Neutrino mass, leptogenesis, and dark matter from the dark sector with U(1)$_\mathsf{D}$

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ABSTRACT: I suggest a new extension of the SM by introducing a dark sector which has several new particles and a local U(1)$_D$ symmetry. The dark particles bring about the new and interesting physics beyond the SM. The model can generate the tiny neutrino mass by a hybrid see-saw mechanism, achieve the leptogenesis at the TeV scale, and account for the cold dark matter. All of the three things collectively arise from the dark sector. In particular, it is very feasible to test the model predictions and probe the dark sector in near future experiments.

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1 Introduction

The standard model (SM) of the particle physics has successfully accounted for all kinds of the physics at or below the electroweak scale, refer to the reviews in Particle Data Group [1], but it can not explain the three important issues: the tiny neutrino mass [2, 3], the matter-antimatter asymmetry [4, 5], and the cold dark matter (CDM) [6, 7]. Many theories have been suggested to solve these problems. The tiny neutrino mass can be generated by the seesaw mechanism [8–10] or origin from the loop-diagram radiative generation [11, 12]. The baryon asymmetry can be achieved by the thermal leptogenesis [13, 14] or the electroweak baryogenesis [15, 16]. The CDM candidates are possibly the sterile neutrino [17, 18], the lightest supersymmetric particle [19], the axion [20], and so on. These theories ordinarily focus on only one of the three problems. In recent years, some inspired ideas attempt to find some connections among the neutrino mass, the baryon asymmetry, and the CDM, for example, the lepton number violation at the super-high scale can lead to the neutrino mass and the leptogenesis [21, 22], the neutrino mass and the leptogenesis can also be implemented by the super-heavy scalar triplet [23], the asymmetric CDM is related to the baryon asymmetry [24, 25], and some sophisticated models unifying them into a frame [26–31]. Although many progresses on these fields have been made all the time, an universal and convincing theory is not established as yet.

What is exactly a realistic theory beyond the SM? The universe harmony and the nature unification are a common belief of mankind. It is very possible that there is a common origin of the tiny neutrino mass, the matter-antimatter asymmetry and the CDM, which relates the three things to each other. Therefore, a new theory beyond the SM should be capable of accounting for the three things collectively, on the other hand, this theory should keep such principles as the simplicity, the fewer number of parameters, and being feasible and promising to be tested in future experiments. If one theory is excessive complexity and unable to be tested, it is unbelievable and infeasible. Based on these

	SM sector				Dark sector				
	Higgs	Lepton			Fermion		Scalar		
	H	l_L	e_R	N_R	N_L	χ_R	ϕ_1	ϕ_2	Φ
$\mathrm{SU}(2)_L$	2	2	1	1	1	1	1	1	2
$\mathrm{U}(1)_Y$	-1	-1	-2	0	0	0	0	0	-1
$\mathrm{U}(1)_{B-L}^{\mathrm{global}}$	0	-1	-1	-1	0	0	1	0	-1
$\mathrm{U}(1)_D$	0	0	0	0	1	1	1	2	1
Z_2	-1	-1	1	1	-1	1	-1	1	1

Table 1. The particle contents and the quantum numbers of the model.

considerations, I suggest a new extension of the SM. The model introduces a dark sector beyond the SM, which contains a few of new particles and has a local gauge symmetry of $\mathrm{U}(1)_D$, in particular, the dark sector provides a common origin of the above three things so that the model can completely account for them. Finally, it is very feasible to test the model and probe the dark sector by the TeV-scale colliders, the underground detectors, and the cosmic ray search.

The remainder of this paper is organized as follows. I outline the model in section 2. Section 3 and section 4 are respectively discussions of the leptogenesis and the dark matter. Section 5 is numerical results and discussions of the model test. Section 6 is devoted to conclusions.

2 Model

The model introduces several new particles and a local gauge symmetry $\mathrm{U}(1)_D$ beyond the SM sector, which are in the dark sector. In addition, it obeys the global symmetry $\mathrm{U}(1)_{B-L}$, i.e., the difference between the baryon number and the lepton one is conserved. Table 1 clearly lists the particle contents and their quantum numbers of the model, all kinds of the notations are self-explanatory.

Here I omit the quark sector and the color subgroup $\mathrm{SU}(3)_C$ since what followed will not involve them. Each of the fermions in table 1 has three generations as usual. $l_L = (\nu_L^0, e_L^-)^T$, $H = (H^0, H^-)^T$, $\Phi = (\Phi^0, \Phi^-)^T$ are all doublets under $\mathrm{SU}(2)_L$, while $N_R, N_L, \chi_R, \phi_1, \phi_2$ are all singlets under the SM group. The particles in the dark sector have all non-vanishing D numbers, while all of the SM particles have no D numbers. Note that N_R is filled into the SM sector but N_L belongs to the dark sector, N_R and N_L will combine to form a heavy neutral Dirac fermion after the model symmetry breakings. χ_R is a neutral Majorana fermion, it will become the CDM. The dark neutral scalars ϕ_1 and ϕ_2 are applied to implement the spontaneous breakings of $\mathrm{U}(1)_D$ and $\mathrm{U}(1)_{B-L}$, while the dark doublet scalar Φ plays a key role in the generations of the neutrino mass and the matter-antimatter asymmetry. Finally, the model has also a hidden Z_2 symmetry, it is

defined by the following discrete transform,

$$f_L \to -f_L, \qquad f_R \to f_R, \qquad H \to -H, \qquad \phi_1 \to -\phi_1, \qquad \phi_2 \to \phi_2, \qquad \Phi \to \Phi, \quad (2.1)$$

and all the gauge fields remain unchanged, where $f_{L,R}$ denote the left-handed and right-handed fermions in table 1. The last line of table 1 lists the Z_2 parity of each field. Note that N_L and χ_R have the same gauge quantum numbers but they have opposite Z_2 parities. By virtue of the assignment of table 1, it is easily verified that all of the chiral anomalies are completely cancelled in the model, namely the model is anomaly-free.

Under the above symmetries, the invariant Lagrangian of the model is composed of the three parts of the gauge kinetic energy terms, the Yukawa couplings and the scalar potentials. The gauge kinetic energy terms are

$$\mathscr{L}_G = \mathscr{L}_{\text{pure gauge}} + \sum_f i\,\overline{f}\,\gamma^\mu D_\mu f + \sum_S (D^\mu S)^\dagger D_\mu S,$$

$$D_\mu = \partial_\mu + i\left(g_2 W_\mu^i \frac{\tau^i}{2} + g_1 B_\mu \frac{Y}{2} + g_0 Z_\mu' \frac{D}{2}\right), \quad (2.2)$$

where f and S respectively denote all kinds of the fermions and scalars in table 1. g_0 and Z_μ' are the gauge coupling coefficient and gauge field which are associated with the local $\text{U}(1)_D$ symmetry. τ^i is the Paul matrices and the other notations are self-explanatory.

The Yukawa couplings are

$$\mathscr{L}_Y = \overline{l_L} Y_e e_R \, i\tau_2 H^* + \overline{l_L} Y_1 N_R H + \overline{l_L} Y_2 C \overline{N_L}^T \Phi$$

$$+ \overline{N_L} Y_N N_R \, \phi_1 + \frac{1}{2} \overline{N_L} Y_N' C \overline{N_L}^T \phi_2 + \frac{1}{2} \chi_R^T C Y_\chi \chi_R \, \phi_2^* + \text{h.c.}, \quad (2.3)$$

where C is the charge conjugation matrix and $C\overline{N_L}^T = N_R^c$, $\chi_R^T C = \overline{\chi_L^c}$. Note that the Z_2 symmetry of eq. (2.1) forbids the explicit mass term $\overline{N_L} M \chi_R$ even though it satisfies all the gauge symmetries. This will guarantee the stability of χ_R since it can not mix with the other fermions. These coupling parameters in eq. (2.3), Y_e, Y_1, etc., are all 3×3 complex matrices in the flavour space, the leading elements of them take such moderate values as $[Y_e, Y_1, Y_2] \sim 0.01$ and $[Y_N, Y_N', Y_\chi] \sim 0.1$. In addition, we can however choose such flavour basis in which Y_e, Y_N, Y_χ are simultaneously diagonal matrices, namely the mass eigenstate basis (see the following eq. (2.14)), thus Y_1 and Y_2 certainly contain some irremovable complex phases, they eventually become CP-violating sources in the lepton sector in comparison with one in the quark sector. Eq. (2.3) will give rise to all kinds of the fermion masses after the scalar fields developing their non-vanishing vacuum expectation values. In particular, the spontaneous breakings of $\text{U}(1)_D$ and $\text{U}(1)_{B-L}$ will bring about significant results, the Y_1 and Y_2 terms can jointly lead to the tiny neutrino mass and the successful leptogenesis, while the Y_χ term will generate the CDM and yield correct annihilation cross-section.

The full scalar potentials are

$$
\begin{aligned}
V_S = {} & \mu_{\phi_1}^2 \phi_1^* \phi_1 + \mu_{\phi_2}^2 \phi_2^* \phi_2 + \mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi \\
& + \lambda_{\phi_1}(\phi_1^* \phi_1)^2 + \lambda_{\phi_2}(\phi_2^* \phi_2)^2 + \lambda_H(H^\dagger H)^2 + \lambda_\Phi(\Phi^\dagger \Phi)^2 \\
& + 2\lambda_0 \phi_1^* \phi_1 \phi_2^* \phi_2 + 2(\lambda_1 \phi_1^* \phi_1 + \lambda_2 \phi_2^* \phi_2)H^\dagger H + 2(\lambda_3 \phi_1^* \phi_1 + \lambda_4 \phi_2^* \phi_2)\Phi^\dagger \Phi \\
& + 2\lambda_5 H^\dagger H \Phi^\dagger \Phi + 2\lambda_6 H^\dagger \Phi \Phi^\dagger H - 2\lambda_7(\phi_1 \phi_2^* H^\dagger \Phi + \text{h.c.}).
\end{aligned}
\tag{2.4}
$$

All kinds of the parameters in eq. (2.4) are chosen and required by the following conditions,

$$
\mu_{\phi_1} \sim 10^3 \, \text{TeV} \quad \text{and} \quad \mu_{\phi_1}^2 < 0, \ [\mu_{\phi_2}, \mu_H, \mu_\Phi] \sim 1 \, \text{TeV} \quad \text{and} \quad \mu_\Phi^2 > 0,
$$

$$
[\lambda_{\phi_1}, \lambda_{\phi_2}, \lambda_H, \lambda_\Phi] \sim 0.1 \qquad \text{and} \quad \text{they are all positive,}
$$

$$
[\lambda_0, \lambda_1, \lambda_2, \cdots, \lambda_7] \lesssim 10^{-6} \qquad \text{and} \quad \lambda_7 \sim 10^{-7} \ \text{is positive.}
\tag{2.5}
$$

Here we assume that there is no CP violation in the scalar sector, in addition, in eq. (2.4) the self-interaction of each scalar is stronger but the interactions among them are feeble, so in eq. (2.5) those self-coupling parameters are far larger than those interactive coupling parameters. $\mu_{\phi_1}^2 < 0$ and $|\mu_{\phi_1}^2| \gg [\mu_{\phi_2}^2, \mu_H^2, \mu_\Phi^2]$ will lead that ϕ_1 first develops a non-vanishing vacuum expectation value at high scale, and then the other scalars are induced to develop non-vanishing vacuum expectation values at low scale via their coupling to ϕ_1, eventually the symmetry breakings proceed along the chain of the following eq. (2.9). $\mu_\Phi^2 > 0$ means that μ_Φ is actually the original mass of the dark doublet scalar Φ. In short, the conditions of eq. (2.5) are natural and reasonable, they can sufficiently guarantee the vacuum stability and the spontaneous breakings of the model symmetries in the proper order.

The vacua of the spontaneous breakings are along the directions of the neutral component of each scalar field. We can rigorously solve the V_S minimum for eq. (2.4), and then derive the vacuum configurations as follows,

$$
\phi_1 \to \frac{\phi_1^0 + v_1 + iG'^0}{\sqrt{2}}, \qquad \phi_2 \to \frac{\phi_2^0 + v_2 + iG^0}{\sqrt{2}},
$$

$$
H \to \begin{pmatrix} \frac{h^0 + v_H + iG''^0}{\sqrt{2}} \\ H^- \end{pmatrix}, \qquad \Phi \to \begin{pmatrix} \frac{\Phi_R^0 + v_\Phi + i\Phi_I^0}{\sqrt{2}} \\ \Phi^- \end{pmatrix},
$$

$$
\langle \phi_1 \rangle = \frac{v_1}{\sqrt{2}}, \qquad \langle \phi_2 \rangle = \frac{v_2}{\sqrt{2}}, \qquad \langle H \rangle = \frac{v_H}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad \langle \Phi \rangle = \frac{v_\Phi}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix},
\tag{2.6}
$$

where the four vacuum expectation values are determined by the tadpole equations as follows,

$$
\mu_{\phi_1}^2 = -\left(\lambda_{\phi_1} v_1^2 + \lambda_0 v_2^2 + \lambda_1 v_H^2 + \lambda_3 v_\Phi^2\right) + \lambda_7 \frac{v_1 v_2 v_H v_\Phi}{v_1^2},
$$

$$
\mu_{\phi_2}^2 = -\left(\lambda_0 v_1^2 + \lambda_{\phi_2} v_2^2 + \lambda_2 v_H^2 + \lambda_4 v_\Phi^2\right) + \lambda_7 \frac{v_1 v_2 v_H v_\Phi}{v_2^2},
$$

$$
\mu_H^2 = -\left(\lambda_1 v_1^2 + \lambda_2 v_2^2 + \lambda_H v_H^2 + (\lambda_5 + \lambda_6)v_\Phi^2\right) + \lambda_7 \frac{v_1 v_2 v_H v_\Phi}{v_H^2},
$$

$$
\mu_\Phi^2 = -\left(\lambda_3 v_1^2 + \lambda_4 v_2^2 + (\lambda_5 + \lambda_6)v_H^2 + \lambda_\Phi v_\Phi^2\right) + \lambda_7 \frac{v_1 v_2 v_H v_\Phi}{v_\Phi^2}.
\tag{2.7}
$$

A physics solution of the vacuum expectation values which fulfil the conditions of eq. (2.5) is a hierarchy such as

$$v_\Phi \sim 0.5\,\text{MeV} \ll v_H \sim v_2 \sim 250\,\text{GeV} \ll v_1 \sim 2000\,\text{TeV}. \tag{2.8}$$

In fact, $v_H = 246\,\text{GeV}$ has been fixed by the electroweak physics, v_2 will be determined by the CDM physics, v_1 and v_Φ will jointly be determined by the tiny neutrino mass and the successful leptogenesis.

According to the assignment of table 1 and the relations of eq. (2.8), the model symmetries are spontaneously broken step by step through the breaking chain as follows,

$$\text{U}(1)_{B-L}^{\text{global}} \otimes \text{U}(1)_D^{\text{local}} \otimes Z_2 = \text{U}(1)_{(B-L)-D}^{\text{global}} \otimes \text{U}(1)_{(B-L)+D}^{\text{local}} \otimes Z_2$$
$$\xrightarrow{\langle\phi_1\rangle \sim 10^6\,\text{GeV}} \text{U}(1)_{(B-L)-D}^{\text{global}} \xrightarrow{\langle\phi_2\rangle \sim 10^2\,\text{GeV}} \text{nothing},$$
$$\text{SU}(2)_L \otimes \text{U}(1)_Y \xrightarrow{\langle H\rangle \sim 10^2\,\text{GeV}} \text{U}(1)_{\text{em}}. \tag{2.9}$$

At the first step, $\langle\phi_1\rangle \sim 10^6\,\text{GeV}$ breaks the local $\text{U}(1)_{(B-L)+D}$ and the discrete Z_2 but the global $\text{U}(1)_{(B-L)-D}$ is kept as a residual symmetry. The ϕ_1^0 component becomes a massive real scalar boson around the v_1 scale, while the pseudo-scalar Goldstone boson G'^0 is eaten by the massless Z'_μ, the latter becomes a massive gauge boson through the Higgs mechanism. In addition, the Y_N term in eq. (2.3) generates a heavy Dirac fermion mass around the v_1 scale by a combination of the neutral N_L and N_R. At the second step, $\langle\phi_2\rangle \sim 10^2\,\text{GeV}$ violates the global $\text{U}(1)_{(B-L)-D}$, ϕ_2^0 and G^0 in eq. (2.6) respectively become a massive real scalar and a massless Goldstone boson, in addition, χ_R obtains a Majorana mass around the v_2 scale, it will become the CDM because of its characteristics (which will be discussed at section 4). Note that the Y'_N term in eq. (2.3) also generates a Majorana mass of N_L around the v_2 scale, but it is far smaller than the Dirac mass of N, so this can not change the nature of N as a Dirac fermion. At the third step, the electroweak breaking is accomplished by $\langle H\rangle \sim 10^2\,\text{GeV}$, the SM particles obtain their masses around the electroweak scale. It should be stressed that the $B - L - D$ violation occurs at the time close to the electroweak breaking due to $v_2 \sim v_H$. Lastly, the above three breakings can also induce the neutral component of the dark doublet Φ developing a smaller $\langle\Phi\rangle \sim 0.5\,\text{MeV}$ via the λ_7 feeble coupling term in eq. (2.4), of course, v_Φ is too small to make an effect on the nature of the heavy Φ whose mass is $\sim \mu_\Phi$.

After the above symmetry breakings are completed, these components of G''^0, G''^0, H^- in eq. (2.6) have been transformed into the gauge sector to generate $M_{Z'}, M_Z, M_W$ through the Higgs mechanism, therefore the scalar sector now includes four CP-even neutral bosons $\phi_1^0, \phi_2^0, h^0, \Phi_R^0$, two CP-odd ones G^0, Φ_I^0, and a pair of charged bosons $\Phi^{\mp}$. The squared mass matrix of the CP-even $(\phi_1^0, \phi_2^0, h^0, \Phi_R^0)$ and one of the CP-odd (G^0, Φ_I^0), and the squared mass of the charged $\Phi^{\mp}$, are together given as follows,

$$
M_+^2 = \begin{pmatrix} 2\lambda_{\phi_1} v_1^2 + \frac{\Omega}{v_1^2} & 2\lambda_0 v_1 v_2 - \lambda_7 v_H v_\Phi & 2\lambda_1 v_1 v_H - \lambda_7 v_2 v_\Phi & 2\lambda_3 v_1 v_\Phi - \lambda_7 v_2 v_H \\ \cdots & 2\lambda_{\phi_2} v_2^2 + \frac{\Omega}{v_2^2} & 2\lambda_2 v_2 v_H - \lambda_7 v_1 v_\Phi & 2\lambda_4 v_2 v_\Phi - \lambda_7 v_1 v_H \\ \cdots & \cdots & 2\lambda_H v_H^2 + \frac{\Omega}{v_H^2} & 2(\lambda_5 + \lambda_6) v_H v_\Phi - \lambda_7 v_1 v_2 \\ \cdots & \cdots & \cdots & 2\lambda_\Phi v_\Phi^2 + \frac{\Omega}{v_\Phi^2} \end{pmatrix},
$$

$$
M_-^2 = \begin{pmatrix} \frac{\Omega}{v_2^2} & -\lambda_7 v_1 v_H \\ -\lambda_7 v_1 v_H & \frac{\Omega}{v_\Phi^2} \end{pmatrix} \xrightarrow{\text{diagonalizing}} \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Omega}{v_2^2} + \frac{\Omega}{v_\Phi^2} \end{pmatrix},
$$

$$
M_{\Phi^{\mp}}^2 = -\lambda_6 v_H^2 + \frac{\Omega}{v_\Phi^2}, \tag{2.10}
$$

where $\Omega = \lambda_7 v_1 v_2 v_H v_\Phi$. M_+^2 is obviously an approximately diagonal matrix because those non-diagonal elements are far smaller than those diagonal elements, of course, this arises from only feeble coupling among the scalar fields, so we can safely neglect the mixing among the CP-even bosons, for example, the mixing angle between ϕ_2^0 and h^0 is $\sim \frac{\lambda_2 v_2 v_H}{\lambda_{\phi_2} v_2^2 - \lambda_H v_H^2} \ll 1$ due to $\lambda_2 \ll 1$. In M_-^2, the mixing angle between G^0 and Φ_I^0 is $\sim \frac{v_\Phi}{v_2} \ll 1$, however, G^0 indeed becomes a zero mass Goldstone boson because the determinant of M_-^2 is vanishing, this is of course an inevitable outcome of the global $B - L - D$ breaking. Eq. (2.10) indicates that $\Phi^{\mp}, \Phi_I^0, \Phi_R^0$ have nearly the same squared mass $\frac{\Omega}{v_\Phi^2} = \frac{\lambda_7 v_1 v_2 v_H}{v_\Phi}$ on account of eq. (2.5) and eq. (2.8), therefore the neutral and charged components of the dark doublet Φ actually keep a degenerating mass in despite of their tiny splits.

In the gauge sector, the squared mass matrix of the three neutral gauge bosons (B_μ, W_μ^3, Z_μ') and the squared mass of the charged gauge bosons $W_\mu^{\pm}$ are given by

$$
M_{NGB}^2 = \frac{1}{4} \begin{pmatrix} g_1^2(v_H^2 + v_\Phi^2) & -g_1 g_2(v_H^2 + v_\Phi^2) & -g_1 g_0 v_\Phi^2 \\ -g_1 g_2(v_H^2 + v_\Phi^2) & g_2^2(v_H^2 + v_\Phi^2) & g_2 g_0 v_\Phi^2 \\ -g_1 g_0 v_\Phi^2 & g_2 g_0 v_\Phi^2 & g_0^2(v_1^2 + 4v_2^2) \end{pmatrix}
$$

$$
\xrightarrow{\text{diagonalizing}} \begin{pmatrix} M_{A_\mu}^2 = 0 & 0 & 0 \\ 0 & M_{Z_\mu}^2 = \frac{g_2^2 + g_1^2}{4}(v_H^2 + v_\Phi^2) & 0 \\ 0 & 0 & M_{Z'_\mu}^2 = \frac{g_0^2}{4}(v_1^2 + 4v_2^2) \end{pmatrix},
$$

$$
M_{W_\mu}^2 = \frac{g_2^2}{4}(v_H^2 + v_\Phi^2), \tag{2.11}
$$

where the photon field A_μ is massless because the determinant of M_{NGB}^2 is vanishing. The mixing angle between Z'_μ and B_μ is $\sim \frac{g_1 v_\Phi^2}{g_0 v_1^2}$, the mixing angle between Z'_μ and W_μ^3 is $\sim \frac{g_2 v_\Phi^2}{g_0 v_1^2}$, obviously, they are nearly zero, so we can leave them out. The mixing angle between B_μ

and W_μ^3 is $\cos\theta_w = \frac{g_2}{\sqrt{g_2^2 + g_1^2}}$, which is namely the weak mixing angle of the SM. In addition, $M_W = \frac{g_2 v_H}{2}\left(1 + \frac{v_\Phi^2}{v_H^2}\right)^{\frac{1}{2}}$ and $M_Z = \frac{M_W}{\cos\theta_w}$ have only a very tiny correction $\sim \frac{v_\Phi^2}{v_H^2}$ to the SM values, which is very difficult to be detected.

In the fermion sector, the mass matrix of the neutral fermions is written as

$$\frac{1}{2}\left(\overline{\nu_L}, \overline{N_L}, N_R^T C, \chi_R^T C\right)
\begin{pmatrix}
0 & \frac{v_\Phi Y_2}{\sqrt{2}} & \frac{v_H Y_1}{\sqrt{2}} & 0 \\
\frac{v_\Phi Y_2^T}{\sqrt{2}} & \frac{v_2 Y_N'}{\sqrt{2}} & \frac{v_1 Y_N}{\sqrt{2}} & 0 \\
\frac{v_H Y_1^T}{\sqrt{2}} & \frac{v_1 Y_N^T}{\sqrt{2}} & 0 & 0 \\
0 & 0 & 0 & \frac{v_2 Y_\chi}{\sqrt{2}}
\end{pmatrix}
\begin{pmatrix}
C\overline{\nu_L}^T \\
C\overline{N_L}^T \\
N_R \\
\chi_R
\end{pmatrix}$$

$$\xrightarrow{\text{diagonalizing}} -\frac{1}{2}\left(\overline{\nu_L'}, \overline{N_L'}, N_R'^T C, \chi_R^T C\right)
\begin{pmatrix}
M_\nu & 0 & 0 & 0 \\
0 & 0 & M_N & 0 \\
0 & M_N^T & 0 & 0 \\
0 & 0 & 0 & M_\chi
\end{pmatrix}
\begin{pmatrix}
C\overline{\nu_L'}^T \\
C\overline{N_L'}^T \\
N_R' \\
\chi_R
\end{pmatrix}$$

$$= -\frac{1}{2}\overline{\nu_L'}M_\nu C\overline{\nu_L'}^T - \overline{N_L'}M_N N_R' - \frac{1}{2}\chi_R^T C M_\chi \chi_R, \tag{2.12}$$

where M_ν, M_N, M_χ are given by eq. (2.14) below, and ν', N' are new fermion fields after the flavour rotation. Because of $v_2 Y_N' \ll v_1 Y_N$, N_L and N_R actually combine into a heavy Dirac fermion. In addition, χ_R has no mixing with the other neutral fermions due to the Z_2 symmetry in eq. (2.1), this leads that it eventually becomes the CDM. At the low energy, the heavy Dirac fermion N has decoupled and it can be integrated out from the two terms of Y_1 and Y_2 in eq. (2.3), thus we can obtain an effective coupling of the left-handed doublet lepton

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}\overline{l_L}(HY_1 M_N^{-1} Y_2^T \Phi^T + \Phi Y_2 M_N^{-1T} Y_1^T H^T)C\overline{l_L}^T + \text{h.c.}. \tag{2.13}$$

According to the assignment of table 1, this effective coupling explicitly violates both one unit of $B - L$ number and one unit of D number, namely violates two unit of $B - L + D$ number but conserves $B - L - D$ number. In fact, eq. (2.13) is exactly a common origin of both the tiny neutrino mass and the leptogenesis.

We can now give all of the model particle masses as follows,

$$M_{Z_\mu'} = \frac{v_1 g_0}{2}, \qquad M_{\phi_1^0} = v_1\sqrt{2\lambda_{\phi_1}}, \qquad M_{\phi_2^0} = v_2\sqrt{2\lambda_{\phi_2}}, \qquad M_{G^0} = 0,$$

$$M_{h^0} = v_H\sqrt{2\lambda_H}, \qquad M_\Phi = \sqrt{\frac{\lambda_7 v_1 v_2 v_H}{v_\Phi}} \approx \mu_\Phi\sqrt{1 + \frac{\lambda_3 v_1^2}{\mu_\Phi^2}},$$

$$M_N = -\frac{v_1}{\sqrt{2}}Y_N, \qquad M_\chi = -\frac{v_2}{\sqrt{2}}Y_\chi, \qquad M_e = \frac{v_H}{\sqrt{2}}Y_e,$$

$$M_\nu = -\frac{v_H v_\Phi}{2}(Y_1 M_N^{-1} Y_2^T + Y_2 M_N^{-1T} Y_1^T) = \frac{v_H^2 v_2 \lambda_7}{\sqrt{2}M_\Phi^2}(Y_1 Y_N^{-1} Y_2^T + Y_2 Y_N^{-1T} Y_1^T). \tag{2.14}$$

M_{h^0} is namely the Higgs boson mass of the SM, which has been measured as $M_{h^0} \approx 125\,\text{GeV}$ [1]. M_Φ is about several TeVs, which is close to its original mass μ_Φ. The tiny Majorana mass of the SM neutrino is generated by eq. (2.12) or equivalently by eq. (2.13), it is jointly suppressed by both the small v_Φ and the heavy M_N. The second equality of M_ν is obtained by use of the M_N equality and the M_Φ one, from a further point of view, the tiny M_ν essentially arises from the λ_7 feeble coupling. Therefore this is a hybrid see-saw mechanism, in particular, it is realized at the TeV scale and it is possibly tested in the future by measuring the parameters in the second equality of M_ν. Finally, the neutrino mass matrix M_ν bears full information of the neutrino mass and the lepton mixing.

Based on eq. (2.5), eq. (2.8) and eq. (2.14), in addition, the mass hierarchy of $N_{1,2,3}$ and one of $\chi_{1,2,3}$ are all taken into account, thus we can infer that the mass spectrum of the model particles are such relations as (GeV as unit),

$$M_{G^0} < M_\nu \sim 10^{-10} \ll M_e < M_{\chi_1} \sim 10 < M_{\chi_2} < M_{\chi_3} \sim M_{h^0} \sim M_{\phi_2^0} \sim 10^2$$
$$< M_\Phi \sim 10^3 < M_{N_1} \sim 10^5 < M_{N_2} < M_{N_3} \sim M_{\phi_1^0} \sim M_{Z'_\mu} \sim 10^6. \tag{2.15}$$

This is easily fulfilled by choosing some suitable values of the coupling parameters in eq. (2.14). However, the mass relations of eq. (2.15) will successfully lead to the leptogenesis and the CDM. Finally, it is worth emphasizing that there are not any super-high scale physics in the model.

3 Leptogenesis

The model can account for the baryon asymmetry through the leptogenesis. Below the v_1 scale but above the v_2 scale, $B - L + D$ is violated by $\langle \phi_1 \rangle$, but $B - L - D$ is conserved, moreover, is anomaly-free. The dark doublet Φ at the TeV scale has two decay modes on the basis of the model couplings and the (2.15) relations, (i) the two-body decay $\Phi \to H + \phi_2$ via the λ_7 term in eq. (2.4), (ii) the three-body decay $\Phi \to l_\alpha + l_\beta + \overline{H}$ via eq. (2.13). Figure 1 shows the tree and loop diagrams of $\Phi \to l_\alpha + l_\beta + \overline{H}$. Note that the three-body decay is mainly mediated via N_1 as shown figure 1, the diagrams in which the decay is mediated via $N_{2,3}$ can be neglected because they are greatly suppressed due to $M_{N_{2,3}}^{-4} \ll M_{N_1}^{-4}$. In term of the quantum number assignment in table 1, explicitly, this process of figure 1 simultaneously violates "-1" unit of $B - L$ number and "-1" unit of D number, namely $\triangle(B-L) = -1$ and $\triangle D = -1$, so one can obtain $\triangle(B-L+D) = -2$ and $\triangle(B-L-D) = 0$ as expected. On the other hand, the decay of figure 1 has a CP asymmetry and is out-of-equilibrium, but the decay of $\Phi \to H + \phi_2$ has no these features. However, the two-body decay rate is much larger than the three-body one, therefore the total decay width of Φ is approximately equal to the decay width of $\Phi \to H + \phi_2$.

Because the two coupling matrices of Y_1 and Y_2 contain the CP-violating sources, the decay rate of $\Phi \to l_\alpha + l_\beta + \overline{H}$ is different from one of its CP-conjugate process $\overline{\Phi} \to \overline{l_\alpha} + \overline{l_\beta} + H$ through the interference between the tree diagram and the loop one. The
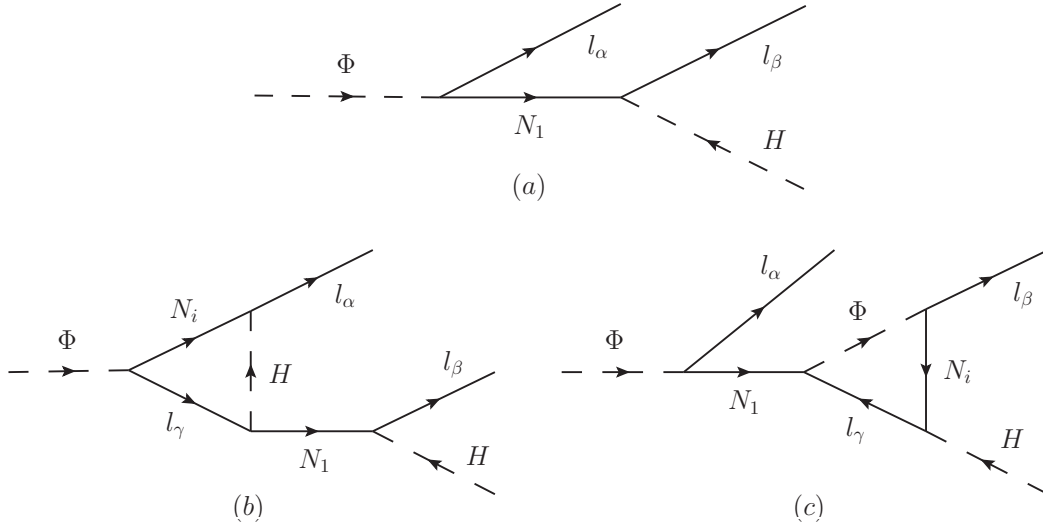
Figure 1. The tree and loop diagrams of the decay $\Phi \to l_\alpha + l_\beta + \overline{H}$ violating $B - L + D$ but conserving $B - L - D$, this decay has the CP asymmetry and is out-of-equilibrium, which eventually leads to the matter-antimatter asymmetry.

CP asymmetry of the two decay rates is defined and calculated as follows,

$$\varepsilon = \frac{\Gamma^+ - \Gamma^-}{\Gamma_\Phi^{\text{total}}} = \frac{(Y_1^\dagger Y_1)_{11} M_\Phi^4 \sum\limits_{i \neq 1} M_{N_i} \, \text{Im}[(Y_1^\dagger Y_2)_{1i}(Y_2^\dagger Y_1)_{1i}]}{768\pi^3 M_{N_1}^3 (\lambda_7 v_1)^2},$$

$$\Gamma^\pm = \sum_{\alpha,\beta} \Gamma\left(\frac{\Phi \to l_\alpha + l_\beta + \overline{H}}{\overline{\Phi} \to \overline{l_\alpha} + \overline{l_\beta} + H}\right) = \Gamma_{\text{tree}} + \Gamma_{\text{loop}}^\pm, \qquad \Gamma_{\text{tree}} = \frac{(Y_1^\dagger Y_1)_{11}(Y_2^\dagger Y_2)_{11} M_\Phi^3}{1536\pi^3 M_{N_1}^2},$$

$$\Gamma_\Phi^{\text{total}} \approx \Gamma(\Phi \to H + \phi_2) = \frac{(\lambda_7 v_1)^2}{8\pi M_\Phi}. \tag{3.1}$$

A careful calculation shows that the imaginary part of the loop integration factor of the (b) diagram is derived from the three-point function $\text{Im}[(C_0 + C_{12})(M_{l_\alpha}^2, s_{12}, M_\Phi^2, M_{N_i}^2, M_H^2, M_{l_\gamma}^2)] = \frac{2\pi i}{M_\Phi^2 - s_{12}}$, where $s_{12} = (p_{\overline{H}} + p_{l_\beta})^2$, but the (c) diagram has in fact no contribution to ε because the imaginary part of its three-point function is vanishing. According to the discussions in section 2, there are $Y_1 \sim Y_2 \sim 0.01$ and $\lambda_7 \sim 10^{-7}$, then we can roughly estimate $\varepsilon \sim 10^{-8}$ by use of eq. (2.8) and eq. (2.15), it is exactly a reasonable and suitable value for the leptogenesis.

A further calculation shows that the decay rate $\Gamma^\pm$ in eq. (3.1) is smaller than the Hubble expansion rate of the universe, namely

$$\Gamma^\pm \approx \Gamma_{\text{tree}} < H(M_\Phi) = \frac{1.66\sqrt{g_*} M_\Phi^2}{M_{\text{Pl}}}, \tag{3.2}$$

where $M_{\text{Pl}} = 1.22 \times 10^{19} \, \text{GeV}$ and g_* is the effective number of relativistic degrees of freedom. Therefore the decay process of figure 1 is actually out-of-equilibrium. At the scale of $T = M_\Phi$, the relativistic states include all of the SM particles, and ϕ_2 and χ_i

in the dark sector, so one can figure out $g_* = 114$ in eq. (3.2). By this time, we have completely demonstrated that the decay process of figure 1 is able to satisfy Sakharov's three conditions [32].

The above discussions are now integrated together, as a result, the decay of figure 1 certainly generates the following asymmetries [33, 34],

$$Y_{B-L} = \frac{n_{B-L} - \overline{n}_{B-L}}{s} = \kappa \frac{\triangle(B-L)\,\varepsilon}{g_*} = \kappa \frac{(-1)\varepsilon}{g_*} \, ,$$

$$Y_D = \frac{n_D - \overline{n}_D}{s} = \kappa \frac{\triangle D\,\varepsilon}{g_*} = \kappa \frac{(-1)\varepsilon}{g_*} \, ,$$

$$Y_{B-L+D} = \kappa \frac{\triangle(B-L+D)\,\varepsilon}{g_*} = \kappa \frac{(-2)\varepsilon}{g_*} \, ,$$

$$Y_{B-L-D} = \kappa \frac{\triangle(B-L-D)\,\varepsilon}{g_*} = 0, \tag{3.3}$$

where s is the entropy density and κ is a dilution factor. The dilution is mostly from the inverse decay. For the three-body inverse decay, the dilution effect is very weak if the departure from thermal equilibrium is severe, so we can take $\kappa \approx 1$ in eq. (3.3). Note that the dilution effect from $N_1 \to \Phi + \overline{l_\alpha}$ is almost nothing because N_1 has early decoupled and its number density is exponentially suppressed by $\frac{M_{N_1}}{M_\Phi} \sim 20$ compared to the Φ one.

At the high energy, the SM sector and the dark sector are connected each other via the heavy particles $Z'_\mu, N_i, \phi_1^0, \Phi$ mediating. As the universe temperature falls below M_Φ, all of the heavy particles have completely decayed and decoupled, thus the connection between the SM sector and the dark sector is gradually discontinued, eventually, at the low energy the SM sector and the dark sector are isolated from each other, the surviving ϕ_1 and χ_i in the dark sector constitute a dark world. As a consequence, the Y_{B-L} asymmetry is totally deposited in the SM sector because ϕ_1 and χ_i in the dark sector have vanishing $B - L$ numbers (see table 1), while the Y_D asymmetry is totally deposited in the dark sector because all of the SM particles have no D numbers (see table 1). In other words, at the low energy, the SM sector has the $B - L$ asymmetry without the D asymmetry, while the dark sector has the D asymmetry without the $B - L$ asymmetry. However, the total Y_{B-L-D} asymmetry in the two sectors is kept to be zero.

When the universe temperature drops to the energy scale $v_2 \sim v_H \sim 250\,\mathrm{GeV}$, the global $B - L - D$ symmetry is broken because ϕ_2 developing $\langle \phi_2 \rangle$ violates two unit of D number. The original complex ϕ_2 is now decomposed into the two neutral real ϕ_2^0, G^0 which are namely their own antiparticles, and also χ_R becomes a neutral Majorana fermion, namely $\chi = \chi^c$. Consequently, the Y_D asymmetry between dark particles and dark antiparticles is totally erased, or rather it is automatically vanishing. Although the total $B-L-D$ conservation in the two sectors is violated, the SM sector always conserves the $B - L$ number, therefore the Y_{B-L} asymmetry in the SM sector is unaffected and unchanged. At this temperature of $v_2 \sim v_H \sim 250\,\mathrm{GeV}$, obviously, the electroweak sphaleron process can fully put into effect in the SM sector [35], thus a part of the Y_{B-L} asymmetry is converted into the baryon asymmetry. This is given by the following relation,

$$\eta_B = \frac{n_B - \overline{n}_B}{n_\gamma} = 7.04\,c_s Y_{B-L} \approx 6.2 \times 10^{-10}, \tag{3.4}$$

where $c_s = \frac{28}{79}$ is the sphaleron conversion coefficient. 7.04 is a ratio of the entropy density to the photon number density. 6.2×10^{-10} is the current value of the baryon asymmetry [36]. Note that χ_i, ϕ_2^0, G^0 in the dark sector do not at all participate in the sphaleron process since they are all singlets under the SM group and isolated from the SM sector. When the universe temperature falls below $T \sim 100\,\text{GeV}$, the sphaleron process is closed and the baryon asymmetry is kept up to the present day. Finally, it should be stressed that the leptogenesis is elegantly achieved at the TeV scale in the model.

4 Dark matter

When the global symmetry of $U(1)_{B-L-D}$ is broken by $\langle \phi_2 \rangle$ at the scale $v_2 \sim v_H$, the dark particles χ_i, ϕ_2^0, G^0 are at first in thermal equilibrium in the dark world. At a later time ϕ_2^0 can completely decay into a pair of χ_i or G^0. However χ_i is a stable particle because it is protected by the two factors. i) The model gauge symmetries prevent it from coupling to the other particles except ϕ_2 (see eq. (2.3)), so it can not decay. ii) The Z_2 symmetry in eq. (2.1) forbids the explicit mass term $\overline{N_L} M \chi_R$, so it can not mix with the other fermions. Therefore χ_i is a stable WIMP. Among the three generation of $\chi_{1,2,3}$, a pair of heavier $\chi_{2,3}$ mainly annihilate into a pair of the lightest χ_1 via the G^0 mediator, as shown (a) in figure 2. At the last step a pair of χ_1 annihilate into a pair of G^0 by the two modes of (b) and (c) in figure 2. A careful analysis shows that the annihilation cross-section of $\chi_{2,3}$ in (a) diagram is much larger than one of χ_1 in (b) and (c) diagrams, therefore, the $\chi_{2,3}$ decoupling is much earlier than the χ_1 one, and the relic abundance of $\chi_{2,3}$ is much smaller than one of χ_1. Consequently, χ_1 becomes the principal particle of the CDM, while $\chi_{2,3}$ only bears a tiny part of the CDM budget, in addition, G^0 becomes a dark background radiation. In short, χ_1 is a desirable candidate of the CDM because its natures and relic abundance are very well consistent with ones of the CDM.

χ_1 becomes a non-relativistic particle when the temperature falls below M_{χ_1}. It has two annihilation channels. (i) $\chi_1 + \chi_1 \rightarrow G^0 + G^0$ via the χ_1 t-channel mediation, as shown (b) in figure 2, note that the χ_1 u-channel mediation is not shown in figure 2 but it is included in the following calculation. (ii) $\chi_1 + \chi_1 \rightarrow G^0 + G^0$ via the ϕ_2^0 s-channel mediation, as shown (c) in figure 2. The total annihilation rate of χ_1 is calculated as follows,

$$\Gamma(\chi_1 + \chi_1 \rightarrow G^0 + G^0) = \langle \sigma v \rangle n_{\chi_1}, \qquad n_{\chi_1} = 2 \left(\frac{M_{\chi_1} T}{2\pi} \right)^{\frac{3}{2}} e^{-\frac{M_{\chi_1}}{T}},$$

$$\sigma v = \frac{M_{\chi_1}^2}{128\pi v_2^4} \left[\left(\frac{1}{(1-4r)^2} + \frac{3-4r}{3(1-4r)} \right) v^2 - \frac{3-4r}{30(1-4r)} v^4 + \cdots \right],$$

$$\langle \sigma v \rangle = a + b \langle v^2 \rangle + c \langle v^4 \rangle + \cdots \approx a + b \frac{6\,T}{M_{\chi_1}},$$

$$v = 2\sqrt{1 - \frac{4M_{\chi_1}^2}{s}}, \qquad r = \frac{M_{\chi_1}^2}{M_{\phi_2^0}^2}, \tag{4.1}$$
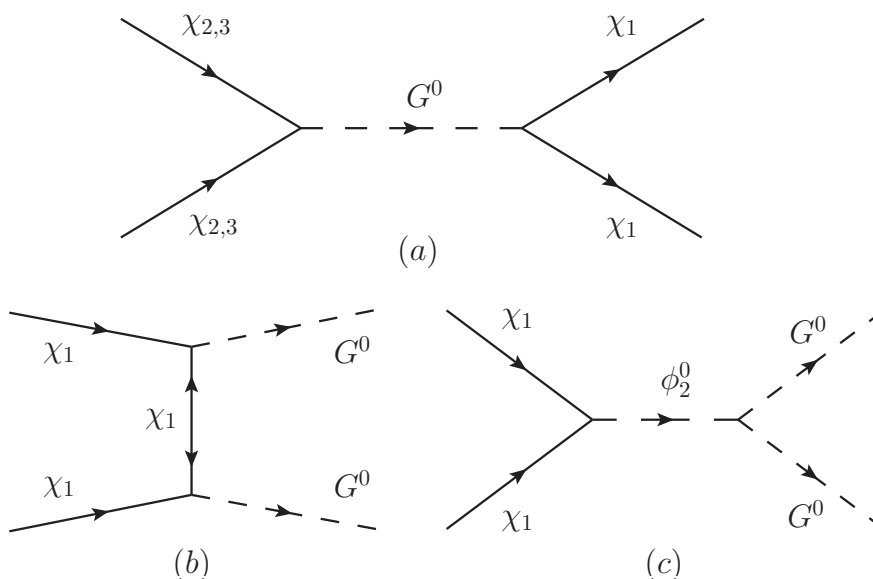
Figure 2. (a) A pair of heavier $\chi_{2,3}$ annihilating into a pair of the lightest χ_1, (b) and (c) A pair of the CDM χ_1 annihilating into a pair of Goldstone bosons G^0, which correctly leads to the "WIMP Miracle".

where a and b are determined by the σv equation, v is a relative velocity of two annihilating particles. Eq. (4.1) clearly shows that the annihilation cross-section essentially arises from a p-wave contribution. In view of eq. (2.8) and eq. (2.15), the thermal average on the annihilation cross-section is actually $\langle \sigma v \rangle \sim 10^{-9}\,\mathrm{GeV}^{-2}$, which is exactly a weak interaction cross-section. This naturally reproduces the so-called "WIMP Miracle" [37, 38].

As the universe temperature decreasing, the annihilation rate of χ_1 becomes smaller than the Hubble expansion rate of the universe, then the annihilation is out-of equilibrium and χ_1 is decoupling. The freeze-out temperature is determined by

$$\Gamma(T_f) = H(T_f) = \frac{1.66\sqrt{g_*(T_f)}\,T_f^2}{M_{\mathrm{Pl}}},$$

$$\Longrightarrow x = \frac{T_f}{M_{\chi_1}} \approx \left(17.6 + \ln\frac{M_{\chi_1}}{\sqrt{g_*(T_f)}x} + \ln\frac{\langle \sigma v \rangle}{10^{-10}\,\mathrm{GeV}^{-2}} \right)^{-1}. \tag{4.2}$$

After χ_1 is frozen out, its numbers in the comoving volume has no change any more. The current relic abundance of χ_1 can be calculated by the following equation [37, 38],

$$\Omega_{\chi_1} h^2 = \frac{0.85 \times 10^{-10}\,\mathrm{GeV}^{-2}}{\sqrt{g_*(T_f)}\,x(a + 3bx)} \approx 0.12. \tag{4.3}$$

0.12 is the current abundance of the CDM [39]. Obviously, both M_{χ_1} and v_2 are jointly in charge of the final results of eq. (4.2) and eq. (4.3). Provided $M_{\chi_1} \sim 60\,\mathrm{GeV}$ and $v_2 \sim 250\,\mathrm{GeV}$, then the solution of eq. (4.2) is $x \sim \frac{1}{25}$, namely the freeze-out temperature is $T_f \sim 2.3\,\mathrm{GeV}$. At this temperature the relativistic particles include *photon, gluon, ν^0,*

e^-, μ^-, u, d, s and G^0, so we can figure out $g_*(T_f) = 62.75$. Finally, we can correctly reproduce $\Omega_{\chi_1} h^2 \sim 0.12$ by eq. (4.1) and eq. (4.3).

Obviously, the G^0 decoupling is exactly at the same temperature as the CDM χ_1 decoupling. Since G^0 is massless and a relativistic decoupling, nowadays it should become a dark background radiation, which is analogous to the CMB photon in the visible world. Because the G^0 decoupling is much earlier than the neutrino decoupling and the photon one, its effective temperature is lower than the neutrino effective temperature and the CMB photon temperature. As a result, the current abundance of G^0, Ω_{G^0}, is smaller than the neutrino abundance $\Omega_\nu \approx 1.7 \times 10^{-3}$ and the CMB photon abundance $\Omega_\gamma \approx 5 \times 10^{-5}$, refer to the review of cosmological parameters in [1]. However, G^0 is in the dark sector and does not interact with the SM matters, so we can not detect it through the ordinary methods.

Two CDM χ_1 can interact each other through the long range exchange of G^0, but its effective potential is a repulsive force since χ_1 is its own antiparticle, therefore there are not any bound states for the CDM χ_1, they can only happen elastic scattering. When its reaction rate is smaller than the universe expansion rate, this elastic scattering will be frozen out and closed. The frozen-out temperature is determined by

$$\Gamma(\chi_1 + \chi_1 \rightarrow \chi_1 + \chi_1) = \langle \sigma v \rangle n_{\chi_1} \approx \frac{M_{\chi_1}^2}{32\pi v_2^4} \overline{v}\, n_{\chi_1} = H(T), \tag{4.4}$$

where $\overline{v} \approx \sqrt{\frac{2T}{\pi M_{\chi_1}}}$ is an average relative velocity. By use of the parameter values in eq. (5.1) below, we can calculate that the frozen-out temperature is $\frac{T}{M_{\chi_1}} \approx \frac{1}{24}$. It is approximately equal to the χ_1 decoupling temperature $\frac{T_f}{M_{\chi_1}} \approx \frac{1}{25}$. The reason for this is obviously that both the scattering cross-section in eq. (4.4) and the annihilation cross-section in eq. (4.1) are a weak interaction cross-section. Therefore, the elastic scattering between the CDM χ_1 is actually frozen out at the same time when they are decoupling. Thereafter the CDM χ_1 are completely free particles except the gravitational influence. In conclusion, the model can simply account for the CDM, in particular, naturally explain the "WIMP Miracle".

5 Numerical results and discussions

We now show some concrete numerical results of the model. All of the SM parameters have been fixed by the current experimental data [1]. Some new parameters in the model can be determined by the current data of the tiny neutrino mass, the baryon asymmetry, and the CDM abundance. For the sake of simplicity, we only choose a set of typical values in the parameter space such as

$$
\begin{aligned}
v_1 &= 2000\,\text{TeV}, & v_2 &= 250\,\text{GeV}, & v_H &= 246\,\text{GeV}, \\
M_\Phi &= 5\,\text{TeV}, & M_{\phi_2^0} &= 150\,\text{GeV}, & M_{h^0} &= 125\,\text{GeV}, \\
M_{N_3} &= 1000\,\text{TeV}, & M_{N_1} &= 100\,\text{TeV}, & M_{\chi_1} &= 58.5\,\text{GeV}, \\
\lambda_7 &= 10^{-7}, & (Y_1^\dagger Y_1)_{11} &= (Y_2^\dagger Y_2)_{11} = 10^{-4}, \\
(Y_1 Y_N^{-1} Y_2^T)_{33} &= 5 \times 10^{-4}, & \text{Im}[(Y_1^\dagger Y_2)_{13}(Y_2^\dagger Y_1)_{13}] &= -4.3 \times 10^{-7},
\end{aligned}
\tag{5.1}
$$
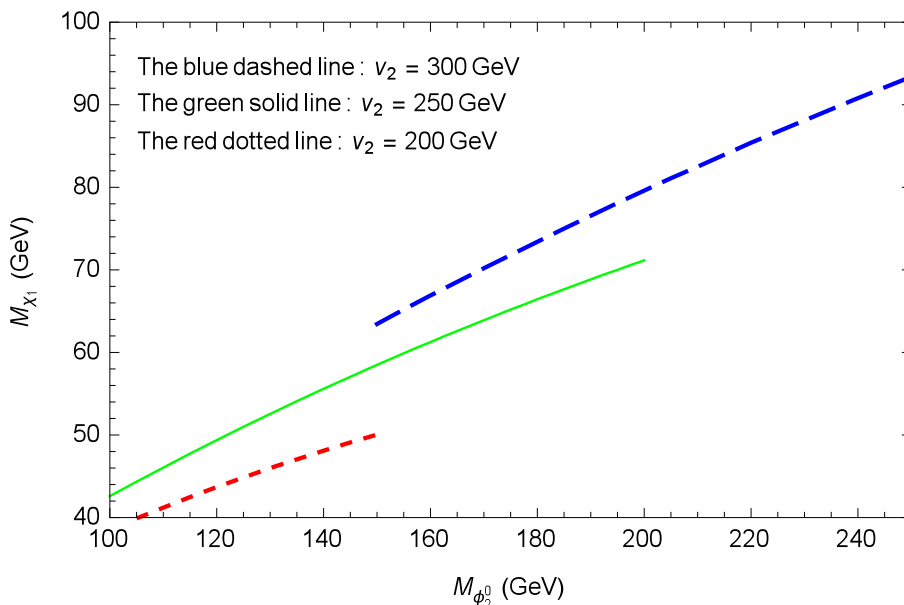
Figure 3. The curves of $M_{\phi_2^0}$ versus M_{χ_1} of the dark neutral scalar and the CDM χ_1 for the three cases of $v_2 = [300, 250, 200]$ GeV, each point of the curves can correctly fit $\Omega_{\chi_1} h^2 \approx 0.12$.

where I use M_Φ as an independent input parameter instead of $v_\Phi = \frac{\lambda_7 v_1 v_2 v_H}{M_\Phi^2} \approx 0.5$ MeV. All of the values in eq. (5.1) are completely in accordance with the model requirements discussed in section 2. Firstly, v_2 and M_{χ_1} are bounded by eqs. (4.1)–(4.3), and $M_{\phi_2^0}$ is possibly close to M_{h^0} due to $v_2 \sim v_H$. Secondly, v_1, M_Φ, M_{N_1} are jointly bounded by eqs. (3.1)–(3.4) as well as fitting the neutrino mass. Lastly, the Yukawa couplings are chosen as the reasonable and consistent values in view of $Y_1 \sim Y_2 \sim 10^{-2}$. It should be stressed that we do not make any fine-tuning in eq. (5.1), only M_{χ_1} and $\text{Im}[(Y_1^\dagger Y_2)_{13}(Y_2^\dagger Y_1)_{13}]$ are taken as the two precise values in order to fit $\Omega_{\chi_1} h^2$ and η_B respectively, while the rest of the parameters are roughly fixed to their order of magnitudes.

Now put eq. (5.1) into the foregoing equations, we can correctly reproduce the desired results,

$$m_{\nu_3} \approx 0.043 \, \text{eV}, \qquad \eta_B \approx 6.2 \times 10^{-10}, \qquad \Omega_{\chi_1} h^2 \approx 0.12, \qquad (5.2)$$

they are in agreement with the current experimental data very well [1]. Here we only give the upper bound of neutrino mass which is assumed as m_{ν_3}. The full experimental data of the neutrino masses and mixing angles can completely be fitted by choosing suitable texture of the matrix $Y_1 Y_N^{-1} Y_2^T$. In addition, we can calculate out $\frac{\Gamma_{\text{tree}}}{H} \approx 0.07$ by eqs. (3.1)–(3.2), this clearly demonstrates that the decay of figure 1 is indeed severely out-of-equilibrium.

Figure 3 shows the three curves of $M_{\phi_2^0}$ versus M_{χ_1} for the three cases of $v_2 = 300$ GeV, $v_2 = 250$ GeV, and $v_2 = 200$ GeV, each point of the curves can correctly fit $\Omega_{\chi_1} h^2 \approx 0.12$. Note that the other parameters are not involved in this fitting. Evidently, a reasonable and moderate value of v_2 is in the range of $200 \, \text{GeV} \lesssim v_2 \lesssim 300 \, \text{GeV}$. If v_2 is too high, the χ_1 annihilation cross-section will be too small, then the χ_1 relic abundance will be overclose.
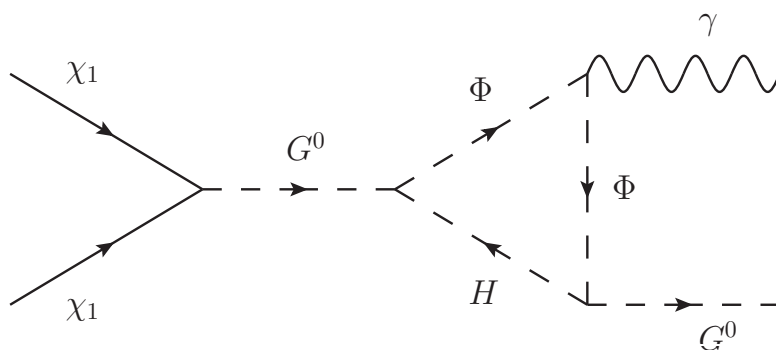
Figure 4. The indirect detection of the CDM χ_1 through a search for the high-energy gamma photon and Goldstone boson in the cosmic rays, and its mass can accurately be measured by the energy relation $E_\gamma = E_{G^0} = M_{\chi_1}$.

Conversely, if v_2 is too low, the χ_1 annihilation cross-section will be too large, then the χ_1 relic abundance will be deficiency. Therefore v_2 should be around the electroweak scale v_H. In addition, the curves clearly indicate that the ϕ_2^0 mass is probably in the area of $100\,\mathrm{GeV} \lesssim M_{\phi_2^0} \lesssim 250\,\mathrm{GeV}$, and the CDM χ_1 mass is probably in the range of $40\,\mathrm{GeV} \lesssim M_{\chi_1} \lesssim 90\,\mathrm{GeV}$. In short, the future experimental search for χ_1 and ϕ_2^0 should focus on this parameter space of figure 3.

In the end, we simply discuss the test of the model. Some new particles can be produced at the TeV-scale colliders. The relevant processes are as follows,

$$p + p \to \gamma + \gamma \to \Phi + \overline{\Phi}, \quad e^- + e^+ \text{ or } p + \overline{p} \to \gamma \to \Phi + \overline{\Phi},$$
$$\Phi \to l_\alpha + l_\beta + \overline{H}, \quad \Phi \to H + \phi_2^0 \text{ or } H + G^0, \quad \phi_2^0 \to \chi_1 + \chi_1 \text{ or } G^0 + G^0. \quad (5.3)$$

At the present LHC [40], we have a chance to search Φ and $\overline{\Phi}$ through two gamma photon fusion if the collider energy can reach their masses, but this detection is very difficult because its cross-section is too small. A better way to produce Φ and $\overline{\Phi}$ is at the $e^- + e^+$ or $p + \overline{p}$ colliders via the gamma photon s-channel mediation as long as the center-of-mass energy is enough high, for instance, the future colliders such as CEPC and ILC have some potentials to achieve this goal [41, 42]. Only if Φ and $\overline{\Phi}$ are produced, firstly, we can directly test the leptogenesis mechanism of the model by the decay asymmetry of $\Phi \to l_\alpha + l_\beta + \overline{H}$ and $\overline{\Phi} \to \overline{l_\alpha} + \overline{l_\beta} + H$. Secondly, this can indirectly shed light on the neutrino mass origin, namely the model see-saw mechanism. Thirdly, we can probe the dark particles ϕ_2^0 and G^0 by $\Phi \to H + \phi_2^0$ and $\Phi \to H + G^0$. Lastly, ϕ_2^0 can decay into a pair of the CDM χ_1 or G^0, by which we can measure the χ_1 mass and find the Goldstone boson. All kinds of the final state signals are very clear in the decay chain of Φ and $\overline{\Phi}$. These search are possibly a intriguing direction in the future collider experiments.

Of course, the model can also be tested by some non-collider experiments. An indirect detection for the CDM χ_1 is a search for the high-energy gamma photon and Goldstone boson in the cosmic rays [43], they arise from an annihilation process of the CDM χ_1 in the dark galactic halo as shown figure 4. Since both gamma photon and Goldstone boson

are massless, their energy are fixed as $E_\gamma = E_{G^0} = M_{\chi_1}$ due to conversation of energy and momentum. If the gamma ray whose energy is 40–90 GeV is found, this is not only a definite signal of the process of figure 4, but also it can tell us the accurate mass of the CDM χ_1. A direct detection is very difficult by means of scattering off nuclei at the underground detectors such as DAMA, XENON, etc. [44], but it is not impossible. The diagram of the scattering process is similar to figure 4 but the photon line becomes an internal one and it is connected with a proton as an external line. In short, it will be very large challenges to actualize the above-mentioned experiments, this needs the researchers make a great deal of efforts, however, its scientific significance is beyond all doubt. We will give an in-depth discussion on the model test in another paper.

6 Conclusions

In summary, I suggest a new extension of the SM by introducing the dark sector with the local $U(1)_D$ symmetry. The particles in the dark sector have all non-vanishing D numbers, while all of the SM particles have no D numbers. The model also conserves the global $B-L$ symmetry and the hidden discrete Z_2 one. The three symmetries are together broken by $\langle\phi_1\rangle$ at the scale of thousands of TeVs, but the global $B-L-D$ is kept as a residual symmetry. This breaking gives rise to heavy neutral gauge boson $M_{Z'}$ and neutral Dirac fermion M_N in the dark sector. When the universe temperature is close to the electroweak scale, the global $B-L-D$ is violated by $\langle\phi_2\rangle$, this generates the CDM χ_1 mass and leads to the "WIMP Miracle". The dark doublet scalar Φ with several TeVs mass can decay into two left-handed doublet leptons and one doublet Higgs of the SM, this process can elegantly achieve the leptogenesis at the TeV scale. The tiny neutrino mass is generated by the hybrid see-saw mechanism, it is suppressed by both the heavy M_N and the small $\langle\Phi\rangle$ induced from the feeble scalar coupling. In brief, the model with fewer parameters is a simple and natural extension of the SM, it can collectively account for the tiny neutrino mass, the matter-antimatter asymmetry, and the CDM. In particular, the model gives some interesting predictions, for example, the leptogenesis at the TeV scale, the CDM χ_1 with dozens GeVs mass, the dark neutral scalar boson ϕ_2^0 with 100–250 GeV mass, the dark background radiation of Goldstone bosons with a tiny abundance, all of them are possibly probed by the TeV collider experiments, the underground detectors, and the cosmic ray search. In short, new physics of the dark sector beyond the SM sector are very attractive and worth researching in depth.

Acknowledgments

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