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Exploring the Connections Between Neutrinos and Dark Matter

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Abstract. The quest to understand the fundamental constituents of the universe and its evolution has led particle physics and cosmology to confront two profound mysteries: the nature of dark matter (DM) and the properties of neutrinos. Once considered entirely distinct phenomena, a growing body of theoretical and experimental work suggests intriguing potential connections between these elusive particles. This paper synthesizes current research exploring the possible links between neutrinos and dark matter, encompassing theoretical frameworks proposing common origins or interactions, the experimental strategies employed to probe these connections, the significant challenges faced, and the promising avenues for future discovery. This paper summarizes mechanisms such as the neutrino portal, sterile neutrino dark matter, shared symmetry breaking scales, and leptogenesis scenarios. This paper reviews the capabilities and limitations of direct and indirect detection experiments, astrophysical observations, accelerator searches, and cosmological probes in constraining or revealing neutrino-DM interactions. Despite substantial progress, key questions regarding the neutrino mass mechanism, the DM particle identity, and the nature of any potential coupling remain open, driving a vibrant and evolving field poised for potential breakthroughs with next-generation experiments.

Keywords: Dark matter, neutrinos, leptogenesis, Accelerator Experiments

1. Introduction

The universe's composition, as revealed by precision cosmology, presents a stark picture: ordinary matter, the stuff of stars, planets, and life, constitutes a mere ~5% of the total energy density. The dominant components are dark energy (~68%) and dark matter (~27%). While dark energy drives the accelerated expansion of the universe, dark matter provides the gravitational scaffolding necessary for the formation of large-scale structures. Despite its pervasive gravitational influence, dark matter remains undetected in laboratory experiments, its fundamental particle nature a central mystery of modern physics.

Simultaneously, the Standard Model (SM) of particle physics, while spectacularly successful, harbors its own profound puzzles related to neutrinos. Once assumed to be massless, neutrino oscillation experiments have definitively proven that neutrinos have mass, a finding that requires physics beyond the SM. The absolute scale of neutrino masses, their nature (Dirac or Majorana), the

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mechanism generating their minuscule masses, and the origin of leptonic CP violation are major unanswered questions.

The convergence of these two great unknowns – dark matter and neutrino mass – has sparked intense theoretical and experimental interest. .This paper explores the multifaceted research landscape investigating potential connections between neutrinos and dark matter. We will delve into theoretical models that propose shared origins or direct interactions, examine the diverse experimental approaches aimed at hunting for evidence of these links, discuss the significant challenges faced, and outline the promising future directions in this dynamic field.

2. Theoretical association frameworks

Theoretical physicists have developed several compelling frameworks suggesting non-trivial relationships between neutrinos and dark matter, often motivated by the desire to explain both phenomena within a unified structure beyond the SM.

2.1. Common origin mechanisms

Shared Symmetry Breaking Scales: Many beyond-SM theories propose that neutrino masses and the stability (or relic density) of dark matter originate from the same high-energy symmetry breaking event. For instance:In Left-Right Symmetric models, the breaking of the `SU(2)_R` gauge group could simultaneously generate right-handed neutrino masses (via the seesaw mechanism) and provide a dark matter candidate (e.g., a right-handed neutrino itself, or a particle in an extended sector).

Models with gauged `B-L` (Baryon minus Lepton number) symmetry: The breaking of `U(1)_{B-L}` generates Majorana masses for right-handed neutrinos (enabling the Type-I seesaw) and can also confer mass to a potential dark matter candidate associated with this symmetry breaking (e.g., a `Z'` boson remnant or a scalar field).

Leptogenesis and Dark Matter Genesis: The observed matter-antimatter asymmetry (baryogenesis) might be linked to neutrino properties through leptogenesis, in which a lepton asymmetry is generated by CP-violating decays of heavy right-handed neutrinos and later converted to a baryon asymmetry via sphaleron processes. Some models intricately connect this leptogenesis mechanism to the production of dark matter in the early universe. For example: Asymmetric Dark Matter (ADM): Proposes that the dark matter density asymmetry is directly tied to the baryon asymmetry, $\backslash\Omega - DM / \Omega \_ b \sim m - DM / m - p\backslash$. If leptogenesis generates the baryon asymmetry, models can be constructed where the same CP-violating processes or related sectors also generate an asymmetry in a dark sector particle, linking the relic densities of visible and dark matter. Neutrino physics, crucial for leptogenesis, thus becomes indirectly linked to DM genesis.

Freeze-in via Neutrino Portal: Dark matter could be produced feebly through its interactions with neutrinos or Higgs/neutrino couplings in the early universe ("freeze-in" production). The relic abundance is then determined by the strength of this feeble coupling, potentially linking the DM density to neutrino Yukawa couplings or masses.

2.2. Typical theoretical models

Sterile Neutrino Dark Matter: Perhaps the most direct and minimalistic link. Sterile neutrinos (ν_s), which are SM gauge singlets, are a necessary ingredient in the seesaw mechanism for generating light neutrino masses. Certain sterile neutrino species, with specific mass ranges (typically keV-

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scale) and mixing angles with active neutrinos, can be viable Warm Dark Matter (WDM) candidates.Production Mechanisms:Dodelson-Widrow (non-resonant oscillations), Shi-Fuller (resonant production via lepton asymmetries), decay of heavier particles (e.g., inflaton, modulus) [1,2]. Signatures:X-ray line from radiative decay $\nu_s \to \nu_a + \gamma$; suppression of small-scale structure (compared to CDM); potential signals in neutrino experiments (e.g., short-baseline anomalies, though controversial) [3].

Neutrino Portal Dark Matter: This framework utilizes the renormalizable coupling between the Higgs boson (H), left-handed lepton doublet (L), and the right-handed neutrino (N_R) – the $y_\nu H L N_R$ term – as a "portal" connecting the SM to a dark sector.

Mechanism: The dark matter particle (χ, a SM singlet) couples directly to the right-handed neutrino N_R (e.g., via a Yukawa coupling $y_\chi \varphi \chi N_R$, where φ might be a dark scalar). The mixing between N_R and active neutrinos induced by the neutrino Yukawa coupling y_ν then provides a pathway for interactions between DM and the SM, mediated by N_R and/or Higgs bosons. The coupling strength y_ν controls both neutrino mass generation ($m_\nu \sim y_\nu^2 v^2 / M_N$) and the DM-SM interaction rate [4].

DM Candidates:Can be fermionic or scalar, produced via thermal freeze-out (if couplings are sufficiently large) or freeze-in (for very small couplings). Offers rich phenomenology for direct and indirect detection, colliders, and neutrino experiments.

Scotogenic Models:These models ingeniously *unify* the origin of neutrino masses and dark matter. The key feature is that neutrino masses are generated radiatively (e.g., at one-loop level) and are inert, meaning they vanish if the dark matter candidate is absent.

Mechanism: The simplest example (Ma model) extends the SM with a second Higgs doublet (η) and fermionic singlets (N_i). A discrete Z_2 symmetry is imposed, under which η and N_i are odd, while all SM particles are even [5]. The lightest Z_2-odd particle (LZP) is stable and constitutes dark matter (either a neutral scalar from η or the lightest N_i). Neutrino masses arise from loops involving the η Higgs and the N_i. The dark matter stability and the radiative neutrino mass generation are intrinsically linked by the Z_2 symmetry.

Neutrino-DM Scattering in Cosmology: While not necessarily requiring a fundamental particle link, models proposing non-gravitational interactions between neutrinos and dark matter particles can have significant cosmological consequences. These interactions can:Delay the time of neutrino decoupling in the early universe, thereby affecting Big Bang Nucleosynthesis (BBN) predictions.

Suppress the free-streaming of neutrinos, altering the matter power spectrum and potentially helping to resolve small-scale structure tensions (e.g., S_8 tension between CMB and large-scale structure surveys).Impact the cosmic microwave background (CMB) anisotropy spectrum, particularly the amplitude of the early Integrated Sachs-Wolfe (eISW) effect [6].

3. Experimental and observational methods

Probing the theoretical connections between neutrinos and dark matter requires a diverse arsenal of experimental and observational techniques, each sensitive to different potential signatures.

3.1. Direct detection experiments

These experiments aim to detect the rare recoil of atomic nuclei (or electrons) caused by the elastic or inelastic scattering of galactic dark matter particles passing through underground detectors. The connection to neutrinos is twofold:Neutrinos as Background: As direct detection experiments push towards unprecedented sensitivity to detect low-mass DM or weak couplings, they inevitably

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encounter the irreducible background from coherent elastic neutrino-nucleus scattering (CEνNS) of atmospheric and solar neutrinos. This "neutrino fog" presents a fundamental sensitivity limit for WIMP searches, necessitating sophisticated background discrimination techniques or multi-target strategies. Detectors capable of measuring CEνNS (like COHERENT) are crucial for characterizing this background.

Searching for DM-Neutrino Interactions: Specific models (like the neutrino portal or models with light mediators) predict DM particles that can scatter off electrons or nuclei via diagrams involving neutrino states or couplings related to neutrino mass generation. Direct detection experiments can search for these exotic recoil spectra. Furthermore, some models predict DM scattering *off* relic neutrinos (Cosmic Neutrino Background - CνB) within the detector, though this signal is exceptionally challenging to detect.

3.2. Indirect detection and astrophysical observations

These methods search for the products of dark matter annihilation or decay (e.g., gamma rays, neutrinos, positrons, antiprotons) accumulating in astrophysical regions with high DM density.

Sterile Neutrino Decay: The most prominent signature is the search for the monoenergetic X-ray photon (` $E_\gamma = m_{\nu_s} / 2$) from the radiative decay of keV-scale sterile neutrino DM in galaxy clusters, the Milky Way halo, or nearby dwarf spheroidal galaxies. Missions like XMM-Newton, Chandra, NuSTAR, and future X-ray observatories (e.g., Athena, XRISM) are key players. Non-detection places stringent constraints on the mixing angle `θ` for a given `m_ν_s` [7].

Neutrinos from DM Annihilation/Decay:** If DM annihilates or decays into SM particles, it can produce high-energy neutrinos. Experiments including IceCube, ANTARES/KM3NeT, and Super-Kamiokande search for excess neutrinos from the Sun (where DM can be gravitationally captured and annihilated), the Galactic Center, or dwarf galaxies. Models linking DM to neutrino sectors (e.g., via portals, or where DM annihilates directly to neutrinos) can be probed. The challenge lies in distinguishing a potential DM signal from the intense background of atmospheric neutrinos.

Cosmological Probes: Large-scale structure surveys (e.g., DES, Euclid, LSST) and the CMB (Planck, SPT, ACT, future CMB-S4) provide powerful constraints:

Sterile Neutrino WDM: Suppresses small-scale structure formation compared to Cold Dark Matter (CDM). Measurements of the Lyman-α forest and satellite galaxy counts constrain the mass and abundance of thermal-relic WDM, impacting sterile neutrino DM models.

Neutrino-DM Interactions: Such interactions can dampen the free-streaming of neutrinos, affecting the matter power spectrum and CMB anisotropy patterns (especially polarization and the eISW effect). Precise cosmological data can constrain the strength of such interactions [8].

Neutrino Mass Sum:Cosmological observations, particularly from the CMB and BAO, provide the tightest upper bounds on the sum of neutrino masses (` $\Sigma m_\nu < 0.12\,\mathrm{eV}$ ` at 95% CL, Planck+BAO). This bound serves as a crucial input for models linking neutrino masses to DM properties [9].

3.3. Accelerator experiments

Particle colliders like the LHC and dedicated beam experiments search for direct production of particles involved in the neutrino-DM connection.

Searches for Heavy Neutrinos (Sterile Neutrinos): Experiments like ATLAS, CMS, LHCb, NA62, and future projects (FCC, SHiP) search for heavy neutral leptons (HNLs) – sterile neutrinos – produced in decays of mesons, W/Z bosons, or via direct production. Their decay signatures (e.g.,

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displaced vertices, lepton number violation) can probe the mass-mixing parameter space that is relevant to both neutrino mass generation and, potentially, lighter sterile neutrino DM production mechanisms involving heavier parents.

Searches for Dark Sector Particles:Colliders and fixed-target experiments aim to produce dark sector particles (mediators, DM itself) predicted in models like the neutrino portal or scotogenic models. Signatures include missing energy, long-lived particles, or exotic decays involving leptons and missing momentum.

Precision Measurements: Precise measurements of SM processes, particularly involving Higgs boson couplings, electroweak precision observables, and rare decays (e.g., lepton flavor violating decays like ` μ ≫ eγ`), can indirectly probe the existence of new particles (like heavy neutrinos or dark sector states) that contribute via loops in models connecting neutrinos and DM.

4. Key scientific questions and challenges

Despite significant theoretical and experimental efforts, fundamental questions and substantial challenges remain.Firstly,the Nature of Dark Matter: A core question is the identity of the elementary particle that constitutes dark matter, as well as the determination of its mass and interaction strength. Secondly,The Neutrino Mass Mechanism: Explore the process of neutrino mass production(seesaw type, radiative, other).Clearly define the absolute scale and grade.The mechanism has profound implications for possible DM connections (e.g., sterile neutrino type, portal couplings).Third,Experimental Sensitivity and Backgrounds: Reaching the sensitivity required to probe the most theoretically motivated coupling strengths (often very weak, especially for freeze-in DM or sterile neutrinos) is a major technical challenge. The intense neutrino background in direct detection and the astrophysical backgrounds in indirect detection are significant hurdles.Astrophysical and Cosmological Uncertainties: Extracting DM signals from indirect detection requires modeling complex astrophysical environments (galactic diffuse emission, unresolved point sources). Cosmological constraints rely on complex simulations of structure formation and depend on assumptions regarding other cosmological parameters (e.g., `σ_8`, `H_0`).Model Dependence: Predictions for observable signatures are highly model-dependent. A null result in one channel (e.g., X-ray decay lines) does not necessarily rule out a neutrino-DM connection but instead only excludes specific realizations of the model. Disentangling potential signals requires multi-messenger and multi-experiment approaches.The Sterile Neutrino Conundrum: While theoretically attractive, the keV sterile neutrino DM scenario faces increasing pressure. Tight constraints from X-ray telescopes rule out large regions of the parameter space. Cosmological structure formation data strongly favors CDM over WDM, requiring sterile neutrino production mechanisms that yield significantly colder spectra than the standard Dodelson-Widrow mechanism (e.g., resonant production). Reconciling the model with all observational constraints remains challenging [10].

5. Conclusion

The exploration of potential connections between neutrinos and dark matter represents a fascinating and rapidly advancing frontier at the intersection of particle physics, astrophysics, and cosmology. Driven by profound unanswered questions about the fundamental constituents of the universe, theoretical frameworks like the sterile neutrino hypothesis, the neutrino portal, scotogenic models, and leptogenesis-linked scenarios provide concrete pathways linking these two elusive sectors.

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This paper presents a comprehensive literature review of the aforementioned research areas. On the one hand,experimental searches are multifaceted, leveraging direct detection (confronting the neutrino fog), indirect detection (hunting for decay lines and annihilation products), accelerator production (probing heavy neutrinos and dark sectors), and cosmological/astrophysical observations (constraining masses, interactions, and structure formation). On the other hand, while no definitive evidence establishing a direct neutrino-DM link has been identified to date, the interplay between theory and experiment has yielded valuable constraints, ruled out specific model parameter spaces, and deepened our understanding of both neutrinos and dark matter individually.

Significant challenges persist, primarily stemming from the inherent elusiveness of the particles involved, the complexity of astrophysical backgrounds, cosmological modeling uncertainties, and the weak nature of any potential interactions. The keV sterile neutrino DM scenario, while elegant, faces mounting observational pressure.

The outlook, however, is exceptionally promising. A new generation of experiments and observatories – featuring unprecedented scale, sensitivity, and technological sophistication – is coming online or in advanced planning stages across all detection methods. The continued synergy between theoretical innovation and these experimental advances holds the potential for transformative discoveries. Whether the connection manifests as a sterile neutrino WDM candidate, a feebly interacting particle revealed through the neutrino portal, a scotogenic partner, the ongoing quest is well-positioned to shed light on not only the nature of dark matter and the origin of neutrino mass but also the fundamental laws governing the universe at its most profound levels. The intricate dance between neutrinos and dark matter remains a central theme in our journey to decode the cosmos.

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