Phenomenology of a Neutrino-DM Coupling: The Scalar Case

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Dark matter (DM) and neutrinos are the two most compelling pieces of evidence of new physics beyond the Standard Model of Particle Physics but these are often treated as belonging to two different sectors. Yet DM-neutrino interactions are known to have cosmological consequences. Here, we study the scenario of a scalar DM candidate coupled to left-handed neutrinos via a Dirac mediator. We determine the mass of a DM candidate that yields the right DM relic abundance in a thermal scenario and it is consistent with large-scale structure formation. In order to satisfy both constraints, a complex DM candidate should have a mass larger than 8.14 keV while the mass of a real DM candidate should be above 18.1 eV, independently of the value of the DM-neutrino coupling.

PRESENTED AT

NuPhys2016, Prospects in Neutrino Physics
Barbican Centre, London, UK, December 12–14, 2016

* Poster presented at NuPhys2016. This work has been supported by the European Research Council under ERC Grant NuMass (FP7-IDEAS-ERC ERC-CG 617143).
1 Introduction

The discovery of neutrino masses together with the presence of dark matter (DM) strongly suggest the existence of new physics beyond the Standard Model of Particle Physics. Consequently, models were proposed to explain both phenomena (and in particular the relic density and neutrino masses) in a minimalistic way [1]. Such attempts generally consider a DM-neutrino interaction term which can lead to a rich phenomenology in the Early Universe. Furthermore, such interactions introduce the possibility of detecting neutrinos that are produced from DM self-annihilation at neutrino detectors on Earth [2]. So far only a limited number of models have been considered in the literature for dark matter-neutrino interactions [3]. However, given that DM particles have not been found yet and that the mechanism by which neutrinos acquire a mass remains unsettled, it is worth investigating a larger number of scenarios and examine whether they are compatible with known constraints.

In this paper, we will consider the scenario of a scalar DM candidate coupled to left-handed neutrinos via a Dirac fermion* so that:

\[ \mathcal{L}_{\text{int}} \supset -g \chi \overline{N}_R \nu_L + \text{h.c.}, \]

(1)

where \( N \) is the Dirac mediator and \( \chi \) the DM candidate. Such coupling can arise by introducing a Dirac SU(2) doublet like in supersymmetric models [3]. If on the other hand, \( N \) is a singlet, the coupling can be generated in Inert Doublet models where the scalar \( \chi \) belongs to an SU(2) doublet. Since the aim of this paper is to study the cosmological implications of the coupling \( g \), we take the DM and mediator masses as free parameters and we don’t discuss any model specific bounds.

The paper is structured as follows: In the next section we will briefly review the different experimental signatures considered to test our scenario and we will discuss the results in Section 3. Finally, we will conclude in Section 4.

2 Cosmological signatures

A DM-neutrino interaction induces processes such as the annihilation of DM to neutrinos and the elastic scattering between neutrinos and DM particles. If this is the dominant annihilation channel for thermal freeze-out, the thermally averaged annihilation cross section of DM to neutrinos will set the amount of DM that we observe today (i.e. the relic density), for which \( \langle \sigma v \rangle_{\text{Th}} \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \) is required. As we impose the DM candidate’s relic density to be smaller or equal to the observed

* This is done as a proof of concept and we leave the full discussion of all possible scenarios consistent with Lorentz invariance where a DM candidate can interact with neutrinos to a future paper that will be released shortly.
abundance, $\Omega_{DM}h^2 = 0.1188$ [4], we obtain a lower bound on the strength of the DM-neutrino interaction.

It has also been shown that the elastic scattering between neutrinos and DM can lead to a suppression of small-scale structures in the Universe (known as collisional damping) [5], since it allows for DM to be in equilibrium with neutrinos even after chemical decoupling. Therefore, the DM takes longer to free-stream and could lead to a further suppression of such structures. By confronting the large-scale structure predictions to observations, the relevant constraint for the scenario considered is [5]

$$\sigma_{el} < 10^{-48} \left( \frac{m_{DM}}{\text{MeV}} \right) \left( \frac{T_0}{2.35 \times 10^{-4} \text{ eV}} \right)^2 \text{cm}^2, \quad (2)$$

for an energy dependent cross section, with $T_0$ the neutrino temperature today.

Finally, in the presence of DM-neutrino interactions, one can search for a flux of neutrinos and anti-neutrinos produced from DM annihilation at rest in regions with a high DM density like the Milky Way. Such a flux would be monochromatic since each neutrino will carry an energy equal to the DM mass and could be detected at neutrino detectors on Earth. For this scenario, the relevant constraints in the total annihilation cross section of DM to neutrinos can be set using the Super-Kamiokande (SK) Phase I data from the supernova relic neutrino search following the analysis done in [2]. Nevertheless, the results including SK Phases I-III are expected to be similar [6].

### 3 Results

We compute the thermal annihilation cross section to left-handed neutrinos and the elastic scattering cross section between DM and left-handed neutrinos in the limit $m_\nu \rightarrow 0$, which is summarized in Table 1. Fig. 1 shows the allowed parameter space considering the relevant constraints. The colored contours correspond to different values for the elastic scattering cross section. It is worth noting that, for the scalar to be a viable DM candidate, $m_N > m_{DM}$ so that the DM remains stable. Consequently, the parameter space below the diagonal in Fig. 1 is excluded.

|                      | Complex DM                  | Real DM                     |
|----------------------|-----------------------------|-----------------------------|
| $\langle \sigma v \rangle \propto$ | $g^4 v^2_{CM} \frac{m_{DM}^2}{(m_{DM}^2 + m_N^2)^2}$ | $g^4 v^4_{CM} \frac{m_N^6}{(m_{DM}^2 + m_N^2)^4}$ |
| $\sigma_{el} \propto$      | $g^4 E_\nu^2 \frac{1}{(m_{DM}^2 - m_N^2)^2}$     | $g^4 E_\nu^4 \frac{m_{DM}^2}{(m_{DM}^2 - m_N^2)^4}$ |

Table 1: Relevant terms of the expressions for the annihilation and the elastic scattering cross sections for a complex and a real DM candidate when $m_{DM} \neq m_N$. 


Figure 1: Relevant parameter space in the $m_N - m_{DM}$ plane with $g = 1$ for complex DM (left) and real DM (right). The light red and orange regions correspond to DM overproduction and the 90% C.L. bound from the SK search using $v_{CM} = \frac{1}{3}$ c and $v_{CM} = 10^{-3}$ c respectively. The dashed area represents the excluded region from collisional damping while the brown vertical line refers to the lower bound from Planck effective number of neutrino species measurement. The red star is the point from which both the relic density and the collisional damping constraints are satisfied.

The cross sections for real DM are more suppressed due to the $v_{CM}^4$ and $E_{\nu}^4$ dependence, which in turn translates into weaker bounds as can be seen in Fig. 1. However, in the degenerate regime (i.e. $m_{DM} \sim m_N$) $\sigma_{el} \propto g^4/m_{DM}^2$ which shows as an enhancement of the elastic cross section along the diagonal in Fig. 1. Moreover, the p and d-wave dependence of the annihilation cross section implies that $\langle \sigma v \rangle$ today is very small since $v_{CM} \sim 10^{-3}$ c today. Consequently, neutrino detectors do not provide any bounds for large DM masses and the constraints from the SK analysis only apply to the complex DM scenario as it is less suppressed.

As can be seen from Table 1, the coupling $g$ enters with the same power in the annihilation and elastic scattering cross sections. Hence, we can impose $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ to get a coupling independent expression for the elastic scattering, which can be compared to the collisional damping constraint in Eq. 2:

$$\sigma_{el} \simeq 5.41 \times 10^{-55} \left( \frac{T_0}{2.35 \times 10^{-4} \text{ eV}} \right)^2 \left( \frac{m_{DM}}{\text{MeV}} \right)^{-2} \left( \frac{\langle \sigma v \rangle}{3 \times 10^{-26} \text{ cm}^3/\text{s}} \right) \text{ cm}^2, \quad (3)$$

for complex DM when $m_N > m_{DM}$ and

$$\sigma_{el} \simeq 1.96 \times 10^{-72} \left( \frac{T_0}{2.35 \times 10^{-4} \text{ eV}} \right)^4 \left( \frac{m_{DM}}{\text{MeV}} \right)^{-4} \left( \frac{\langle \sigma v \rangle}{3 \times 10^{-26} \text{ cm}^3/\text{s}} \right) \text{ cm}^2, \quad (4)$$

for real DM when $m_N > m_{DM}$, where we have assumed $E_{\nu} \sim T_0$ today. Therefore, if we want to satisfy the collisional damping and relic density constraints in the limit...
$m_N > m_{DM}$, we require DM masses larger than 8.14 keV (18.1 eV) and mediator masses larger than 87.7 MeV (6.97 keV) for complex (real) DM for any coupling $g$ (red star in Fig. 1). Nevertheless, it has been shown that the effective number of neutrino species when DM is in thermal equilibrium with neutrinos is only consistent with Planck measurements for $m_{DM} \gtrsim 10$ MeV for both scenarios [7]. This corresponds to $m_N \gtrsim 3.55$ GeV for complex DM and $m_N \gtrsim 0.14$ GeV for real DM and imposes stronger bounds than the collisional damping constraint.

This analysis shows that there are subtleties when analyzing the different scenarios that can lead to a very distinct phenomenology. This is also the case when, for example, one considers a Majorana mediator instead of a Dirac mediator since this could produce Lepton Number Violating processes such as $\chi \chi \rightarrow \nu_L \nu_L$.

4 Conclusion

The study of neutrino-DM interactions is a powerful tool to constraint the masses of the DM and its mediator since it provides a variety of cosmological observables to contrast with the theoretical predictions. Furthermore, the complementarity of such observables with model-specific predictions allows us to understand better what the nature of the DM particle could be. Here we have only discussed the scenario of scalar DM coupled to neutrinos via a Dirac mediator, but a full study of all the possible scenarios will help us to determine the allowed values of the parameter space for DM candidates and mediators of different spins.

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