NEUTRINO PORTAL DARK MATTER*

V. González Macías, J. Wudka

Department of Physics and Astronomy, UC Riverside
Riverside, CA 92521-0413, USA

J.I. Illana

CAFPE and Depto. de Física Teórica y del Cosmos, Universidad de Granada
18071 Campus de Fuentenueva, Granada, Spain

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A simple model for dark matter is presented where the main interactions with the Standard Model involve neutrinos.

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1. Dark matter paradigm

Dark matter (DM) provides the best current hypothesis for explaining the rotation curves of galaxies, the high galaxy velocities within clusters, the strength of the gravitational lensing effects of galaxy clusters, and the fluctuation spectrum in the cosmic background radiation. DM would then constitute about 23% of the mass-energy density of the universe, while dark energy comprises about 73%, with ordinary matter accounting for the remaining 4% [1].

In order to meet the requirements that DM *(i)* is stable; *(ii)* interacts weakly with the Standard Model (SM); and *(iii)* is dark, we assume that all particles in the dark sector transform non-trivially under a symmetry group $\mathcal{G}_{\rm DM}$ (whose nature we will not have to specify); that DM–SM interactions are generated by the exchange of heavy mediators that are neutral under $\mathcal{G}_{\rm DM}$ and $\mathcal{G}_{\rm SM}$, the local symmetry of the SM; and that all particles in the dark sector are invariant under $\mathcal{G}_{\rm SM}$, and all SM particles are assumed to be $\mathcal{G}_{\rm DM}$-invariant. In addition, we will assume that the mediators are weakly coupled.

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2. Effective theory of DM–SM interactions

Within the paradigm presented, these interactions are of the form of [2]

$$\mathcal{L}_{\rm eff} \sim \frac{1}{\varLambda^k}\mathcal{O}_{\rm SM} \times \mathcal{O}_{\rm DM}\,, \tag{1}$$

where $\mathcal{O}_{\rm DM,SM}$ are invariant under $\mathcal{G}_{\rm SM}$ and $\mathcal{G}_{\rm DM}$ (but need not be Lorentz scalars), and $\varLambda$ is a typical mediator mass. The leading interactions are then generated by the lowest-dimensional operator combinations (lowest value of k) which are tree-level generated (no loop-suppression factor [3]). Note that this last property is dependent on the mediator type.

Assuming a generic dark sector containing scalars $\varPhi$, fermions $\varPsi$ and vectors X, the leading interactions of dimension ≤ 6 that are generated at ≤ 1 loops by fermion or scalar mediators are:

Dim.	Category	
4	I	$\lvert\phi\rvert^2\left(\varPhi^\dagger\varPhi\right)$
5	II	$\lvert\phi\rvert^2\bar\varPsi\varPsi$
	III	$\left(\bar\varPsi\varPhi\right)\left(\phi^T\epsilon\ell\right)$
6	V	$\lvert\phi\rvert^2\bar\varPsi\varPhi\varPsi'\,,\quad \lvert\phi\rvert^2X^2_{\mu\nu}\,,\quad \varPhi^2\bar\psi\varphi\psi'\,,\quad \varPhi^2B^2_{\mu\nu}\,,\quad \varPhi^2\left(W^I_{\mu\nu}\right)^2$
	VII	$J^{(i)}_{\rm SM}\cdot J^{(a)}_{\rm dark}\quad (i=\ell,\phi;\; a=\varPhi,{\rm L},{\rm R})$

where ϕ is the SM scalar isodoublet, ℓ a SM left-handed fermion isodoublet, B the ${\rm U}(1)_Y$ gauge field, $\mathcal{O}^{(4)}_{\rm SM,DM}$ dimension 4 operators whose effects are subdominant and whose specific forms will not be needed, and

$$\begin{aligned} J^{(\psi)\,\mu}_{\rm SM} &= \bar\psi\gamma^\mu\psi\,, & J^{(\phi)\,\mu}_{\rm SM} &= \frac{1}{2i}\phi^\dagger \overset{\leftrightarrow}{D^\mu}\,\phi\,,\\ J^{({\rm L,R})\,\mu}_{\rm dark} &= \bar\varPsi\gamma^\mu P_{\rm L,R}\varPsi\,, & J^{(\varPhi)\,\mu}_{\rm dark} &= \frac{1}{2i}\varPhi^\dagger \overset{\leftrightarrow}{\mathcal{D}^\mu}\,\varPhi\,. \end{aligned} \tag{2}$$

Note that $J^{(\phi)}$ contains a term proportional to the Z vector boson.

The operator in category I generates the well-known Higgs portal interaction, while the one in category III generates a neutrino portal coupling that we will discuss in some detail below.

3. Effective Lagrangian for the neutrino portal scenario

We assume a dark sector that contains at least one fermion and one scalar which transform in the same way under $\mathcal{G}_{\rm DM}$. We also assume that all mediators are Dirac fermions we denote by $\mathcal{F}$. In this case, the effective

Lagrangian takes the form $c_{\rm I}|\phi|^2|\Phi|^2 + \mathcal{L}^{(\mathcal{F}-{\rm tree})} + \mathcal{L}^{({\rm loop})}$, and is obtained by integrating all modes whose scale is of the order of the mediator mass Λ or higher. These modes include the $\mathcal{F}$ whose exchange generate $\mathcal{L}^{(\mathcal{F}-{\rm tree})}$ at tree-level, as well as the high frequency SM and DM field components that generate $\mathcal{L}^{({\rm loop})}$ (and can also get contributions from loops involving the $\mathcal{F}$):

$$\begin{aligned}\mathcal{L}^{(\mathcal{F}-{\rm tree})} &= \frac{c_{\rm III}}{\Lambda}\left(\bar\Psi\Phi\right)\left(\tilde\phi^\dagger\ell\right) + \ldots\,,\\ \mathcal{L}^{(\mathcal{F}-{\rm loop})} &= \frac{c_{\rm II}}{16\pi^2\Lambda}|\phi|^2\bar\Psi\Psi + \sum_{a=\ell,\phi;\, i=L,R,\Phi}\frac{c_{\rm VII}^{(a|i)}}{(4\pi\Lambda)^2}J_{\rm SM}^{(a)}\cdot J_{\rm dark}^{(i)} + \ldots\,,\end{aligned} \tag{3}$$

where we ignored terms in category V since their effects are subdominant. The term $\propto c_{\rm III}$ determines the relic abundance and indirect detection cross section for the DM. The terms $\propto c_{\rm II}$, $c_{\rm VII}$ determine the direct detection cross section, and also contribute to the relic abundance when the DM mass is $\sim M_H/2$ or $\sim M_Z/2$.

In the following, we will assume that $m_\Phi > m_\Psi$. Then, the neutrino portal coupling $(\bar\ell\tilde\phi)(\Phi^\dagger\Psi) \supset (v/\sqrt{2})\bar\nu_{\rm L}\Phi^\dagger\Psi$ implies that the Φ will promptly decay to the Ψ: this is a model of fermionic DM. In contrast, if $m_\Phi < m_\Psi$, the scalars constitute the DM and the model reduces to the Higgs-portal scenario.

4. Constraints on the model

Relic abundance. The DM relic abundance is obtained in the standard way. The relevant processes are listed in figure 1.

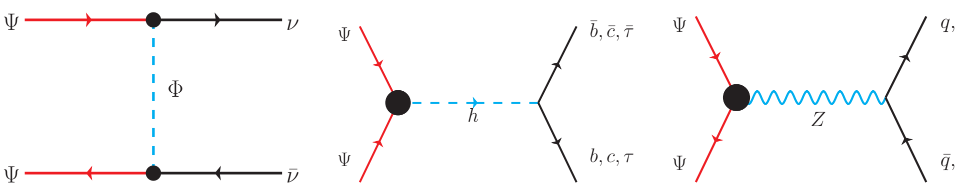

Fig. 1. Processes responsible for generating the DM relic abundance. The heavy dots denote loop-generated interactions so that the corresponding graphs are important only in the resonance regions $m_\Psi \sim M_H/2$, $M_Z/2$.

The constraint derived from the PLANCK data, $\Omega_{\rm DM}h^2 = 0.1198 \pm 0.0036$ (3σ) [4] generates one constraint on the model parameters, as illustrated in figure 2. Outside the resonance regions $(m_\Psi \sim M_H/2,\ M_Z/2)$

$$\Lambda_{\rm eff} = \sqrt{1+\frac{m_\Pi^2}{m_\Psi^2}}\frac{\Lambda}{c_{\rm III}} \simeq \sqrt{\frac{m_\Omega}{m_\Psi}}\ {\rm TeV}\,;\quad m_\Omega \simeq 74\ {\rm GeV}\quad (\text{non-resonant region})\,. \tag{4}$$

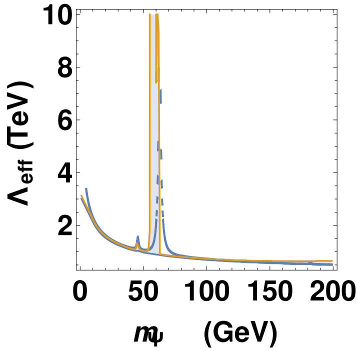

Fig. 2. Relic abundance constraints; $\Lambda_{\rm eff}$ is defined in (4).

Direct detection. Direct detection cross section is obtained from the terms $\propto c_{\rm II,\,VII}$ in (3)

$$\mathcal{L}^{(\mathcal{F}-\rm loop)} \supset \frac{v c_{\rm II}}{16\pi^2 \Lambda} H \bar{\Psi}\Psi - \frac{g}{2c_{\rm w}} \frac{v^2}{16\pi^2\Lambda^2} \bar{\Psi} \not{Z} \left(c_{\rm VII}^{(\phi|L)} P_L + c_{\rm VII}^{(\phi|R)} P_R \right) \Psi \qquad (5)$$

which are loop generated and so naturally suppressed. The resulting constraint generated by data from the LUX [5] and ATLAS experiment (see [2] for details) is given in figure 3.

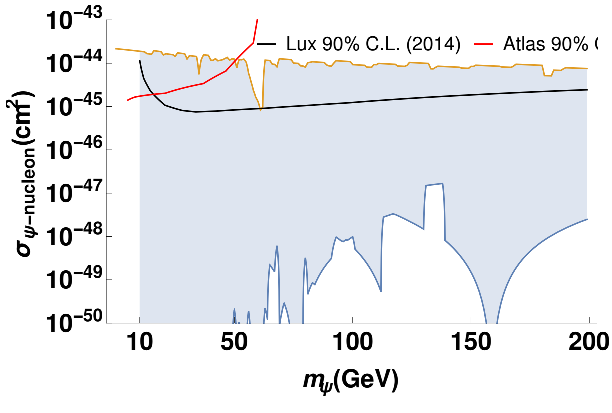

Fig. 3. Direct detection constraint on the model; shaded area below the lower line corresponds to points in parameter space allowed by the LUX and ATLAS constraints and consistent with the relic abundance.

Indirect detection. The main annihilation channel for our model for DM is $\Psi\Psi \to \nu\nu$, corresponding to a monochromatic neutrino line at the energy of $m_\Psi/2$. The $\gamma\gamma$ signal (at the same energy) is very suppressed, so that no significant restrictions are generated by current data [2].

5. UV completion

Generating a model that explicitly contains the mediators $\mathcal{F}$ is straightforward. The simplest Lagrangian is

$$\begin{aligned}\mathcal{L} \;=\; & \bar{\ell} i \not{D} \ell + \bar{\Psi}\left(i\not{\partial} - m_\Psi\right)\Psi + \bar{\mathcal{F}}\left(i\not{\partial} - M\right)\mathcal{F} + |\partial\Phi|^2 - m_\Phi^2|\Phi|^2 \\ & + \left(\bar{\ell}Y^{(e)}e\phi + \bar{\ell}Y^{(\nu)}\mathcal{F}\tilde{\phi} + \bar{\Psi}\tilde{z}\mathcal{F}\Phi + \text{H.c.}\right)\end{aligned} \tag{6}$$

which conserves the lepton number. The Yukawa couplings $Y^{(\nu)}$ will not generate masses for the SM neutrinos despite the labelling (see below).

After spontaneous symmetry breaking, the neutral fermion sector mass eigenstates consist of heavy fields N with mass $O(M)$ and massless left-handed fields n_L that play the role of the SM neutrinos. The $\mathcal{F}$–ν sector of the model is the same as the one used in the inverse seesaw mechanism [6] for neutrino mass generation in the absence of a Majorana mass. If a small Majorana mass is added, $-\mathcal{F}^T C\tilde{\mathcal{M}}\mathcal{F} + \text{H.c.}$, it generates a small mass for the n_L, $\epsilon^T\tilde{\mathcal{M}}\epsilon$ (for $|\epsilon| \ll 1$).

The effective Lagrangian coefficients can then be derived. For the simple case of a single mediator of mass $M = \Lambda$, we find

$$c_\mathrm{III} = \frac{\sqrt{2}\,\mu z}{v}\,, \qquad c_\mathrm{II} = -\left[c_\mathrm{III}^2 + 2z^2 c_\mathrm{I}\ln\left(\frac{\Lambda}{m_\Phi}\right)\right]. \tag{7}$$

In addition, the $\mathcal{F}$–ν mixing modifies the couplings to the Higgs and gauge bosons. The most significant constraints come from the n_L couplings to the Z

$$-\frac{g}{2c_\mathrm{W}}\bar{n}_\mathrm{L}\left(\mathbb{1} - \delta^2\right)\not{Z} n_\mathrm{L} \qquad \delta^2 = \frac{\boldsymbol{\mu}M^{-2}\boldsymbol{\mu}}{\mathbb{1} + \boldsymbol{\mu}M^{-2}\boldsymbol{\mu}}\,. \tag{8}$$

The limits on the deviations from the SM in invisible decay of the Z, then imply

$$\frac{\Delta\Gamma(Z \to \text{inv})}{\Gamma(Z \to \text{inv})} = \frac{2}{3}\mathrm{tr}\delta^2 < 0.009 \quad (3\sigma) \quad \Rightarrow \quad \delta_{e,\mu,\tau} < 0.014 \quad (3\sigma) \tag{9}$$

that (roughly) implies $\Lambda > 10Y^{(\nu)}$ TeV. Limits from τ and pion decays (generated from deviations in the W couplings) are somewhat weaker.

Since the relic abundance cross section is $\propto \sum\delta_i^2$, there is some tension between (9) and the relic abundance constraint. Preliminary results indicate that the regions $35\,\text{GeV} < m_\Psi < 60$ GeV and $m_\Psi > 65$ GeV are excluded.

6. Conclusions

The neutrino portal scenario works well for relatively light DM masses (below 35 GeV) and in the Higgs resonant region, but it is difficult to confirm. The clearest signature is a monochromatic neutrino line. Collider constraints are derived mainly from the Z and H invisible widths. There are other promising aspects of this approach to DM. For example, there is a clear possibility of having DM-assisted lepton number violation, allowing for a realistic leptogenesis scenario; we are currently working on this aspect of the model.

In closing, it is worth noting that there are other potentially interesting interactions between the dark and SM sectors that might be worth exploring.

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