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Indirect Detection Signatures of Dark Matter Annihilation/Decay to Right-Handed Neutrinos

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Abstract. Very much so.

Contents

1 Overview

Right handed neutrinos (RHN), also referred to as sterile neutrinos or heavy neutral leptons, are one of the most well-motivated extensions to the Standard Model, featuring in many models of neutrino mass generation. In such models, RHNs are often part of an extended sector that also contains dark matter. Such frameworks have been extensively studied in the literature under the broad umbrella of neutrino portal dark matter [1–9], where the RHNs act as the portal connecting dark matter to the visible sector.

If sterile neutrinos are heavier, dark matter annihilates or decays directly to SM neutrinos via the mixing between the sterile and active neutrinos (see e.g. [1, 9]). On the other hand, if dark matter is heavier than the RHNs, dark matter annihilates or decays exclusively to RHNs, and subsequent decays of the RHNs into SM particles then give rise to visible signals. Such signals have been employed in the past to explain various putative dark matter signals such as the Galactic Center excess [10] and high energy neutrinos at IceCube [11]. Such signals are fairly insensitive to the exact nature of the underlying model, since dark matter annihilations (or decays) produce an isotropic distribution of RHNs with energy m_{DM}(or $m_{DM}/2$). The decay lifetimes of the RHNs are constrained by the seesaw mechanism and can generally be considered prompt on astrophysical scales (exceptional cases occur when considering dark matter annihilation/decay in the sun [12], or RHNs with extremely long lifetimes [13]). Therefore, the spectra of visible signals (in photons, neutrinos, charged leptons, antiprotons) are essentially determined by only two parameters: the dark matter mass m_{DM} and the right handed neutrino mass m_N. The goal of our paper is to perform an extensive study of such signals in terms of these parameters. Indirect detection signals of dark matter annihilation into right handed neutrinos have been studied for specific cases: for $m_N = 1 - 5$ GeV in [12], and for $m_N = 10 - 1000$ GeV in [14].

2 Framework

Effective operator between dark matter X and RHNs N facilitate either annihilations or decays. N couples to the SM via Dirac mass term LHN. Everything follows from this.

Describe how we compute the N branching ratios.

We consider a theory with a single Majorana RH neutrino which couples to the SM via a Yukawa interaction. In general, the terms in the Lagrangian density containing the RH neutrino will be:

$$\mathcal{L} \supset i\hat{\bar{\nu}}^\dagger \bar{\sigma}_\mu \partial^\mu \hat{\bar{\nu}} - \frac{1}{2}\hat{m}_{\hat{\bar{\nu}}}\left(\hat{\bar{\nu}}\hat{\bar{\nu}} + \hat{\bar{\nu}}^\dagger\hat{\bar{\nu}}^\dagger\right) + \epsilon^{ab}Y_\nu^i \Phi_a L_{bi}\hat{\bar{\nu}} - \tag{2.1}$$

Here, Φ_a is the Higgs doublet, L_{bi} is the lepton doublet for the ith generation (assumed to be such that the charged lepton mass matrix is diagonal), and $\hat{\bar{\nu}}$ is the RH neutrino represented as a two-component Majorana spinor. The vector Y_ν^i is a Yukawa vector coupling the ith lepton doublet to the RH neutrino. Expanding the Higgs around its vacuum expectation value, the neutrino mass terms are:

$$\mathcal{L}_{\text{mass},\nu} \supset -\frac{1}{2}\hat{m}_{\hat{\bar{\nu}}}\left(\hat{\bar{\nu}}\hat{\bar{\nu}} + \hat{\bar{\nu}}^\dagger\hat{\bar{\nu}}^\dagger\right) - \frac{v}{\sqrt{2}}Y_\nu^i\hat{\nu}_i\hat{\bar{\nu}} = -\frac{1}{2}\mathcal{N}^T\begin{pmatrix}\mathbf{0}_{3\times 3} & \frac{v}{\sqrt{2}}Y_\nu \\ \frac{v}{\sqrt{2}}Y_\nu^T & \hat{m}_{\hat{\bar{\nu}}}\end{pmatrix}\mathcal{N} \tag{2.2}$$

Here $\mathcal{N} = \begin{pmatrix}\hat{\nu}_1 & \hat{\nu}_3 & \hat{\nu}_3 & \hat{\bar{\nu}}\end{pmatrix}^T$ is a vector composed of all neutrinos. For simplicity, we will assume that only a single entry of Y_ν is non-zero. We set $Y_{\hat{\nu}}^k = y$ and $Y_{\hat{\nu}}^i = 0$ for $i \neq k$. In this case, we may remove the active neutrinos $\hat{\nu}_i$ for $i \neq k$ from mass matrix and take them to be mass eigenstates. Then, our neutrino mass terms reduce to

$$\mathcal{L}_{\text{mass},\nu} \supset= -\frac{1}{2}\begin{pmatrix}\hat{\nu}_k & \hat{\bar{\nu}}\end{pmatrix}\underbrace{\begin{pmatrix}0 & \frac{v}{\sqrt{2}}y \\ \frac{v}{\sqrt{2}}y & \hat{m}_{\hat{\bar{\nu}}}\end{pmatrix}}_{M_\nu}\begin{pmatrix}\hat{\nu}_k \\ \hat{\bar{\nu}}\end{pmatrix} \tag{2.3}$$

The neutrino mass matrix can be diagonalized using Takagi diagonalization via a unitary matrix Ω where $\Omega^T M_\nu \Omega = \text{diag}(m_\nu^k, m_{\bar{\nu}})$. The explicit form of Ω is:

$$\Omega = \begin{pmatrix}-i\cos\theta & \sin\theta \\ i\sin\theta & \cos\theta\end{pmatrix} \tag{2.4}$$

The parameters $y, \hat{m}_{\hat{\bar{\nu}}}$ are related to $m_{\bar{\nu}}$ and θ via:

$$y = \frac{\sqrt{2}m_{\bar{\nu}}\tan\theta}{v}, \qquad \hat{m}_{\hat{\bar{\nu}}} = m_{\bar{\nu}}\left(1 - \tan^2\theta\right). \tag{2.5}$$

In addition, the left-handed neutrino mass is $m_\nu^k = m_{\bar{\nu}}\tan^2\theta$. To obtain the interactions between the RH neutrino and SM particles, we use $\hat{\bar{\nu}} = -i\cos\theta\nu_k + \sin\theta\bar{\nu}$, where the unhatted fields ν_k and $\bar{\nu}$ are mass eigenstates.

From the Yukawa interaction given above, we find that the RH neutrino interacts with the Higgs and Goldstones via:

$$\mathcal{L} \supset G^+ \tag{2.6}$$

3 Results

We can start collecting plots here.

Acknowledgments

This is the most common positions for acknowledgments. A macro is available to maintain the same layout and spelling of the heading.

A More Info

As needed

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