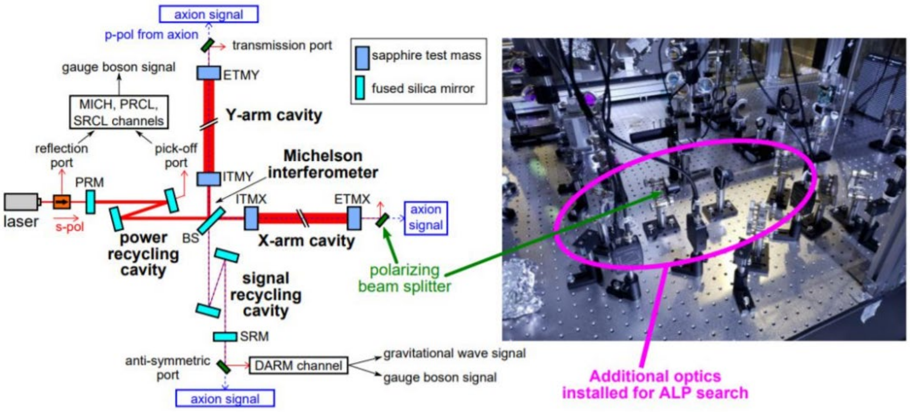

Figure 4. Left-hand side is a diagram outlining the setup of KAGRA, which is used for axion search. Right-hand side is a photograph showing the polarization optics that have been positioned within the X-arm cavity transmission area to aid in the search for ALPs [12].

3.2.5. Other axion detection experiments. Regarding axions escaping from neutron stars, Buschmann et al. [13] proposed that at the cores of neutron stars, the axions pass through the strong magnetic field of the stars, and convert into x-ray photons. They also used previous observed excessive x-ray data to fit in their model. They conclude that axion mass should be lower than 10^{-5} eV.

In addition to the pursuit of cosmological axion detection, alternative approaches involve solar axion searches, which aim to identify axions originated from the Sun’s centre [10]. Furthermore, laser-based experiments endeavor to achieve the direct conversion of laser photons into axions [11]. Figure 5 illustrate a recent axion-photon coupling and axion mass window [11].

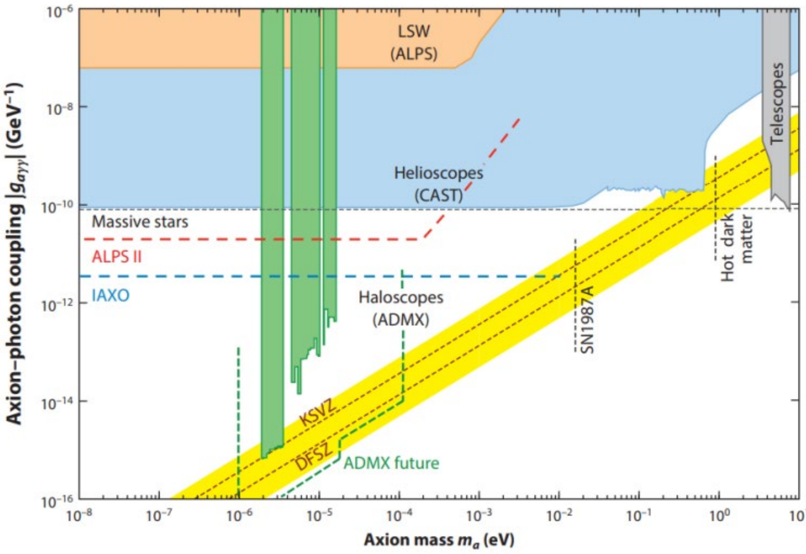

Figure 5. Restrictions on coupling constant between photon and axion, and estimated range of detection that is expected to be achieved through ongoing experiment upgrades [11].

3.3. Sterile neutrinos

Sterile neutrinos are a hypothetical particle, which were initially proposed in 1992 to address the solar neutrino problem [14]. That is, a fourth neutrino which is "sterile" and does not interact with matter via the weak nuclear force like active neutrinos. However, it is believed that they could still interact with active neutrinos through a process called neutrino oscillation, which occurs when a neutrino changes from one flavor to another as it travels through space. The surge in attention of sterile neutrino was primarily driven by the emergence of experimental anomalies, which could potentially be elucidated by the presence of a fourth neutrino. One such anomaly was the observed excess of electron antineutrinos in the Liquid Scintillator Neutrino Detector (LSND) experiment [15], lending further credence to the hypothesis of sterile neutrinos.

Furthermore, sterile neutrinos constitute a compelling research area, with the notable hypothesis that heavy sterile neutrinos may serve as dark matter candidates [16]. According to this hypothesis, sterile neutrinos only interact with matter through gravitational force, thus contributing to the overall mass of a region of space. In contrast, standard model neutrinos are not suitable dark matter candidates due to their extremely small masses. The physics and calculations on sterile neutrino as dark matter have been recently reviewed in [16], which shows how sterile neutrinos gain mass from the (type I) seesaw model. Moreover, In order for sterile neutrinos to form in the universe, it is necessary that they engage in some form of interaction with other matter, albeit potentially through non-standard mechanisms. The authors in [16] illustrate three possible formation mechanisms for sterile neutrinos accounting for dark matter, with one of the method predicting sterile neutrinos with keV mass scale produced by mixing.

In the following subsections, a selection of experimental approaches designed for the detection of sterile neutrinos is presented, illustrating the diverse strategies that have been employed by researchers in this field.

3.3.1. The MiniBooNE experiment. The MiniBooNE experiment [17] employs a spherical tank with a diameter of 12 meters, which contains around 800 tons of mineral oil that serves as both the target material and scintillator for neutrino interactions. The detector's inner surface is lined with 1,520 photomultiplier tubes (PMTs) that capture and amplify scintillation photons produced by charged particles resulting from neutrino interactions. The neutrino beam is generated at Fermilab using a high-energy proton beam, which produces mesons that decay into neutrinos. The MiniBooNE experiment was created to examine the LSND findings and observed an excess of electron neutrino events known as the MiniBooNE low-energy excess (LEE). Such anomaly could be probably caused by sterile neutrino production, but this interpretation is still being debated in the scientific community.

3.3.2. The IceCube experiment. The IceCube experiment [18], situated at the South Pole, is a large-scale neutrino observatory designed to detect high-energy neutrinos originating from astrophysical sources. It consists of an array of over 5,000 digital optical modules (DOMs) embedded in a cubic kilometer of Antarctic ice, extending from a depth of 1,450 meters to 2,450 meters beneath the surface. The DOMs detect Cherenkov radiation, which is emitted by charged particles created as a result of neutrino interactions with the ice.

In the context of sterile neutrino searches, the IceCube experiment examines its data for any anomalous neutrino events that could potentially indicate the presence of sterile neutrinos [19]. These anomalous events may manifest as deviations from the expected neutrino flux, energy distribution, or interaction rates based on the standard three-flavor neutrino oscillation model. Despite extensive data analysis, the IceCube experiment has not yet found conclusive evidence for the existence of sterile neutrinos [19]. Consequently, the experiment has been instrumental in establishing constraints on the potential existence and properties of these elusive particles. These constraints, derived from the lack of observed anomalies, provide valuable information on the range of sterile neutrino mass, mixing angles, and other parameters that are still compatible with the experimental data.

The IceCube experiment primarily targets high-energy neutrinos, with its sensitivity to sterile neutrinos contingent on specific mass ranges and mixing parameters [19]. Although it imposes stringent constraints on certain sterile neutrino parameter regions, it cannot entirely exclude their existence. Complementary techniques and further experimental efforts are essential for advancing the search for these elusive particles and elucidating their role in the universe.

3.3.3. Other experiments. The Daya Bay experiment [20], situated in China, has contributed to constraining the potential existence of sterile neutrinos by quantifying electron antineutrino disappearance rates in a nuclear reactor-based investigation. Absent any evidence for sterile neutrino oscillations, the experiment established upper bounds on the mixing parameters associated with sterile neutrinos. Other experiments like Super-Kamiokande [21] and DANSS [22], have also searched for sterile neutrinos using different techniques and detectors, but so far, no conclusive evidence for sterile neutrinos has been found.

3.4. WIMPs

WIMPs (Weakly Interacting Massive Particles) represent a leading dark matter candidate due to their massive nature, weak interactions with ordinary matter, and expected stability or longevity [23]. These particles are typically proposed in Standard Model extensions, such as supersymmetry (SUSY), wherein each Standard Model particle possesses a "superpartner" with distinct quantum properties. The lightest superpartner, often a neutralino, serves as a WIMP candidate [23].

A number of experimental endeavors have been undertaken to identify WIMPs, encompassing direct detection approaches such as XENON [24], LUX [25], and DarkSide [26]; indirect detection technique exemplified by Fermi-LAT [27]; and collider searches, notably at the Large Hadron Collider (LHC) [28]. Although no definitive detection has occurred, WIMPs remain a compelling dark matter candidate with ongoing investigations into their potential role in the universe.

3.5. Self-interacting dark matter (SIDM)

As discussed in [1], besides axions, sterile neutrinos and WIMPs, alternate theories of particle dark matter have also been proposed. One prominent hypothesis suggesting that dark matter particles engage in strong self-interactions, potentially mediated by a light vector boson. Contrasting with cold dark matter (CDM) particles, which have no collision, dark matter with self-interacting particles carry a yet-to-be-identified dark force. The dark matter distribution in two ultra-diffuse galaxies was studied, by comparing simulated data from both SIDM and CDM models with observational data. The findings demonstrated a preference for the SIDM scenario. However, it is crucial to note that the authors needed to make several assumptions during the simulations, given the unknown nature of the dark force.

4. Comparisons among axions, sterile neutrinos and WIMPs

In this section, a comparative analysis is conducted among the three particle dark matter candidates. Each subsection examines a specific aspect of the candidates.

4.1. Origins and theoretical motivation

Axions, sterile neutrinos, and WIMPs represent distinct particle dark matter candidates, each with unique origins and motivations. Axions, initially suggested to address the strong CP problem through the PQ mechanism, can naturally account for dark matter under certain conditions. Sterile neutrinos, incorporated to explain phenomena like neutrino oscillations, could potentially belong to an extended family of particles beyond the Standard Model, with their role as dark matter candidates dependent on mass and mixing parameters. WIMPs arise from extensions to the Standard Model, such as supersymmetry, which introduces new interactions and constituents, including the neutralino as a prime example.

4.2. Properties

Axions possess a minuscule mass, typically ranging from μeV to meV, and exhibit exceedingly weak couplings to photons and other particles [6]. Sterile neutrinos encompass a broad spectrum of masses;

however, those with keV-scale mass are particularly considered as potential dark matter candidates [16]. WIMPs, on the other hand, typically exhibit masses within the GeV to TeV range and engage in weak interactions with Standard Model particles through the weak force. In addition to their respective masses, experiments investigating axions, sterile neutrinos, and WIMPs focus on distinct parameters: the coupling constant for axions, which describes the strength of their interactions with photons and other particles; the mixing angle for sterile neutrinos, which quantifies the degree of oscillation between active and sterile neutrinos; and the cross-section for WIMPs, which measures the probability of their interactions with ordinary matter, typically through the weak force.

Axions exhibit very weak self-interactions, which are typically inconsequential for their role as dark matter [6]. Sterile neutrinos have self-interactions that depend on the specific model and are generally presumed to be weak [16]. WIMPs, on the other hand, are usually assumed to possess negligible self-interactions, although proposals for self-interacting dark matter models with WIMP-like particles do exist [29].

4.3. Dark matter accounting and production

WIMPs could account for the entirety of dark matter if their properties match theoretical predictions, and they can be generated thermally in primordial universe by freeze-out [23]. Axions, on the other hand, can contribute to a substantial fraction or even the totality of dark matter if their mass and coupling constants fall within specific ranges [30]. They can be produced non-thermally via the misalignment mechanism in the early universe [30]. Sterile neutrinos could potentially constitute all of the dark matter, contingent upon their mass and mixing parameters being suitable [16]. They can be produced through various mechanisms, such as neutrino oscillations, freeze-in, or through interactions with other particles in the early universe [16].

4.4. Implication from cosmology and astrophysics

From galaxy structure implications. WIMP-based cold dark matter models predict cuspy central density profiles in galaxies, which can conflict with observations of some dwarf galaxies [31]. In contrast, ultra-light axions or fuzzy dark matter naturally produce cored density profiles, potentially addressing small-scale issues with the cold dark matter model [32]. Sterile neutrinos of keV-scale can alleviate some small-scale problems caused by CDM model but may also produce different structures in the early universe [33].

Furthermore, there are astrophysical constraints on WIMPs coming from observations of gamma-ray and cosmic-ray emissions, and the cosmic microwave background (CMB) [34]. Axion constraints arise from observations of stellar cooling rates and the CMB [11]. While observations on X-ray, large-scale structure formation, and the CMB produce constraints on sterile neutrinos [16]. In terms of Sensitivity to astrophysical assumptions. Indirect detection methods for WIMPs are often sensitive to the distribution and density profiles of dark matter in galaxies, introducing uncertainties in constraints or potential signals. Axion detection via astrophysical sources is sensitive to magnetic field models and the axion-photon coupling, but laboratory searches are generally less dependent on astrophysical assumptions [30]. X-ray searches from sterile neutrino decay are sensitive to the distribution of galactic dark matter and the properties of the X-ray background [16].

Moreover, the three dark matter candidates can have varying impacts on the early universe, baryon asymmetry, and gravitational wave signatures.

In terms of cosmic inflation and the early universe, the impact of WIMPs is generally minimal. Axions, on the other hand, play a more significant role in primordial universe, largely determined by the misalignment mechanism, which can have implications for the generation of primordial density fluctuations [30]. Sterile neutrinos can influence the thermal history of primordial universe through their production and decay processes, potentially affecting the large-scale structure formation and the CMB [16].

Regarding the connection to baryon asymmetry, some models of WIMP dark matter can be related to the creation of the baryon asymmetry in the universe through mechanisms such as electroweak baryogenesis or leptogenesis [35]. Axions are generally not directly involved in generating the baryon asymmetry but could be part of a broader framework that addresses both dark matter and the matter-antimatter asymmetry [36]. Baryon asymmetry could also involve sterile neutrinos playing a role through mechanisms like leptogenesis, where their decay can produce an imbalance between matter and antimatter [37].

As for gravitational wave signatures, the direct impact of WIMPs on gravitational wave signals is typically minimal. In contrast, the decay of axionic topological defects can generate gravitational wave signals that could be detectable by future observatories [38]. The direct impact of sterile neutrinos on gravitational wave signals is generally minimal as well, but they might influence the dynamics of compact objects or the formation of large-scale structures in ways that produce indirect signatures [39].

4.5. Experiments

WIMP detection experiments include direct detection experiments like XENON [24], LUX[25], and DarkSide [26]; indirect detection experiments such as Fermi-LAT [27]; and collider experiment searches, exemplified by the LHC [28]. Axion searches employ resonant cavities, for instance, ADMX [11] and CASPEr [19], and astrophysical observations of axion-like signatures in the cosmic microwave background or galactic magnetic fields [30]. Sterile neutrino detection methods involve X-ray searches like Chandra [40] that searches for X-ray emission lines from decay of sterile neutrinos, as well as neutrino oscillation experiments such as MiniBooNE [17] and IceCube [18].

The experimental timeline for these dark matter candidates stretches back several decades. WIMP experiments have been running since the 1990s, with increasingly sensitive detectors being developed. Axion searches began in the late 1980s and have seen continuous improvements in sensitivity. Interest in keV-scale sterile neutrinos as dark matter candidates has grown over the past two decades, with various searches being conducted. The costs of these experiments can vary significantly. WIMP experiments typically involve large-scale underground detectors or high-energy colliders, which can be expensive to construct and operate. Axion experiments tend to be smaller in scale and generally less expensive than WIMP experiments, but they still require sophisticated and sensitive equipment. The costs of sterile neutrino searches can range from relatively low-cost X-ray observatory analyses to large-scale neutrino experiments.

Despite extensive searches, no conclusive detection of WIMPs has been made, and constraints on their properties have become increasingly stringent. Axions have not been directly detected, but ongoing experiments are reaching the sensitivity levels needed to probe their properties. Sterile neutrinos have not been directly detected either, but experimental and observational efforts continue to explore their potential role as dark matter.

4.6. Future prospects and technological advancements

The search for dark matter candidates, such as axions, sterile neutrinos, and WIMPs, continues to advance, driven by improvements in experimental sensitivities and technological innovations. For WIMPs, the ongoing development of increasingly sensitive detectors will either provide evidence for their existence or further constrain their properties, enabling researchers to refine theoretical models. In the case of axions, technological advancements in detection methods, including improved resonant cavities and novel techniques, hold the promise of significantly enhancing the prospects of discovering axions in the coming years [11]. Meanwhile, the development of more sensitive X-ray observatories and refined analysis techniques for neutrino oscillation experiments could boost the chances of detecting or constraining sterile neutrino dark matter [39].

5. Conclusion

The motivation for comparing WIMPs, axions, and sterile neutrinos is to better understand the various candidates for dark matter and how each would affect the field of particle physics, astrophysics, and cosmology. By comparing their properties, detection prospects, and theoretical motivations, one can gain insights into the strengths and weaknesses of each candidate and identify which particles might have the most promising potential for future research. This task is particularly relevant in light of the ongoing experimental works to detect dark matter and the lack of definitive evidence for any specific candidate so far.

WIMPs, are hypothesized to have GeV to TeV mass range and interact weakly with ordinary matter. Their main strength lies in their theoretical motivation: they naturally arise in the Standard Model extensions, such as supersymmetry. WIMPs can also provide a relic density that corresponds to the dark matter abundance when they have the right mass and interaction cross-section. Moreover, they are considered cold dark matter, which means that their velocities are non-relativistic during structure formation, consistent with the current understanding of cosmic structure formation. However, WIMPs face some challenges. The lack of direct experimental evidence, despite extensive searches, puts stringent constraints on their properties. Additionally, their theoretical motivation has weakened due to the absence of any clear signs of supersymmetry or other new physics at the LHC.

Axions are light, pseudoscalar particles with masses in the range of micro- to milli-electronvolts. They are well-motivated theoretically as an answer to the strong CP problem, which explains why the strong force does not violate CP symmetry. Axions can also provide the correct dark matter abundance through the misalignment mechanism. In terms of astrophysics, ultra-light axions or fuzzy dark matter can alleviate some of the challenges encountered at small scales in CDM model, such as the cusp-core problem in dwarf galaxies. However, axions have their own challenges. The introduction of axions requires an additional global symmetry, known as the Peccei-Quinn symmetry, which could be broken by quantum gravity effects. Additionally, axions have extremely weak interactions, making their detection challenging and requiring highly sensitive and specialized experimental setups.

Sterile neutrinos are hypothetical particles that do not interact via the weak force, unlike the known active neutrinos. Their main strength is their potential connection to the observed neutrino masses and mixing, as well as to the creation of the matter-antimatter asymmetry through leptogenesis. As warm dark matter candidates, keV-scale sterile neutrinos can also address some of the problems encountered at small scales in CDM model. Sterile neutrinos can also be constrained by a variety of experimental and observational techniques, such as X-ray observations, neutrino oscillation experiments, and large-scale structure formation studies. Nevertheless, sterile neutrinos face challenges in naturally accommodating both neutrino oscillation data and dark matter requirements, as they often require specific mass and mixing parameters. Furthermore, their production mechanisms in the early universe can be complex and model-dependent, making it difficult to pin down their exact properties and abundance.

In conclusion, each dark matter candidate has its own set of strengths and weaknesses. WIMPs offer a strong connection to particle physics and potential new physics, but their experimental detection has proven elusive so far. Axions provide a well-motivated solution to the strong CP problem and have unique astrophysical implications, but their detection requires highly specialized techniques. Sterile neutrinos have a natural connection to neutrino physics and the matter-antimatter asymmetry, but their parameter space is tightly constrained, and their production mechanisms can be complex. Furthermore, given the distinct strengths and weaknesses of each candidate, dark matter could be possibly composed as a combination of WIMPs, axions, and sterile neutrinos. Exploring and discussing mixed dark matter scenarios can provide further insights into the complex nature of dark matter and its role in the universe. The comparison between WIMPs, axions, and sterile neutrinos highlights the unique theoretical motivations, experimental prospects, and astrophysical implications of each dark matter candidate. While no single candidate is definitively favored over the others, our analysis underscores the importance of pursuing a multi-pronged approach to dark matter research, combining experimental efforts and theoretical developments to probe the full range of possible candidates. Understanding the particle nature of dark matter will not only have significant impact on our understanding of the cosmos but will also potentially unveil new physics outside of the Standard Model.

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