Two Component FIMP DM in a $U(1)_{B-L}$ Extension of the SM

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Abstract

In this work, we discuss two component fermionic FIMP dark matter (DM) in a popular $B-L$ extension of the standard model (SM) with inverse seesaw mechanism. Due to the introduced $\mathbb{Z}_2$ discrete symmetry, a keV SM gauge singlet fermion is stable and can be a warm DM candidate. Also, this $\mathbb{Z}_2$ symmetry helps the lightest right-handed neutrino, with mass of order GeV, to be a long-lived or stable particle by choosing a corresponding Yukawa coupling to be very small. Firstly, in the absence of a GeV DM component (i.e., without tuning its corresponding Yukawa coupling), we consider only a keV DM as a single component DM produced by the freeze-in mechanism. Secondly, we study a two component FIMP DM scenario and emphasize that the correct ballpark DM relic density bound can be achieved for a wide parameter space.

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1. INTRODUCTION

The standard model (SM) is a very successful theory in describing nature. But it can not explain a number of phenomena - two of the most important ones being the presence of dark matter (DM) and non-zero tiny neutrino mass. To address these two issues, we need to extend the SM particle content and/or its gauge group. The non-thermal DM production via the so-called freeze-in mechanism [1] provides a simple alternative to the standard thermal WIMP scenario. In the freeze-in mechanism, the DM is very feebly interacting with the cosmic soup, and as a result never attains thermal equilibrium in the early universe. Hence it is named Feebly Interacting Massive Particles (FIMPs). Due to their very feeble interactions, FIMPs easily escape the direct/indirect detection bounds while satisfying the measured value for the DM relic density (RD). In the present work based on [2], we explain the above two puzzles by extending the SM gauge group by a $U(1)_{B-L}$ gauge symmetry as a simple extension of the SM.

2. TEV SCALE $B-L$ EXTENSION OF THE SM WITH INVERSE SEESAW (BLSMIS):

The $B-L$ extension of the SM is based on the gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}.$$

In this model, nine additional SM singlet fermions (N_R^i and $S_{1,2}^i$, $i = 1,2,3$) are needed to explain the naturally small neutrino masses through the inverse seesaw mechanism [3, 4, 5]. In addition, an extra neutral gauge boson Z' associated to $U(1)_{B-L}$ and an extra SM singlet scalar, ϕ_H, are introduced. The full Lagrangian is given by

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + (D^\mu\phi_H)^\dagger D_\mu\phi_H + \frac{i}{2}\bar{N}_R\gamma^\mu D_\mu N_R \\ &+ \frac{i}{2}\bar{S}_1\gamma^\mu D_\mu S_1 + \frac{i}{2}\bar{S}_2\gamma^\mu D_\mu S_2 - \mathcal{V}(\phi_h,\phi_H) \\ &- (Y_\nu \bar{L}\tilde{\phi}_h N_R + Y_S \bar{N}_R^c \phi_H S_2 + h.c.),\end{aligned}$$

where where $F'_{\mu\nu}$ is the $U(1)_{B-L}$ field strength, D_μ is the covariant derivative, $\tilde{\phi}_h = i\sigma_2\phi_h$ and $\mathcal{V}(\phi_h,\phi_H)$ is the potential (for more details, see [5]). After the $B-L$ and electroweak symmetries breaking and the SM Higgs doublet ϕ_h and the SM singlet ϕ_H take their vacuum expectation values (vevs), v and v', respectively, the mass matrix of the neutrinos is given by

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & 0 & 0 \\ M_D^T & 0 & M_N & 0 \\ 0 & M_N^T & \mu_S & 0 \\ 0 & 0 & 0 & \mu_S \end{pmatrix},$$

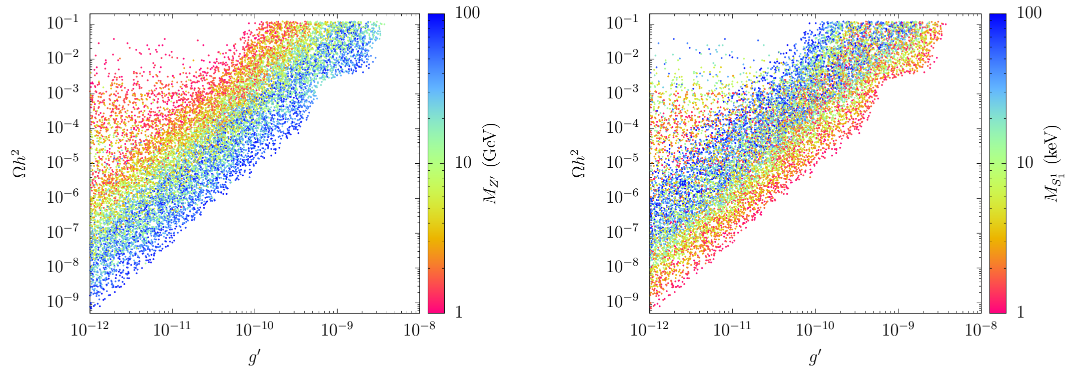

FIGURE 1: Allowed points in $(g', \Omega h^2)$ plane after imposing a constraint $\Omega h^2 \leq 0.12$, as an upper bound on the WDM RD, Ωh^2.

where $M_D = \frac{1}{\sqrt{2}} Y_\nu v$ and $M_N = \frac{1}{\sqrt{2}} Y_S v'$. Due to the added $\mathbb{Z}_2$ symmetry, S_1 is completely decoupled and it only interacts with Z' with a coupling g'. Thus its mass is given as,

$$M_{S_1} = \mu_S \, . \tag{1}$$

Also, the light and heavy neutrino masses, respectively, are given by

$$M_{\nu_l} \simeq M_D M_N^{-1} \mu_S (M_N^T)^{-1} M_D^T, \; M_{\nu_{H,H'}} \simeq M_N. \tag{2}$$

One can naturally obtain the light neutrino masses M_{ν_l} to be of order eV with μ_S of order keV and M_N of order TeV, keeping Yukawa coupling Y_ν of order one which leads to interesting signatures at the large hadron collider (LHC) [6]. Therefore, the lightest one, S_1^1, will be a stable particle and hence a warm DM (WDM) candidate. Also, the lightest heavy right-handed (RH) neutrino ν_H^1 can be a DM (with mass of order GeV) by tuning its corresponding Yukawa coupling to be very small [7, 8].

3. WARM DM AS FIMP

As mentioned above, a WDM S_1^1 is produced by the freeze-in mechanism only from its coupling with Z'. Therefore, the corresponding gauge coupling g' is taken to be very feeble $\sim \mathcal{O}(10^{-10})$ with the result that S_1^1 is never in thermal equilibrium with the cosmic soup. Due to small g', Z' also interacts very feebly with the cosmic soup and never achieves thermal equilibrium,

$$\frac{\Gamma_{Z'}}{H(T = M_{Z'})} < 1, \tag{3}$$

where $\Gamma_{Z'}$ is the total decay width of Z' and H is the Hubble parameter. The Boltzmann equation (BE) of Z' distribution function of is given by [9]

$$\hat{L} f_{Z'} = \sum_{i=1,2} \mathcal{C}^{h_i \to Z'Z'} + \mathcal{C}^{Z' \to \text{all}}, \tag{4}$$

where $f_{Z'}$ is the Z' distribution function, $\mathcal{C}^{h_i \to Z'Z'}$ is the collision term of Z' production from the decays of scalars $h_{1,2}$ and $\mathcal{C}^{Z' \to \text{all}}$ is Z' decay collision term (for the expression of these collision terms, see [10, 11]). Once we get $f_{Z'}$, we then can determine its co-moving number density by using:

$$Y_{Z'} = \frac{45\, g}{4\pi^4 g_s(M_{\text{sc}}/z_0)} \int_0^\infty d\xi_p \, \xi_p^2 \, f_{Z'}(\xi_p, z) \, . \tag{5}$$

The keV DM S_1^1 can be produced from $f\bar{f} \to Z' \to S_1^1 S_1^1$ (annihilation contribution) and from $Z' \to S_1^1 S_1^1$ (decay contribution). To determine $Y_{S_1^1}$, we solve the following BE [10, 11, 12],

$$\begin{aligned} \frac{dY_{S_1^1}}{dz} &= \frac{4\pi^2}{45} \frac{M_{\text{Pl}} \, M_{\text{sc}} \sqrt{g_\star}}{1.66\, z^2} \sum_f \langle \sigma v_{f\bar{f} \to S_1^1 S_1^1} \rangle \left[\left(Y_f^{\text{eq}} \right)^2 - Y_{S_1^1}^2 \right] \\ &+ \frac{2\, M_{\text{Pl}}\, z \sqrt{g_\star}}{1.66\, M_{\text{sc}}^2 \, g_s} \langle \Gamma_{Z' \to S_1^1 S_1^1} \rangle_{\text{NTH}} \left(Y_{Z'} - Y_{S_1^1} \right) . \end{aligned} \tag{6}$$

The corresponding RD of the WDM S_1^1 is given by [11]

$$\Omega\, h^2 \simeq 2.755 \times 10^8 \left(M_{S_1^1}/\text{GeV} \right) \, Y_{S_1^1}(\infty) \, . \tag{7}$$

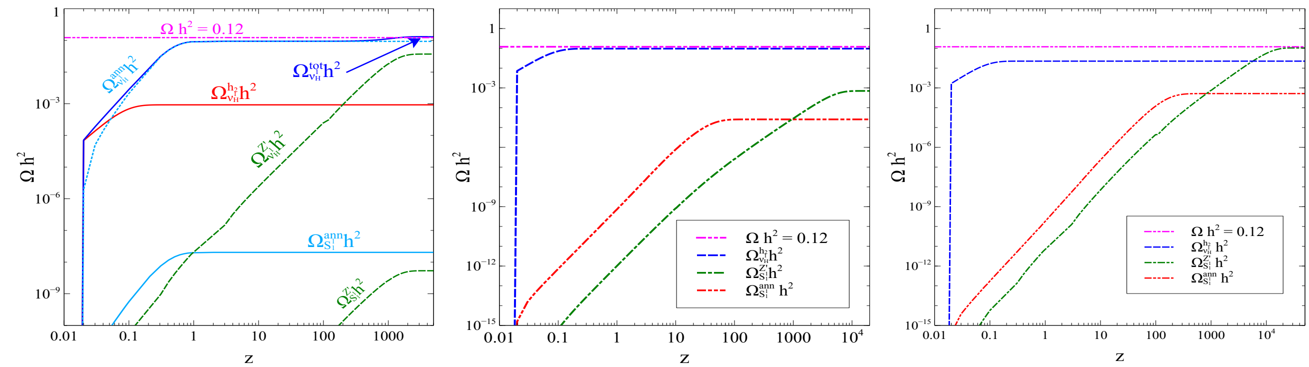

FIGURE 2: Variation of relative RD contributions of ν_H^1 and S_1^1 as a function of z. Here, in left panel: $M_{Z'} = 1$ TeV, $M_{\nu_H^1} = 70$ GeV, $M_{S_1^1} = 10$ keV, $g' = 9.0 \times 10^{-12}$, $\alpha = 0.01$ rad, and $z_0 = 0.01$; in center (right) panel: $M_{Z'} = 10$ GeV (2.5 GeV), $M_{\nu_H^1} = 8$ GeV (2 GeV), $M_{S_1^1} = 10$ keV (100 keV), $g' \simeq 2.4 \times 10^{-11}$, $M_{h_2} = 5$ TeV, $\alpha = 0.01$ rad, and $z_0 = 0.01$.

From Fig. 1, it is clearly seen that Ωh^2 is inversely proportional to $M_{Z'}$ and directly proportional to $M_{S_1^1}$. More explicitly, for a fixed g' value, larger Ωh^2 values correspond to smaller $M_{Z'}$ values (red points) and larger $M_{S_1^1}$ values (blue points). Also, it is worth noting that many points ($\sim$ 84% of the scanned points) have a small DM RD ($\Omega h^2 \leq 10^{-2}$). Therefore, we discuss in the next section a two component FIMP DM possibility to get an extra RD contribution from the lightest heavy RH neutrino, ν_H^1, as a GeV scale DM.

4. TWO COMPONENT FIMP DM

As mentioned, the lightest heavy RH neutrino, ν_H^1, can be a stable particle by tuning its corresponding Yukawa coupling to be very small $\leq 3 \times 10^{-26}(\mathrm{GeV}/M_N)^{1/2}$ [7, 8]. Therefore, it can be an extra DM component, with mass of order GeV. The dominant ν_H^1 pair annihilation channels to SM particles are mediated by the neutral gauge boson Z' and the scalars $h_{1,2}$. The coupling of ν_H^1 pair with Z' is $g'/2$, while with h_i is given by

$$\lambda_{\nu_H^1 \nu_H^1 h_i} = \sqrt{2}\, g' \, \frac{M_{\nu_H^1}}{M_{Z'}} O_i \, , \tag{8}$$

where $O_1 = \sin\alpha$ and $O_2 = \cos\alpha$ (α is the scalar mixing angle). Therefore, ν_H^1 pair annihilation is proportional to extremly feeble coupling g'. Due to this feeble g', ν_H^1 will never reach thermal equilibrium and is produced by the freeze-in mechanism. The BE associated with ν_H^1 production is as follows [10, 11, 12]

$$\begin{aligned} \frac{dY_{\nu_H^1}}{dz} &= \frac{4\pi^2}{45} \frac{M_{\rm Pl}\, M_{\rm sc} \sqrt{g_\star}}{1.66\, z^2} \sum_f \langle \sigma v_{f\bar{f} \to \nu_H^1 \nu_H^1} \rangle \left[\left(Y_f^{\rm eq} \right)^2 - Y_{\nu_H^1}^2 \right] \\ &+ \frac{2\, M_{\rm Pl}\, z \sqrt{g_\star}}{1.66\, M_{\rm sc}^2\, g_s} \Bigg[\langle \Gamma_{Z' \to \nu_H^1 \nu_H^1} \rangle_{\rm NTH} \left(Y_{Z'} - Y_{\nu_H^1} \right) \\ &+ \sum_{i=1,2} \langle \Gamma_{h_i} \rangle \left(Y_{h_i}^{\rm eq} - Y_{\nu_H^1} \right) \Bigg]. \end{aligned} \tag{9}$$

Thermal average of the $h_{1,2}$ decay width is defined as [10]

$$\langle \Gamma_{h_i} \rangle = \frac{K_1(z)}{K_2(z)} \Gamma_{h_i} \, , \tag{10}$$

where Γ_{h_i} is the total h_i decay width. The corresponding RD of ν_H^1 is given by [11]

$$\Omega_{\nu_H^1} h^2 = 2.755 \times 10^8 \left(M_{\nu_H^1} / \mathrm{GeV} \right) \, Y_{\nu_H^1}(\infty) \, . \tag{11}$$

Finally, the total RD of this two component DM is given by

$$\Omega^{\rm tot} h^2 = \Omega_{\nu_H^1} h^2 + \Omega_{S_1^1} h^2 \, . \tag{12}$$

It is clearly seen that the DM production depends crucially on the mass of the mother particles ($M_{Z'}, M_{h_2}$) and the DM mass. Assuming $M_{h_2} > 2M_{Z'} > 4M_{S_1^1}$, we divide the ν_H^1 spectrum into two regions according to its dominant production modes:

1. Region I, where $M_{Z'} > 2M_{\nu_H^1}$ and ν_H^1 production is Z' dominated,
2. Region II, where $M_{Z'} < 2M_{\nu_H^1}$ and ν_H^1 production is h_2 dominated.

In region I, as shown in Fig. 2 (left), $\Omega^{Z'}_{\nu_H^1} h^2$ is larger than $\Omega^{h_2}_{\nu_H^1} h^2$ because the latter is suppressed by a factor of their partial decays ratio ($\simeq 12 M^2_{\nu_H^1} M_{h_2} / M^3_{Z'} \simeq \mathcal{O}(0.1)$). Also, $\Omega_{S_1^1} h^2$ is negligible compared to $\Omega_{\nu_H^1} h^2$ even though they have same gauge coupling g' and their mediator masses (M_{h_2} and $M_{Z'}$) are of the same order ($\sim$ TeV). This is because the RD of a DM candidate is directly proportional to its mass. Therefore, the contribution of the keV mass S_1^1 to the DM total RD as compared to the GeV mass ν_H^1 is suppressed by a factor $\simeq M_{S_1^1}/M_{\nu_H^1} \simeq \mathcal{O}(10^{-7})$. In region II, as shown in Fig. 2 (center, right), Z' decays to ν_H^1 pair is kinematically forbidden, and ν_H^1 production consequently is h_2 dominated. Therefore, a major portion of the two DM candidates (ν_H^1 and S_1^1) is produced almost independently from the h_2 and Z' mediated processes, respectively. Moreover, in region I this possibility did not exist because both ν_H^1 and S_1^1 are produced dominantly via Z' and have the same number density.

5. CONCLUSION

We studied two problems beyond the SM, namely, the non-vanishing tiny neutrino masses and the existence of the DM within the BLSMIS. In the BLSMIS, S_1^1 can be a WDM, being odd under a $\mathbb{Z}_2$ symmetry. We studied S_1^1 as a FIMP WDM and found that a large portion of the parameter space gives a small contribution to the DM RD. Hence, as a possible scenario in the BLSMIS, we considered a two component FIMP DM to get an extra contribution to the DM RD. In this scenario, the lightest heavy RH neutrino, ν_H^1, can contribute independently to the DM RD as a GeV scale DM. For $M_{Z'} > 2M_{\nu_H^1}$, the production of ν_H^1 through the Z' mediator has the dominant contribution to the total DM RD, while for $M_{Z'} < 2M_{\nu_H^1}$, h_2 mediated processes will contribute dominantly to ν_H^1 production and the Z' mediated processes will contribute dominantly to S_1^1 production. In this region, we emphasized that both FIMP candidates, S_1^1 and ν_H^1, have relevant contributions to the total DM RD.

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