Interplay between dark matter and leptogenesis in a common framework

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ABSTRACT: We consider the interplay between dark matter and leptogenesis in a common framework, where three right-handed neutrinos, one fermionic dark matter and two singlet scalars are introduced into the Standard Model. The mixing of the two singlet scalars not only determines the dark matter relic density but also connects right-handed neutrino with dark matter. We consider that the baryon asymmetry is generated via the resonant leptogenesis and the right-handed neutrino masses are at the TeV level. We consider a viable parameter space satisfying the relic density constraint, and the parameter space is more flexible in the case of a larger mixing angle. We found that the existence of dark matter in the model can not only dilute the baryon asymmetry but can also generate a larger baryon asymmetry due to the process of dark matter annihilation into a pair of right-handed neutrinos. Both the dilution effect and enhanced effect can occur so that influence the observed baryon asymmetry.

KEYWORDS: Baryo-and Leptogenesis, Models for Dark Matter

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1 Introduction

The observed baryon asymmetry and dark matter relic density in the universe [1] are two long-standing problems that can provide us with new hints for new physics. Moreover, the baryon asymmetry can be obtained through the leptogenesis mechanism [2–6], which is also related to the problem of tiny neutrino masses. As for the dark matter, the correct relic density can be produced conservatively by Freeze-out [7] or Freeze-in [8] depending on the strength of the interactions associated with dark matter and the initial density of dark matter in the early universe.

A common framework for unified dark matter as well as leptogenesis can be found in ref. [9], which can explain quantitatively both the observed baryon asymmetry of our universe and dark matter relic density. However, this extension is difficult to be falsified. On the other hand, according to the fact of $\Omega_h^2 \approx 5 \Omega_b h^2$ [1], where $\Omega_h^2 \approx 0.12$ is the observed dark matter relic density and $\Omega_b h^2$ is the baryon density, a shared mechanism to generate baryon asymmetry and dark matter simultaneously will be much more attractive for the quantitative relationship, and related discussions can be found in refs. [10–14]. Especially, when comes to leptogenesis, the right-handed neutrinos may not only couple to the Standard Model (SM) but also a hidden sector where the dark matter resides, and a lepton asymmetry as well as dark matter production can be both generated by the out-of-equilibrium decay of the right-handed neutrinos [15, 16]. However, such scenarios often indicate asymmetric dark matter (ADM) [17–20], where relic dark matter is not determined by the annihilation cross section but asymmetry between particle-antiparticle number densities of dark matter.
From the point of the standard leptogenesis and WIMP (weakly interacting massive particles) DM scenario, it seems that there is little connection between leptogenesis and dark matter. On the one hand, a lepton asymmetry is generated by the decay of right-handed neutrino (RHN) out of equilibrium, then the lepton asymmetry is converted into baryon asymmetry by the sphaleron process. Such a process always happens at a high scale and demands the right neutrino mass larger than $10^9$ GeV with Davidson-Ibarra bound [21] while dark matter is still in thermal equilibrium. On the other hand, dark matter will make little difference in baryon asymmetry result in the case of Freeze-in due to the weak interaction. Alternatively, low-scale leptogenesis will be more attractive because high-scale leptogenesis is difficult to be tested at colliders. The degenerate right-handed neutrino mass can contribute to a resonant enhancement to the CP violation so that one can obtain the baryon asymmetry with right-handed mass at the TeV scale, which is the so-called resonant leptogenesis [22]. Other low-scale leptogenesis scenarios such as the Akhmedov-Rubakov-Smirnov (ARS) mechanism can be found in [23–25]. Although we can decrease right-handed neutrino mass to a low scale, dark matter may still be hardly relevant to leptogenesis since the dark matter will freeze out earlier than leptogenesis in the case of dark matter mass much larger than right-handed neutrino mass.

In fact, the symmetric WIMP DM can be connected with baryon asymmetry via the so-called WIMPy miracle [26], where the WIMP DM annihilation is directly responsible for baryogenesis. In the WIMPy baryogenesis, the Sakharov conditions are satisfied with: baryon number violation, CP violation and departure from thermal equilibrium, then a non-zero baryon number asymmetry can be generated from dark matter annihilation, and one can obtain the observed baryon asymmetry as well as dark matter relic density simultaneously. Furthermore, the WIMPy leptogenesis has also been discussed in [27], in which the lepton asymmetry arises from dark matter annihilation processes which violate CP and lepton number, and the lepton asymmetry is then converted into baryon asymmetry by electroweak sphalerons.

In this paper, we will not focus on the new mechanism to generate the baryon asymmetry and dark matter relic density but focus on the interplay between dark matter and baryon asymmetry. Therefore, we discuss them in a conservative choice that dark matter relic density is generated by the Freeze-out mechanism and baryon asymmetry is obtained via resonant leptogenesis, and the latter means right-handed neutrino masses are degenerate. Although baryon asymmetry is not generated by dark matter annihilation with the WIMPy miracle, the existence of dark matter can affect the baryon asymmetry result as long as dark matter production is related to right-handed neutrinos. We consider the case that right-handed neutrino masses are approximate to the dark matter mass. Such a region will be much more interesting since either dark matter or right-handed neutrinos are out-of-equilibrium and dark matter Freeze-out as well as leptogenesis can occur nearly at the same time. Generally speaking, new processes related to right-handed neutrinos will keep right-handed neutrino number density close to equilibrium so that dilute the baryon asymmetry. However, dark matter can also annihilate into a pair of right-handed neutrinos therefore baryon asymmetry will be strengthened. Notice that right-handed mass can be at the TeV scale in the case of successful resonant leptogenesis, and we demand the dark matter mass also at the TeV scale.

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We will not give a UV-completion model in this work, but a minimal scenario including right-handed neutrino and dark sector. For the dark sector, we introduce a singlet scalar $S$ and a fermion $\chi$, where $\chi$ carries $i$ charge and $S$ with $-1$ charge under discrete $Z_4$ symmetry. $S$ obtains vacuum expectation value and $\chi$ acquires mass after spontaneously breaking. For the visible sector, we introduce three right-handed neutrinos $N_j$ ($j = 1, 2, 3$) as well as a singlet scalar $\phi$ to the Standard Model (SM). The singlet $\phi$ also obtains the non-zero vev and couples to the three right-handed neutrinos with $\phi N_i N_j$. As for the scalar $\phi$, we have the following comments. Firstly, the singlet-neutrino couplings break the accidental global lepton-number symmetry of the SM, which is similar to the right-handed neutrino Majorana masses in the seesaw Lagrangian. As mentioned in ref. [24], this indicates such Yukawa couplings are possible to present in any low energy effective theory that contains the singlet scalar $\phi$ and a set of sterile neutrinos. Then, we assume the singlet $\phi$ is odd under a $Z_2$ symmetry of the scalar potential, such $Z_2$ symmetry can be the resident symmetry of a new gauge symmetry such as $U(1)_{B-L}$ after spontaneously breaking and the $Z_2$ symmetry can limit the couplings in the scalar potential. On the other hand, the $Z_2$ symmetry in the scalar potential may be at most an approximate symmetry that is explicitly broken by the singlet-neutrino couplings due to the small couplings. Last but not least, the introduction of the $Z_2$ symmetry can decrease the input parameters in the model and simplify our discussion. $\phi$ does not couple to $\chi$ directly because of the different discrete symmetry and we introduce $S$ to the model. As a result, the mixings of the scalars can induce processes related to dark matter and right-handed neutrinos. We consider the decoupling limit that both mixing angles of the singlet scalars with SM Higgs can be negligible so that contribution of the SM Higgs to the dark matter production can be ignored, and dark matter relic density is related to the mixing of the singlet scalars.

The paper is arranged as followed, we describe our framework in section 2. In section 3, we give the Blotzman equations related to baryon asymmetry and dark matter. In section 4, we give the evolution of dark matter with different parameters. In section 5, we scan the parameter space the satisfying dark matter relic density constraint as well as baryon asymmetry constraint and discuss the relationship between dark matter and baryon asymmetry. We give a summary in the last part.

2 The model framework

In this part, we give the framework including dark matter and right-handed neutrino. For the dark sector, we introduce one singlet scalar $S$ and a fermion $\chi$, where $\chi$ as the dark matter carries $i$ charge under a discrete $Z_4$ symmetry and $S$ charge is $-1$. $S$ can obtain non-zero vev $v_s$ after spontaneously symmetry breaking (SSB) so that $\chi$ will acquire mass. We also introduce three right-handed neutrinos and another singlet scalar $\phi$ to the Standard Model. The additional Lagrangian is given as followed,

$$L = -y \bar{LN}H - \frac{1}{2} M_n \bar{N}^c N - \frac{1}{2} \lambda_{mn} \bar{N}^c N - \frac{1}{2} \lambda_{sx} \bar{S} \chi - V(S, H, \phi),$$  \hspace{1cm} (2.1)$$

suppressing the generation indexes, where $L$ is the SM leptons and $H$ is the SM Higgs doublet. The term $V(S, H, \phi)$ in eq. (2.1) involves Higgs potential and other terms with the
singlet scalar $S$ as well as $\phi$. We assume the singlet $\phi$ is $Z_2$ odd in the scalar potential and obtain the vacuum expectation value $v_b$ after SSB. Therefore, the term $V(S, H, \phi)$ can be given by,

$$V(S, H, \phi) = -\mu H^2 + \lambda H^4 - \mu_s S^2 + \lambda_s S^4 - \mu_p \phi^2 + \lambda_p \phi^4 + \lambda_{hs} H^2 S^2 + \lambda_{hp} H^2 \phi^2 + \lambda_{sp} S^2 \phi^2.$$  

(2.2)

Note that we have no terms such as $H^2 S \phi$ because $S$ and $\phi$ carry different charges. In the unitary gauge, $H, S$ and $\phi$ can be given by,

$$H = \left( \begin{array}{c} 0 \\ v + h \sqrt{2} \end{array} \right), \quad S = v_s + s \sqrt{2}, \quad \phi = v_b + \tilde{\phi} \sqrt{2},$$  

(2.3)

where $v = 246$ GeV is the SM vacuum expectation value. We consider the decoupling limit that $\lambda_{hp}, \lambda_{hs} \ll 1$ so that the mass matrix $M_h$ for scalars after SSB can be simplified by,

$$M_h = \begin{pmatrix} 2\lambda_s v_s^2 & \lambda_{sp} v_b v_s & 0 \\ \lambda_{sp} v_b v_s & 2\lambda_p v_b^2 & 0 \\ 0 & 0 & 2\lambda v^2 \end{pmatrix}.$$  

(2.4)

The mass matrix $M_h$ can be diagonalized by the matrix $U$ with

$$U = \begin{pmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$  

(2.5)

where $\theta$ is the mixing angle of the two singlet scalars. Correspondingly, after rotation from the flavor eigenstate to the mass eigenstate, we have three Higgses defined by,

$$\begin{pmatrix} h_1 \\ h_2 \\ h_0 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} s \\ \phi \\ h \end{pmatrix},$$  

(2.6)

where $h_0$ is the SM Higgs, and $h_{1,2}$ are the new Higgs particles in the model. Particularly, $h_1$ and $h_2$ can mix with each other, and the mixing angle $\theta$ will also determine dark matter relic density. Furthermore, we choose Higgs masses as well as the mixing angle as the inputs so that parameters related to singlet scalars in the model can be expressed as follows,

$$\lambda_s = \frac{m_1^2 \cos^2 \theta}{2v_s^2} + \frac{m_2^2 \sin^2 \theta}{2v_s^2},$$

$$\lambda_p = \frac{m_1^2 \sin^2 \theta}{2v_b^2} + \frac{m_2^2 \cos^2 \theta}{2v_b^2},$$

$$\lambda_{sp} = \frac{(m_2^2 - m_1^2) \sin 2\theta}{2v_b v_s}.$$  

(2.7)

where $m_{1,2}$ are the $h_{1,2}$ mass. To obtain a stable potential, we have

$$4\lambda_s \lambda_p - \lambda_{sp}^2 > 0, \quad \lambda_{sp} > 0,$$  

(2.8)
known as co-positivity constraints \cite{28}, and the perturbativity constraints are given by $\lambda_{sp,s,p} < 4\pi$.

We consider a conservative choice of the decoupling limit that the mixings of singlets with SM doublets are negligible. Therefore, the contribution of SM particles to the dark matter production such as $ff \rightarrow \chi\chi$ are highly suppressed where $f$ represents the SM fermions, and the left relevant processes with dark matter are the right-handed neutrinos as well as the $h_{1,2}$. It is worth stressing that the most stringent bounds on the mixing angle $\alpha$ of the SM Higgs arise from the $W$ boson mass correction \cite{29}, and the current constraint is given by $|\sin\alpha| \lesssim 0.24$ at 95\% C.L. according to \cite{30}.

In this work, we assume the vacuum expectation value $v_b$ as a free parameter and both $v_b$ and $v_s$ are beyond EWPT (electroweak phase transition) scale. For simplicity, we fix $v_b = 2$ TeV as a constant in the following discussion. After SSB, dark matter mass $m_\chi$ can be given by $m_\chi = \lambda_{sx} v_s/2\sqrt{2}$, the term $(M_n + \lambda_{mn} v_b/\sqrt{2})/2$ gives the Majorana mass matrix of the right-handed neutrino with $M_n$ being the bare mass term of right-handed neutrinos, and the dynamical origin of $M_n$ is left unspecified for our work. The matrix $\lambda_{mn}$ characterizes the strength of the Yukawa coupling of $\phi N N$ while $\lambda_{sx}$ describes the strength of singlet-DM Yukawa interaction.

Notice that the existence of the singlet scalar $\phi$ can also induce a successful low-scale leptogenesis by the scalar-singlet-mediated one-loop diagrams due to the Yukawa coupling with right-handed neutrinos \cite{24} only if $M_n$ and $\lambda_{mn}$ can not be diagonalized simultaneously, and we ignore the effect of $\phi$ on leptogenesis in our work.

In this work, we consider the interplay between dark matter and leptogenesis in a minimal framework, we assume dark matter relic density is generated via the Freeze-out mechanism, and dark matter production processes related to SM particles are highly suppressed under the decoupling limit, while almost contribution to DM relic density comes from the new Higgses as well as right-handed neutrinos. On the other hand, we consider the observed baryon asymmetry is generated by resonant leptogenesis, and annihilation of right-handed neutrinos to dark matter may keep the neutrino number close to thermal equilibrium which dilutes the baryon asymmetry. Inversely, more right-handed neutrinos can be generated by the inverse process so that the baryon asymmetry will be strengthened. In both cases, the final baryon asymmetry can be influenced by the introduction of dark matter.

3 Boltzmann equations

In this section, we discuss the Boltzmann equations of $N$ and dark matter. In our work, we consider the decoupling limit that the mixings of both singlets with SM doublets are negligible. Under such consideration, dark matter production is mainly related to right-handed neutrinos as well as $h_{1,2}$, while the contribution from SM particles is highly suppressed. Extra contribution to the leptogenesis can arise from the channels $NN \rightarrow \chi\chi$, which is also related to dark matter. Notice that DM can annihilate into pairs of scalars that are heavier than the DM particles, which is similar with the so-called forbidden DM scenario \cite{31}. On the other hand, we assume $m_N < m_{1,2}$ and ignore the contribution of $NN \rightarrow h_{1,2}h_{1,2}$ to the BAU.
The Boltzmann equations for the $N$ abundance $Y_N$, dark matter abundance $Y_X$ and the total $(B - L)$ asymmetry $Y_{B-L}$ are given by [32],

\[
\frac{s_N H_N}{z^4} \frac{dY_N}{dz} = -\left( \frac{Y_N}{Y_{Neq}} - 1 \right) (\gamma_D + 2\gamma_{hs} + 4\gamma_{ht}) - \left( \frac{Y_N^2}{Y_{Neq}^2} - \frac{Y_X^2}{Y_{Xeq}^2} \right) 2\gamma_{N\chi}
\]

\[
\frac{s_N H_N}{z^4} \frac{dY_{B-L}}{dz} = -\left( \frac{Y_{B-L}}{2Y_{Leq}} + \epsilon_{CP} \left( \frac{Y_N}{Y_{Neq}} - 1 \right) \right) \gamma_D - \frac{Y_{B-L}}{Y_{Leq}} \left( 2(\gamma_N + \gamma_{N\chi} + \gamma_{ht}) + \frac{Y_N}{Y_{Neq}} \gamma_{hs} \right)
\]

\[
\frac{s_N H_N}{z^4} \frac{dY_X}{dz} = -\left( \frac{Y_X^2}{Y_{Xeq}^2} - \frac{Y_N^2}{Y_{Neq}^2} \right) 2\gamma_{N\chi} - \left( \frac{Y_X^2}{Y_{Xeq}^2} - 1 \right) 2\gamma_{N\chi}
\] (3.1)

where $\epsilon_{CP}$ is the CP asymmetry parameter. The CP asymmetry $\epsilon_i$ can be given by [33]:

\[
\epsilon_i = \frac{\sum_j \Gamma_{N_i \to \ell_j H} - \Gamma_{N_i \to \ell_j H*}}{\sum_j \Gamma_{N_i \to \ell_j H} + \Gamma_{N_i \to \ell_j H*}}
\]

(3.2)

\[
= -\sum_{j 
eq i} \frac{m_{N_i} \Gamma_{N_j}}{m_{N_j}^2} \left( V_{ij}^2 + S_{ij} \right) \frac{\text{Im}(yy^*)_i}{(yy^*)_i(yy^*)_ij},
\]

(3.3)

where

\[
V_{ij} = 2 \frac{m_{N_i}^2}{m_{N_j}^2} \left[ \left( 1 + \frac{m_{N_i}^2}{m_{N_j}^2} \right) \ln \left( 1 + \frac{m_{N_i}^2}{m_{N_j}^2} \right) - 1 \right],
\]

(3.4)

\[
S_{ij} = \frac{m_{N_i}^2 (m_{N_j}^2 - m_{N_j}^2)}{(m_{N_j}^2 - m_{N_i}^2)^2 + m_{N_i}^2 \Gamma_{N_j}^2},
\]

(3.5)

are respectively the vertex correction and RHN self-energy correction to the decay process with $m_{N_i}$ the $N_i$ mass and $\Gamma_{N_i}$ the $N_i$ decay width. On the other hand, the tiny left-handed neutrino masses $m_\nu$ are generated via the Type-I seesaw mechanism with [32]:

\[
m_\nu \sim \frac{y_{\nu}^2}{m_N} \sim 0.06 \text{ eV} \times \left( \frac{y}{10^{-6}} \right)^2 \left( \frac{1 \text{ TeV}}{m_N} \right).
\]

(3.6)

For the $O(\text{TeV})$ leptogenesis, we have $y \sim 10^{-6}$, and this makes the contribution of terms $\gamma_{hs,ht,N,N\chi}$ rather small since they are proportional to $y^2$ or $y^4$.

For eq. (3.1), we have the following comments. Firstly, one can omit the reaction rates in eq. (3.1) except $\gamma_D$, $\gamma_{N\chi}$ as well as $\gamma_{N\chi}$ for simplicity, and according to the first two equations of eq. (3.1), one can obtain:

\[
\frac{dY_{B-L}}{dz} + \left( \frac{z^4}{s_N H_N} \frac{\gamma_D}{2Y_{Leq}} \right) Y_{B-L} = -\epsilon_{CP} \left[ \frac{dY_N}{dz} + \frac{z^4}{s_N H_N} 2\gamma_{N\chi} \left( \frac{Y_N^2}{Y_{Neq}^2} - \frac{Y_X^2}{Y_{Xeq}^2} \right) \right]
\]

(3.7)

The analytical expression of $Y_{B-L}$ can be given by:

\[
Y_{B-L} = \epsilon_{CP} \int_{z_0}^z dz' \left[ \frac{dY_N}{dz'} + \frac{z'^4}{s_N H_N} 2\gamma_{N\chi} \left( \frac{Y_N^2}{Y_{Neq}^2} - \frac{Y_X^2}{Y_{Xeq}^2} \right) \right] \times \exp \left\{ - \int_{z'}^z dz'' \frac{z''^4}{s_N H_N} \frac{\gamma_D(z'')}{2Y_{Leq}} \right\}
\]

(3.8)
where we adopt $z_{\text{in}} = 1$ as the lower limit of the integral [32]. Note that eq. (3.8) can be simplified into the general expression for leptogenesis if $\gamma_{N_X} \approx 0$:

$$Y_{B-L} \approx \epsilon_{\text{CP}} \int_{z_{\text{in}}}^{z} dz' \frac{dY_N}{dz'} \times \exp\left\{ - \int_{z'}^{z''} dz''' \frac{z'''}{s_N H_N} \frac{\gamma_D(z''')}{2 Y_{\text{Leq}}} \right\},$$  

(3.9)

and this means that dark matter makes no difference on the BAU. Roughly speaking, the sign of $(Y_{X}^{2}/Y_{\text{eq}}^{2} - Y_{\text{Neq}}^{2}/Y_{\text{Xeq}}^{2})$ in eq. (3.8) can influence the generated lepton asymmetry, which indicates the possibility of the BAU result being enhanced or diluted compared with the case of no dark matter. In addition, $Y_{X}$ is also related to the reaction rate $\gamma_{N_X}$, which will influence the enhanced effect or the dilution effect.

One optional trick to estimate eq. (3.8) is that one can assume $Y_{X}/Y_{\text{Xeq}} \approx 1$, $Y_{N}/Y_{\text{Neq}} + 1 \approx 2$ and $dY_{N}/dz \approx dY_{\text{Neq}}/dz$ [32] initially so that eq. (3.8) can be given by:

$$Y_{B-L} \approx \epsilon_{\text{CP}} \int_{z_{\text{in}}}^{z} dz' \frac{dY_{\text{Neq}}}{dz'} \frac{\gamma_D(z')}{\gamma_D(z')+4\gamma_{N_X}(z')} \times \exp\left\{ - \int_{z'}^{z''} dz''' \frac{z'''}{s_N H_N} \frac{\gamma_D(z''')}{2 Y_{\text{Leq}}} \right\}.$$  

(3.10)

Obviously, the $\epsilon_{\text{CP}}$ and $\gamma_D$ in the above equation can generate the lepton asymmetry, but $\gamma_{N_X}$ tends to wash out such asymmetry since $\gamma_{N_X}$ tends to push $N$ back to the equilibrium. In addition, the BAU is independent of $Y_{X}$ but related to the reaction rate $\gamma_{N_X}$. The above analysis indicates that the BAU will be diluted due to the existence of dark matter compared with the case of no dark matter at the early stage.

The BAU obtains contributions from three right-handed neutrinos when we assume the right-handed neutrinos are degenerate. If the decay widths of the three right-handed neutrinos are comparable, then the generated BAU should be three times that mere one right-handed neutrino decay. On the other hand, if the decay widths have a hierarchy, the CP asymmetries will also do so and the generated BAU can be dominated by one of the right-handed neutrinos [33], so that a one-flavor discussion will be sufficient, and we consider such a scenario in this work and we have $\epsilon_{\text{CP}} = \epsilon_{1}$. For simplicity, we assume that dark matter is also determined by mere one right-handed neutrino, and we will have a similar conclusion when we consider three right-handed neutrinos. We denote $N$ as $N_{1}$ and $\lambda_{mn}$ as the Yukawa coupling of $\phi N_{1}N_{1}$ for simplicity. $z$ is defined by $z = m_{N}/T$ with $T$ being the temperature. $H_N$ and $s_N$ correspond to the Hubble rate and entropy density respectively. $Y_{\text{Neq}}$ as well as $Y_{\text{Xeq}}$ correspond to the abundance of right-handed neutrino and dark matter at thermal equilibrium respectively, which can be given by:

$$Y_{\text{Neq}}(z) = \frac{45 z^2}{2 \pi^4 g_*} K_2(z),$$

$$Y_{\text{Xeq}}(z) = \frac{45 z^2 m_{\chi}^2}{m_N^2 \pi^4 g_*} K_2 \left( \frac{z m_{\chi}}{m_N} \right)$$

(3.11)

and $Y_{\text{Leq}}$ is the lepton abundance at thermal equilibrium with

$$Y_{\text{Leq}} = \frac{6}{s_N} \frac{m_N^3 \zeta(3)}{4 \pi^2}$$

(3.12)

where $g_* = 106.75$ is the effective degree of freedom, $\zeta(x)$ is the Riemann zeta function and $K_2(x)$ is the Bessel function.
The term $\gamma_D$ is the reaction rate for $N \rightarrow HL$, $\gamma_{hs}$ and $\gamma_{ht}$ are the reaction rate of s-channel $NL \rightarrow qt$ and t-channel $Nt \rightarrow Lq$ mediated by Higgs, where $t$ is the top quark. The terms $\gamma_N$ and $\gamma_{Nt}$ in the $(B - L)$ asymmetry equations are the s-channel and t-channel contributions of $ LH \rightarrow \bar{L}H$, which can wash out the baryon asymmetry. We follow the results of [33], and the analytic expressions for these terms can be found in [33]. We have new terms involving dark matter as well as RHN. The term $\gamma_{N\chi}$ represents the reaction rate of $NN \rightarrow \chi\chi$, which is defined by,

$$\gamma_{N\chi} = \frac{m_N}{8\pi^2z} \int_{\max\{4m_N^2,4m_{\chi}^2\}}^{\infty} dx \sigma_{N\chi}(x) x^2 K_1 \left( \frac{z}{m_N\sqrt{x}} \right)$$

(3.13)

where $K_1(x)$ is the modified Bessel function, $x$ is the squared center-of-mass energy and $\sigma_{N\chi}(x)$ is the reduced cross section of $NN \rightarrow \chi\chi$, which is given by,

$$\sigma_{N\chi}(x) = \frac{1}{4} \theta(\sqrt{x} - 2m_N) \lambda^2 \left(1, \frac{m_N^2}{x}, \frac{m_{\chi}^2}{x}\right) \cos^2 \theta_{\lambda x} \left( \frac{m_{\chi}^2 - m_N^2}{2} (x - 4m_N^2) \right)$$

$$\times \frac{\lambda(1,m_{\chi}^2, m_N^2)}{8\pi(x - m_{\chi}^2)^2(x - m_N^2)^2}$$

(3.14)

where $\lambda(a, b, c) = \sqrt{(a - b - c)^2 - 4bc}$, $\theta(\sqrt{x} - 2m_N)$ is the theta function. Note that the contribution of right-handed neutrinos to dark matter can be ignored in the limit of $\sin 2\theta \rightarrow 0$ so that dark matter relic density is determined by the new Higgses, and dark matter will make no difference in the baryon asymmetry.

The term $\gamma_{\chi h}$ represents the sum of the reaction rate for $\chi\chi \rightarrow h_1h_1, h_2h_2$ and $h_1h_2$. Relevant processes are given in figure 1, we have the following results of the reduced cross section,

$$\hat{\sigma}_{\chi\chi \rightarrow h_1h_1}(x) = \frac{1}{4} \theta(\sqrt{x} - 2m_N) \lambda^2 \left(1, \frac{m_N^2}{x}, \frac{m_{\chi}^2}{x}\right) \sigma_{11}$$

$$\hat{\sigma}_{\chi\chi \rightarrow h_1h_2}(x) = \frac{1}{4} \theta(\sqrt{x} - 2m_N) \lambda^2 \left(1, \frac{m_N^2}{x}, \frac{m_{\chi}^2}{x}\right) \sigma_{12}$$

$$\hat{\sigma}_{\chi\chi \rightarrow h_2h_2}(x) = \frac{1}{4} \theta(\sqrt{x} - 2m_N) \lambda^2 \left(1, \frac{m_N^2}{x}, \frac{m_{\chi}^2}{x}\right) \sigma_{22}$$

(3.15)

where $\sigma_{ij}$ corresponds to the cross section of $\chi\chi \rightarrow h_ih_j$ with $i, j = 1, 2$. The cross sections related to the processes of figure 1 are calculated with Calchep [34], and the expressions
Therefore, flavor effects in the charged-lepton sector are not expected to have a major influence on our results [23].

Focus on the strong wash-out regime that 

\[ T \approx \sqrt{2m_\chi (x-m_1^2)}m_\chi (x+2m_1^2)v_b \]

+ 2 \cos^2 \theta \lambda_{sx}(m_2^2-m_1^2)m_\chi (x+2m_1^2)^2 \sin^2 \theta v_b + \sqrt{2} \cos^2 \theta \sin^2 \theta (3m_\chi^2 (m_2^2-x+m_1^2 (x-2m_1^2)))

+ 2 \lambda_{sx}^2 (m_1^2-m_2^2)(m_1^2-3m_2^2+2x)^2 v_b)^2

(3.16)

\[ \sigma_{11} = \frac{1}{128m_\chi^2 \pi (x-m_1^2)^2(x-m_2^2)^2 v_b^2} \sqrt{\frac{(x-4m_1^2)(x-4m_2^2)}{s^2}} \sin^2 \theta \]

\times (3\sqrt{2} m_\chi^2 (x-m_1^2) \sin^2 \theta + 2 \cos^5 \theta \lambda_{sx} (m_2^2-m_1^2) m_\chi (x+2m_1^2) v_b

+ 2 \cos^2 \theta \lambda_{sx} (m_2^2-m_1^2)m_\chi (x+2m_1^2)^2 \sin^2 \theta v_b + \sqrt{2} \cos^2 \theta \sin^2 \theta (3m_\chi^2 (m_2^2-x+m_1^2 (x-2m_1^2)))

+ 2 \lambda_{sx}^2 (m_1^2-m_2^2)(m_1^2-3m_2^2+2x)^2 v_b)^2 \]

and

\[ \sigma_{22} = \frac{1}{128m_\chi^2 \pi (x-m_1^2)^2(x-m_2^2)^2 v_b^2} \sqrt{\frac{(x-4m_2^2)(x-4m_1^2)}{x^2}} \cos^2 \theta \]

\times (3\sqrt{2} m_\chi^2 (x-m_1^2) \cos^5 \theta - 2 \cos^2 \theta \lambda_{sx} (m_2^2-m_1^2) m_\chi (x+2m_1^2) v_b \sin^2 \theta

- 2 \lambda_{sx} (m_1^2-m_2^2)m_\chi (x+2m_1^2)^2 \sin^2 \theta v_b + \sqrt{2} \cos^2 \theta \sin^2 \theta (3m_\chi^2 (m_2^2-x+m_1^2 (x-2m_1^2)))

+ 2 \lambda_{sx}^2 (m_2^2-m_1^2)(m_1^2-3m_2^2+2x)^2 v_b)^2 \]

(3.17)

For the reaction rate of $\chi \chi \rightarrow h_1 h_1, h_1 h_2$ and $h_2 h_2$, we have

\[ \gamma_{h_1 h_1} = \frac{m_N}{8\pi^2 x} \int_{\max\{4m_1^2,4m_2^2\}}^{\infty} dx \hat{\sigma}_{\chi \chi \rightarrow h_1 h_1} (x) x^{3/2} K_1 \left( \frac{z}{m_N \sqrt{x}} \right) \]

(3.19)

\[ \gamma_{h_1 h_2} = \frac{m_N}{8\pi^2 x} \int_{\max\{m_1+m_2,4m_2^2\}}^{\infty} dx \hat{\sigma}_{\chi \chi \rightarrow h_1 h_2} (x) x^{3/2} K_1 \left( \frac{z}{m_N \sqrt{x}} \right) \]

(3.20)

\[ \gamma_{h_2 h_2} = \frac{m_N}{8\pi^2 x} \int_{\max\{4m_2^2,4m_2^2\}}^{\infty} dx \hat{\sigma}_{\chi \chi \rightarrow h_2 h_2} (x) x^{3/2} K_1 \left( \sqrt{x} \frac{z}{m_N} \right) \]

(3.21)

Note that we have ignored the contribution of $\chi \chi \rightarrow \nu \nu$ and $\chi \chi \rightarrow N \nu$ due to the tiny heavy-light neutrino mixing angle, where $\nu$ represents neutrino. On the other hand, the interactions involving dark matter as well as $h_{1,2}$ do not enter the baryon asymmetry equation at this order and therefore can not wash out the asymmetry.

We assume our universe started with the total $(B-L)$ charge zero, and the non-zero baryon asymmetry $Y_B$ can be dynamically generated above the sphaleron decoupling temperature $T_{sph} = 131.7$ GeV [35], which is given by $Y_B = \frac{28}{79} Y_{B-L}$ [22]. Alternatively, we focus on the strong wash-out regime that $m/m_\nu \gg 1$, where $m$ is the effective neutrino mass defined by $v^2(y y^*)/m_N$ and $m_\nu \approx 1.08 \times 10^{-3}$ eV is the equilibrium neutrino mass. Therefore, flavor effects in the charged-lepton sector are not expected to have a major influence on our results [23].
Figure 2. Evolution of dark matter relic density with dark matter mass $m_\chi$, where the black line is the observed value with $\Omega h^2 = 0.12$ [38] where we fix $\sin \theta = 0.01$. The blue line is the benchmark line we choose $m_2 = 1500$ GeV, $m_1 = 1000$ GeV, $\lambda_{sx} = 0.1$, $\lambda_{mn} = 0.1$ and $m_N = 800$ GeV, and other colored lines correspond to the case varying one of the parameters.

4 Dark matter

Technically, we implement the model with Feynrules [36], and calculate the relic density with MicrOMEGAs [37] numerically. We give the evolution of dark matter relic density with dark matter mass $m_\chi$ in figure 2 and figure 3 corresponding to $\sin \theta = 0.01$ and $\sin \theta = 0.9$ respectively, where dark matter mass is set within $[400 \text{ GeV}, 2000 \text{ GeV}]$. In both figures, the black line is the observed value with $\Omega h^2 = 0.12$ [38]. The blue line is the benchmark line we choose $m_2 = 1500$ GeV, $m_1 = 1000$ GeV, $\lambda_{sx} = 0.1$, $\lambda_{mn} = 0.1$ and $m_N = 800$ GeV, and other colored lines correspond to the case varying one of the parameters.

In figure 2, the small $\sin \theta$ value limits the contribution of right-handed neutrinos to dark matter, and new Higgses play a more important role in determining DM relic density. The relic density increases with the increase of $m_\chi$ but we have a peak in the case of $m_\chi \approx 1/2m_1$ due to the $s$-channel resonant-enhanced processes of $\chi\chi \rightarrow NN$. However, such a resonant-enhanced effect does not decrease relic density a lot due to the small $\sin \theta$ as we mentioned above. On the other hand, the small dark matter-scalar Yukawa coupling $\lambda_{sx}$ induces a small annihilation cross section so that dark matter is over-abundant, and dark matter relic density much decreases in the case of $\lambda_{sx} = 1$, where the processes of dark matter annihilation into new Higgses are dominant and the peak arising from $s$-channel enhanced resonant is not obvious.

According to figure 3, we have different results in the case of $\sin \theta = 0.9$ since right-handed neutrinos can also play important role in determining dark matter relic density. We have a resonant region at about $m_\chi = 1/2m_1$, where the relic density drops sharply, and intersect with the relic density constraint curve. What’s more, we have another peak in the case of $m_\chi \approx m_1$, where the t-channel Higgs-mediated processes open so that decreasing the relic density. In both figures, the lines correspond to different $\lambda_{mn}$ and $m_N$ are almost coincide with the benchmark line, which indicates $m_N$ and small $\lambda_{mn}$ can make little difference on relic density.
Aside from the observed relic density constraint, direct detection for dark matter puts the most stringent limit on the dark matter parameter space. Concretely speaking, for dark matter mass $m_\chi \gtrsim 2$ GeV, the direct detection experiments give the most stringent constraint on the spin-independent DM matter scattering with nucleon, and XENON1T \cite{46} gives a stringent bound for $m_\chi > 6$ GeV. On the other hand, considering neutrino floor limit \cite{47,48} on the current probe sensitive to dark matter, WIMP dark matter is facing a serious crisis since there is no evidence for the existence of dark matter. Fortunately, in our work, direct detection constraint is much weak since processes involving dark matter are new Higgses as well as right-handed neutrinos but SM particles are almost irrelevant.

5 Discussion

5.1 Part I

In this section, we discuss the interplay between dark matter and leptogenesis in our framework. Firstly, we discuss the parameter space related to dark matter. There are seven parameters in our model with

$$m_\chi, m_1, m_2, \sin \theta, \lambda_{sx}, \lambda_{mn}, m_N.$$  \hspace{1cm} (5.1)

For different $\sin \theta$, we will have different parameter space depending on the contribution of right-handed neutrino to relic density. Therefore, we consider two cases of $\sin \theta = 0.01$ and $\sin \theta = 0.9$, where right-handed neutrinos can play an important role in determining dark matter relic density in the latter case. For $m_1$ and $m_2$, we consider two cases with $m_2 = 1.5 m_1$ and $m_2 = 0.8 m_1$ for simplicity. Particularly, we will come to the Forbidden-DM case when $m_\chi < m_{1,2}$, while the scalars that are produced in DM annihilation can
The results satisfying dark matter relic density constraint in the following figures, we have a wider parameter space for $m$ with $m_1 > m_2$ set $m_2 = 0.8m_1$. Due to the small mass splitting of $m_\chi$ with $m_2$, dark matter mass can decrease to about 500 GeV with the correct relic density as in figure 9 and figure 11. On the other hand, we will have a wider parameter space for $\lambda_{mn} - \lambda_{sx}$ in the case of $\sin \theta = 0.01$ and $\sin \theta = 0.9$. We give the result of $m_N - m_\chi$ satisfying dark matter constraint in figure 9 and figure 11 corresponding to the case of $\sin \theta = 0.01$ and $\sin \theta = 0.9$ respectively, where points with different colors represent $m_2$ taking different values. Similarly, we have a more flexible parameter space for $m_N - m_\chi$ for the light $m_2$. We give the results satisfying dark matter relic density constraint in the following figures, where figure 4 to figure 7 correspond to $m_2 = 1.5m_1$, and figure 8 to figure 11 is $m_2 = 0.8m_1$.

In figure 4 and figure 5, we have $\sin \theta = 0.01$ and $m_2 = 1.5m_1$, and the dominant processes related to dark matter relic density are $\chi \chi \rightarrow h_{1,2}h_{1,2}$. The viable region for $\lambda_{sx}$ satisfying relic density constraint is limited at $O(1)$ level. For a smaller $\lambda_{sx}$, the DM annihilation cross section can be so small that DM will be over-abundant and for the larger $\lambda_{sx}$, we will have dark matter under-abundant due to the large cross section. On the other hand, $\lambda_{sx}$ is also related to dark matter mass, and a larger $\lambda_{sx}$ always corresponds to a larger $m_\chi$ as we can see from figure 4. As we mentioned above, $\lambda_{mn}$ makes little difference in the dark matter relic density in this case that one can always obtain the correct relic density among the chosen parameter space with $0.001 < \lambda_{mn} < 0.1$. In figure 5, we give the result of the $m_N - m_\chi$ satisfying DM relic density constraint, where points with different colors represent $m_1$ taking different values. Since the contribution of the right-handed neutrino to relic density is limited like $\lambda_{mn}$ in this case, we also have a flexible region for $m_N$ value. For $m_\chi < 400$ GeV, the process of $\chi \chi \rightarrow h_{1,2}$ is suppressed due to the large relative mass splitting of $m_\chi$ with $m_1$ [31], and such region is excluded for the over-abundant dark matter.

In figure 6 and figure 7, we give the results in the case of $\sin \theta = 0.9$, where annihilation of dark matter into right-handed neutrinos will also make difference on the relic density, and we have a wider parameter space for $\lambda_{sx}$ with $1 < \lambda_{sx} < 1.8$ as we can see in figure 6. On the other hand, $m_\chi$ will not just increase with the increase of $\lambda_{sx}$ like the case of $\sin \theta = 0.01$ because of the extra processes. In figure 7, we give the result of the $m_N - m_\chi$ satisfying DM relic density constraint, where points with different colors represent $m_1$ taking different values. Notice that we will also come to the Forbidden-DM scenario with $\chi \chi \rightarrow NN$ in the case of $m_\chi < m_N$, and we can have the similar result with $\sin \theta = 0.01$ when the relative mass splitting of $m_\chi$ with $m_N$ is large so that $\chi \chi \rightarrow NN$ is highly suppressed.

For $m_\chi < 400$ GeV, the process of $\chi \chi \rightarrow h_{1,2}$ is suppressed due to the large relative mass splitting of $m_\chi$ with $m_1$ [31], and such region is excluded for the over-abundant dark matter. We give the results satisfying dark matter relic density constraint in the following figures, where figure 4 to figure 7 correspond to $m_2 = 1.5m_1$, and figure 8 to figure 11 is $m_2 = 0.8m_1$.

In figure 4 and figure 5, we have $\sin \theta = 0.01$ and $m_2 = 1.5m_1$, and the dominant processes related to dark matter relic density are $\chi \chi \rightarrow h_{1,2}h_{1,2}$. The viable region for $\lambda_{sx}$ satisfying relic density constraint is limited at $O(1)$ level. For a smaller $\lambda_{sx}$, the DM annihilation cross section can be so small that DM will be over-abundant and for the larger $\lambda_{sx}$, we will have dark matter under-abundant due to the large cross section. On the other hand, $\lambda_{sx}$ is also related to dark matter mass, and a larger $\lambda_{sx}$ always corresponds to a larger $m_\chi$ as we can see from figure 4. As we mentioned above, $\lambda_{mn}$ makes little difference in the dark matter relic density in this case that one can always obtain the correct relic density among the chosen parameter space with $0.001 < \lambda_{mn} < 0.1$. In figure 5, we give the result of the $m_N - m_\chi$ satisfying DM relic density constraint, where points with different colors represent $m_1$ taking different values. Since the contribution of the right-handed neutrino to relic density is limited like $\lambda_{mn}$ in this case, we also have a flexible region for $m_N$ value. For $m_\chi < 400$ GeV, the process of $\chi \chi \rightarrow h_{1,2}$ is suppressed due to the large relative mass splitting of $m_\chi$ with $m_1$ [31], and such region is excluded for the over-abundant dark matter.

In figure 6 and figure 7, we give the results in the case of $\sin \theta = 0.9$, where annihilation of dark matter into right-handed neutrinos will also make difference on the relic density, and we have a wider parameter space for $\lambda_{sx}$ with $1 < \lambda_{sx} < 1.8$ as we can see in figure 6. On the other hand, $m_\chi$ will not just increase with the increase of $\lambda_{sx}$ like the case of $\sin \theta = 0.01$ because of the extra processes. In figure 7, we give the result of the $m_N - m_\chi$ satisfying DM relic density constraint, where points with different colors represent $m_1$ taking different values. Notice that we will also come to the Forbidden-DM scenario with $\chi \chi \rightarrow NN$ in the case of $m_\chi < m_N$, and we can have the similar result with $\sin \theta = 0.01$ when the relative mass splitting of $m_\chi$ with $m_N$ is large so that $\chi \chi \rightarrow NN$ is highly suppressed.

For $m_\chi < 400$ GeV, the process of $\chi \chi \rightarrow h_{1,2}$ is suppressed due to the large relative mass splitting of $m_\chi$ with $m_1$ [31], and such region is excluded for the over-abundant dark matter. We give the results satisfying dark matter relic density constraint in the following figures, where figure 4 to figure 7 correspond to $m_2 = 1.5m_1$, and figure 8 to figure 11 is $m_2 = 0.8m_1$.

In figure 4 and figure 5, we have $\sin \theta = 0.01$ and $m_2 = 1.5m_1$, and the dominant processes related to dark matter relic density are $\chi \chi \rightarrow h_{1,2}h_{1,2}$. The viable region for $\lambda_{sx}$ satisfying relic density constraint is limited at $O(1)$ level. For a smaller $\lambda_{sx}$, the DM annihilation cross section can be so small that DM will be over-abundant and for the larger $\lambda_{sx}$, we will have dark matter under-abundant due to the large cross section. On the other hand, $\lambda_{sx}$ is also related to dark matter mass, and a larger $\lambda_{sx}$ always corresponds to a larger $m_\chi$ as we can see from figure 4. As we mentioned above, $\lambda_{mn}$ makes little difference in the dark matter relic density in this case that one can always obtain the correct relic density among the chosen parameter space with $0.001 < \lambda_{mn} < 0.1$. In figure 5, we give the result of the $m_N - m_\chi$ satisfying DM relic density constraint, where points with different colors represent $m_1$ taking different values. Since the contribution of the right-handed neutrino to relic density is limited like $\lambda_{mn}$ in this case, we also have a flexible region for $m_N$ value. For $m_\chi < 400$ GeV, the process of $\chi \chi \rightarrow h_{1,2}$ is suppressed due to the large relative mass splitting of $m_\chi$ with $m_1$ [31], and such region is excluded for the over-abundant dark matter.
The interplay between dark matter and leptogenesis is determined by the process of $\chi\chi \rightarrow NN$ and the inverse process $NN \rightarrow \chi\chi$ together. These two processes are not always in thermal equilibrium since the number density of either $N$ or $\chi$ can be highly exponent suppressed when the temperature is below the mass of $N(\chi)$. For the process of $\chi\chi \rightarrow NN$, more right-handed neutrinos that can decay have been generated and the baryon asymmetry is enhanced while for the inverse process right-handed neutrinos annihilate into the dark matter which dilutes the baryon asymmetry.

Notice that the cross section of such a process is proportional to $\lambda_{sx}^2\lambda_{mn}^2\sin^2\theta$, and dark matter as well as baryon asymmetry will be less relevant due to the smaller $\sin\theta$, $\lambda_{sx}$ and $\lambda_{mn}$. In addition, according to the above discussion, the parameter space of $m_\chi - \lambda_{sx}$ is
Figure 8. Results of the $\lambda_{mn} - \lambda_{sx}$ satisfying dark matter relic density constraint in the case of $\sin\theta = 0.01$ and $m_2 = 0.8m_1$, where points with different colors correspond to $m_\chi$ taking different value.

Figure 9. Results of the $m_N - m_\chi$ satisfying dark matter relic density constraint in the case of $\sin\theta = 0.01$ and $m_2 = 0.8m_1$, where points with different colors correspond to $m_2$ taking different value.

Figure 10. Results of the $\lambda_{mn} - \lambda_{sx}$ satisfying dark matter relic density constraint in the case of $\sin\theta = 0.9$ and $m_2 = 0.8m_1$, where points with different colors correspond to $m_\chi$ taking different value.

Figure 11. Results of the $m_N - m_\chi$ satisfying dark matter relic density constraint in the case of $\sin\theta = 0.9$ and $m_2 = 0.8m_1$, where points with different colors correspond to $m_2$ taking different value.

well constrained in the case of $\sin \theta = 0.01$. Therefore, we consider the case of $\sin \theta = 0.9$ in order to discuss the interplay between dark matter and leptogenesis. We fix $m_1 = 1200$ GeV and consider the parameter space satisfying relic density constraint.

We evolve the Boltzmann equations in the case of $m_2 = 1.5m_1$ and $m_2 = 0.8m_1$ respectively with eq. (3.1), where $\epsilon_{CP}$ is set to be $10^{-4}$. To obtain the baryon asymmetry, we also fix $\tilde{m} = 0.01$ eV so that the related Yukawa couplings can be given by $y = \sqrt{\frac{2m_N \tilde{m}}{m}}$.

In figure 12, we give the relationship between the baryon asymmetry $Y_B$ and dark matter mass in the case of $m_2 = 1.5m_1$, where dark matter mass is constrained within [450 GeV, 900 GeV]. For the heavier dark matter, dark matter can make little difference in the baryon asymmetry since the heavier dark matter may be frozen-out while right-handed neutrinos are still in thermal equilibrium. The black line corresponds to the baryon
Figure 12. Relationship between baryon asymmetry $Y_B$ and dark matter mass $m_\chi$, where we fixed $m_1 = 1200$ GeV, $m_2 = 1.5m_1$ and $\sin \theta = 0.9$. The black line is the result without dark matter, while other colored lines correspond to the case that $m_N$ takes value from 600 GeV to 800 GeV. The asymmetry value without dark matter when evaluating Boltzmann equations, and other colored lines correspond to $m_N$ taking values from 600 GeV to 800 GeV. The colored points in the lines are some benchmark points around 600 GeV to 800 GeV corresponding to $m_N$. Note that the region above the black line represents the baryon asymmetry is strengthened while the leptogenesis result is diluted below the black line.

For $m_N = 600, 700$ and 800 GeV, the left part of the curves corresponding to the light dark matter mass region are above the black line, which indicates the baryon asymmetry is strengthened. Particularly, we have a peak corresponding to $m_\chi \approx m_1/2$, where the baryon asymmetry is strengthened due to the resonant effect. As dark matter mass becomes larger, the dilution effect becomes efficient so that the generated baryon asymmetry is smaller than the case without dark matter.

In figure 13, we give the relationship between baryon asymmetry $Y_B$ and dark matter mass in the case of $m_2 = 0.8m_1$. Contrary to the case of $m_2 = 1.5m_1$, the curves are all below the black line with $m_N = 600, 700$ and 800 GeV, which means baryon asymmetry is diluted with the process $NN \rightarrow \chi \chi$ induced by the lighter $m_2$. However, we can also find a peak in the case of $m_\chi \approx m_1/2$ where the process of $NN \rightarrow \chi \chi$ is resonant-enhanced.

It is worth stressing that with the increase of dark matter mass, the baryon asymmetry will be approximate to the value without dark matter case until the result is almost not affected by the existence of dark matter, which corresponds to the case that dark matter freeze-out is much earlier than leptogenesis freeze-out. Similarly, for the smaller dark matter mass, dark matter will also make little difference in the baryon asymmetry since leptogenesis freeze-out is much earlier than dark matter freeze-out.

Furthermore, we evolve the baryon asymmetry in the case of $m_2 = 1.5m_1$ to obtain the observed result in figure 14 and figure 15. In figure 14, we choose a set of parameters satisfying dark matter relic density constraint with:

$$m_\chi = 650 \text{ GeV}, \quad m_1 = 1170 \text{ GeV}, \quad \lambda_{sx} = 1.425, \lambda_{mn} = 0.1, \quad m_N = 800 \text{ GeV}$$
Figure 13. Relationship between baryon asymmetry $Y_B$ and dark matter mass $m_\chi$, where we fixed $m_1 = 1200 \text{ GeV}$, $m_2 = 0.8m_1$ and $\sin \theta = 0.9$. The black line is the result without dark matter, while other colored lines correspond to the case that $m_N$ takes value from 600 GeV to 800 GeV.

In addition, we fix $\epsilon_{\text{CP}} = 9.23623 \times 10^{-6}$ to obtain the right BAU. The green line corresponds to the evolution of the BAU without dark matter, and the black line is the observed BAU. The fact that the green line is above the red line at the beginning means the BAU is diluted, which is consistent with the analysis in section 3. On the other hand, the red line is always below the green line which means the process of $NN \rightarrow \chi \chi$ is always dominant over the inverse process so that the baryon asymmetry is diluted due to the existence of the dark matter. The final baryon asymmetry without dark matter is larger than the observed result, in other word, dark matter induces the correct BAU via the dilution process.

In figure 15, the parameters are set by:

$m_\chi = 590 \text{ GeV}, \quad m_1 = 1170 \text{ GeV}, \quad \lambda_{sz} = 0.89, \quad \lambda_{mn} = 0.1, \quad m_N = 600 \text{ GeV}$

What’s more, we fix $\epsilon_{\text{CP}} = 1.475664 \times 10^{-6}$ to obtain the right BAU. Similarly, the green line is above the red line at the beginning. However, with the decrease of the temperature, the process $\chi \chi \rightarrow NN$ is gradually dominated over $NN \rightarrow \chi \chi$ and the red line is above the green line so that the BAU is enhanced due to the existence of dark matter. On the other hand, the final BAU without dark matter is smaller than the observed result, which means the right BAU is determined by the existence of the dark matter via the enhanced process.

5.3 Part III

According to the above discussion, the interplay between dark matter and leptogenesis is more explicit in the case of $m_2 = 1.5m_1$ and $\sin \theta = 0.9$. In this part, we consider the combined constraint of the dark matter relic density and baryon asymmetry on the parameter space with $m_2 = 1.5m_1$ and $\sin \theta = 0.9$, where the observed BAU is $Y_B^{\text{obs}} \approx 10^{-10} [1, 42]$. We consider parameters satisfying dark matter relic density in Part. 5.1 and evolve the Boltzmann equations to obtain the baryon asymmetry. On the other hand, to estimate the
Figure 14. Evolution of the baryon asymmetry in the case of $m_2 = 1.5m_1$, where the black line represents the observed baryon asymmetry, the red line corresponds to the result of the baryon asymmetry, while the green line represents the evolution of baryon asymmetry without dark matter in the model. The correct BAU induced by the dilution effect.

Figure 15. Evolution of the baryon asymmetry in the case of $m_2 = 1.5m_1$, where the black line represents the observed baryon asymmetry, the red line corresponds to the result of the baryon asymmetry, while the green line represents the evolution of baryon asymmetry without dark matter in the model. The correct BAU induced by the enhanced effect.

effect of dark matter on the BAU, we should also compare the obtained baryon asymmetry value with the result without dark matter. In figure 16 and figure 17, we obtain the baryon asymmetry by fixing $\epsilon_{CP}$ different values. In figure 16, we set $\epsilon_{CP} = 10^{-5}$ and the baryon asymmetry without dark matter is about $4.6 \times 10^{-10}$ while in figure 17, we fix $\epsilon_{CP} = 10^{-6}$ so that the baryon asymmetry without dark matter is about $4.6 \times 10^{-11}$ within the chosen parameter space. Compared with the observed BAU value, it is obvious that the dilution process should be dominant to generate the correct BAU for $Y_B \approx 4.6 \times 10^{-10}$ and more right-handed neutrinos should be generated to obtain the right BAU in the latter case.

According to figure 16 and figure 17, the purple line represents the relation $m_\chi = m_N$, the red (blue) points represent the generated baryon asymmetry larger (smaller) than the result without dark matter and not satisfying the observed BAU result, and the green points are equal to the observed BAU.

The blue points scatter on both sides of the purple line, which indicates the dilution effect can make a difference with suitable parameters in either $m_\chi > m_N$ or $m_\chi < m_N$ even though the process $NN \rightarrow \chi\chi$ is suppressed in the former case. Similarly, the enhanced effect can also have an impact when $m_\chi < m_N$ as we can see some red points lie below the purple line in figure 16. In addition, most of the red points lie in the low dark matter mass region since the process $\chi\chi \rightarrow NN$ is less efficient within the chosen parameter space for the large dark matter mass, which is consistent with the conclusion in Part II.

In figure 17, we encounter the opposite case since more right-handed neutrinos should be generated to guarantee the correct BAU, and most of the green points lie in the enhanced region. Although the baryon asymmetry is generated via the resonant leptogenesis, the existence of the dark matter in the model can play an important role in determining the BAU, since both the dilution effect and enhanced effect can occur to generate the correct baryon asymmetry.
Figure 16. Results of the $m_N - m_\chi$ satisfying dark matter relic density constraint, where the purple line represents $m_\chi = m_N$. The red points represent the generated baryon asymmetry larger than the result $Y_B \approx 4.6 \times 10^{-10}$ without dark matter so that the BAU is enhanced, the blue points correspond to the case the baryon asymmetry value smaller than the result without dark matter but not satisfying the observed BAU, and the green points correspond to value satisfying the observed BAU.

Figure 17. Results of the $m_N - m_\chi$ satisfying dark matter relic density constraint, where the purple line represents $m_\chi = m_N$. The red points represent the generated baryon asymmetry larger than the result $Y_B \approx 4.6 \times 10^{-11}$ without dark matter but not satisfying the observed BAU, the blue points correspond to the case the baryon asymmetry value smaller than the result without dark matter so that the BAU is diluted, and the green points correspond to value satisfying the observed BAU.

6 Summary

In this work, we discuss the interplay between dark matter and leptogenesis in a common framework. We do not give a UV-completion model but consider a minimal scenario including right-handed neutrino and a fermion dark matter. Dark matter and right-handed neutrino are connected by the mixing of two singlet scalar fields. We consider the decoupling limit that mixings of SM doublets with the singlet fields negligible, and dark matter relic density is determined by the two new Higgs particles and right-handed neutrinos. On the other hand, we consider the right-handed neutrino masses are degenerate at the TeV level and the baryon asymmetry is generated by the resonant leptogenesis. As for the two singlet scalar fields, we consider two cases with $m_2 = 1.5m_1$ and $m_2 = 0.8m_1$ for simplicity. We scan the parameter space satisfying relic density constraint in the case of $\sin \theta = 0.9$ and $\sin \theta = 0.01$, and found a more flexible parameter space in the case of $\sin \theta = 0.9$, where $NN \rightarrow \chi \chi$ can also play an important role in determining dark matter relic density. Then, we discuss the relationship between dark matter and leptogenesis in the case of $\sin \theta = 0.9$ since dark matter will make little difference in the leptogenesis in the case of small $\sin \theta$. We generate the baryon asymmetry via the resonant leptogenesis, and the existence of dark matter in the model can not only dilute the baryon asymmetry result but may also strengthen the baryon asymmetry since more right-handed neutrinos can be generated via the process of $\chi \chi \rightarrow NN$, and both the enhanced effect and dilution effect can occur in either case of $m_\chi > m_N$ and $m_\chi < m_N$. 

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A Formulas

We give the complete expressions of the cross section for the $\chi\chi \rightarrow h_{1,2}h_{1,2}$ in this part. For $\chi\chi \rightarrow h_1h_1$, we have

$$
\sigma_{11} = \frac{F_{11}^1 + F_{11}^2 + F_{11}^3 + F_{11}^4}{64\pi(-4m_{\chi}^4 + (-2m_{\chi}^2 + s)^2)}
$$

(A.1)

where $F_{11}^i$ ($i = 1, 2, 3, 4$) are defined by

$$
F_{11}^1 = \frac{(4m_{\chi}^2 - s)\sqrt{(s-4m_{\chi}^2)(s-4m_{\chi}^2)}}{2m_{\chi}^4 v_b^2} \left( -\frac{\cos^2\theta \sin^2\theta}{m_{\chi}^2 - s} \right)^2 \left( -2\sqrt{2} \lambda_{\chi\chi} \sin\theta v_b^2 (\sin^2\theta - 2\cos^2\theta) + 
(m_1^2 - m_2^2) 2\cos^2\theta \lambda_{\chi\chi} m_{\chi} v_b (2m_1^2 + m_2^2) + 3\sqrt{2} m_{\chi}^2 \sin\theta (\cos^2\theta m_1^2 + m_2^2 \sin^2\theta) \right) 
+ \frac{6 \sin^2\theta \cos^2\theta}{(m_{\chi}^2 - s)(s - m_{\chi}^2)}
$$

(A.2)

$$
F_{11}^2 = \frac{8 \cos^2\theta \lambda_{\chi\chi}^2 \sin^2\theta}{(m_{\chi}^2 - s) v_b^2} \left( \sqrt{2} \cos^2\theta \lambda_{\chi\chi} m_{\chi} v_b (2m_1^2 + m_2^2) + \cos^2\theta \sin^2\theta (4\lambda_{\chi\chi}^2 v_b^2 (m_1^2 - m_2^2) + 3m_{\chi}^2 m_{\chi}^2) \right) 
+ \sqrt{2} \cos^2\theta \lambda_{\chi\chi} m_{\chi} \sin^2\theta v_b (2m_1^2 + m_2^2) + \sin^2\theta (2\lambda_{\chi\chi}^2 v_b^2 (m_2^2 - m_1^2) + 3m_{\chi}^2 m_{\chi}^2) 
\left( 2\sqrt{(s-4m_{\chi}^2)(s-4m_{\chi}^2)} - (2m_1^2 - 8m_{\chi}^2 + s) \log \left( \frac{\sqrt{(s-4m_{\chi}^2)(s-4m_{\chi}^2)} - 2m_1^2}{2m_1^2 - \left( \sqrt{(s-4m_{\chi}^2)(s-4m_{\chi}^2)} + s \right)} \right) \right)
$$

(A.3)

$$
F_{11}^3 = \frac{24 \lambda_{\chi\chi}^2 \sin^2\theta}{(m_{\chi}^2 - s) v_b^2} \left( \sqrt{2} \cos^2\theta \lambda_{\chi\chi} m_{\chi}^2 m_{\chi} v_b + \sqrt{2} \cos^2\theta \lambda_{\chi\chi} m_{\chi}^2 m_{\chi} \sin^2\theta v_b + \cos^2\theta \sin^2\theta (2\lambda_{\chi\chi}^2 v_b^2 (m_1^2 - m_2^2) 
+ m_{\chi}^2 m_{\chi}^2 - m_{\chi}^2 m_{\chi}^2 \sin^2\theta \right) \left( 2m_1^2 - 8m_{\chi}^2 + s \log \left( \frac{\sqrt{(s-4m_{\chi}^2)(s-4m_{\chi}^2)} - 2m_1^2}{2m_1^2 - \left( \sqrt{(s-4m_{\chi}^2)(s-4m_{\chi}^2)} + s \right)} \right) 
- 2\sqrt{(s-4m_{\chi}^2)(s-4m_{\chi}^2)} \right)
$$

(A.4)
\[
F_{11}^4 = 16\lambda_{sx}^4 \sin^4 \theta \left(\frac{(m_1^4 + 4m_2^4 (s - 4m_\chi^2)) \log \left(\frac{\sqrt{(s-4m_1^2) (s-4m_2^2)} - s + 2m_1^2}{2m_1^2 - s}\right)}{2m_1^2 - s} - \frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} \right)
\]

(A.5)

For \(\chi \chi \rightarrow h_1 h_2\), we have

\[
\sigma_{12} = \frac{F_{12}^1 + F_{12}^2 + F_{12}^3 + F_{12}^4}{32\pi((s - 2m_\chi^2)^2 - 4m_\chi^2)}
\]

where \(F_{12}^i\) (\(i = 1, 2, 3, 4\)) are defined by

\[
F_{12}^1 = \frac{1}{2} \cos^2 \theta \sin^2 \theta \frac{\sqrt{(s-4m_1^2) (m_1^4 - 2m_2^4 (m_2^4 + s) + (m_2^4 - s)^2)}}{s}
\]

\[
\left(-\frac{16\lambda_{sx}^4 (2m_2^4 (m_2^4 - m_2^4)^2 + s (-8m_1^2 (m_1^4 + m_2^4) + 3m_1^2 m_2^2 + 16m_1^4 + 2m_2^4 s^2)}{m_1^4 m_2^4 + m_1^4 (m_2^4 (s - 2m_2^4) - 2m_2^4 s)} + m_1^4 m_2^4 - m_2^4 (m_2^4 (s - 2m_2^4) - 2m_2^4 s) + m_1^4 (m_2^4 - s)^2\right)
\]

\[
\frac{32\cos \theta \lambda_{sx}^2 (3\cos \theta \lambda_{sx}^2 (\cos^2 \theta m_1^2 + m_2^2 \sin^2 \theta) - \sqrt{2} \lambda_{sx} (m_2^2 + 2m_2^4) m_1 \sin \theta v_b + 2 \cos \theta \lambda_{sx} (m_2^2 + 2m_2^4) m_1 \sin \theta v_b + 2 \cos \theta (4m_2^2 - s) \sin^2 \theta \frac{1}{m_2^4 m_1^2 - 4m_2^4 v_b^2} (3\sqrt{2} \cos \theta \lambda_{sx} (\cos^2 \theta m_1^2 + m_2^4 \sin^2 \theta) - \frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} (s - m_2^4) v_b^2)
\]

\[
\lambda_{sx} (m_1^4 - m_2^4) (\cos^2 \theta - 2 \sin^2 \theta) v_b^2 - \frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} (s - m_2^4) v_b^2)
\]

\[
2 \lambda_{sx} (m_2^2 + 2m_2^4) m_1 \sin \theta v_b + 2 \sqrt{2} \cos \theta \lambda_{sx} (m_1^2 - m_2^4) (\cos^2 \theta - 2 \sin^2 \theta) v_b^2 - \frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} (s - m_2^4) v_b^2)
\]

\[
2 \sqrt{2} \lambda_{sx} (m_1^2 - m_2^4) \sin \theta (\frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} (s - m_2^4) v_b^2)
\]

\[
2 \cos \theta \lambda_{sx} (m_1^2 - m_2^4) \sin \theta (\frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} (s - m_2^4) v_b^2)
\]

\[
2 \sqrt{2} \lambda_{sx} (m_1^2 - m_2^4) \sin \theta (\cos^2 \theta m_1^2 + m_2^4 \sin^2 \theta) (\frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} (s - m_2^4) v_b^2)
\]

\[
2 \lambda_{sx} (m_2^2 + 2m_2^4) m_1 \sin \theta v_b + 2 \sqrt{2} \lambda_{sx} (m_1^2 - m_2^4) (\cos^2 \theta - 2 \sin^2 \theta) v_b^2 + \frac{1}{2} \frac{\sqrt{(s-4m_1^2) (s-4m_2^2)}}{s} (s - m_2^4) v_b^2)
\]

\[
\frac{1}{(m_1^2 - s) v_b^2} 32 \lambda_{sx}^2 \sin \theta \sqrt{2} \cos \theta \lambda_{sx} (2m_1^2 + m_2^4) m_1 v_b + \sqrt{2} \cos \theta \lambda_{sx} (2m_1^2 + m_2^4) m_1 \sin \theta v_b + \cos \theta \lambda_{sx} (2m_1^2 + m_2^4) m_1 \sin \theta v_b + \cos \theta \sin \theta (3m_1^2 m_2^2 + 4 \lambda_{sx} (m_1^2 - m_2^4) v_b^2) + \sin \theta (3m_1^2 m_2^2 + 2 \lambda_{sx} (m_1^2 - m_2^4) v_b^2))
\]

(A.7)

\[
F_{12}^2 = 8 \cos^2 \theta \lambda_{sx}^4 \sin^2 \theta \frac{2m_1^2 m_2^4 - 32m_1^2 m_2^2 + 8m_1^2 s}{m_1^4 + m_2^4 - s} + m_1^2 + m_2^4 - 8m_2^2 - 8m_1^2 - s
\]

\[
\log \left(\frac{m_1^2 + \sqrt{(s-4m_1^2) (m_1^4 - 2m_1^2 (m_2^4 + s) + (m_2^4 - s)^2)}}{s} + m_2^4 - s\right)
\]

\[
\frac{m_1^2 + \sqrt{(s-4m_1^2) (m_1^4 - 2m_1^2 (m_2^4 + s) + (m_2^4 - s)^2)}}{s} + m_2^4 - s
\]

(A.8)
\[ F_{12}^3 = -4\sqrt{2}\cos^2\theta \lambda_{x\chi}^2 \sin^3\theta (m_1^2 + m_2^2 - 8m_\chi^2 + s) \frac{(3\sqrt{2} m_\chi^2 \sin\theta (\cos^2\theta m_1^2 + m_2^2 \sin^2\theta) +}{(m_1^2 - s) v_b^2} \\
\]
\[ 2\cos\theta \lambda_{x\chi} (2m_1^2 + m_2^2) m_\chi v_b - 2\sqrt{2} \lambda_{x\chi} (m_1^2 - m_2^2) \sin\theta (-2\cos^2\theta + \sin^2\theta) v_b^2 \]
\[ \log \frac{m_1^2 + s}{m_1^2 - s} \left( \frac{(s-4m_\chi^2)(m_1^4-2m_2^2(m_2^2+s)+(m_2-s)^2)}{s^3} - 1 \right) + m_2^2 \right) + m_2^2 \right) \] 
\[ (A.9) \]
\[ F_{12}^4 = 4\sqrt{2}\cos^3\theta \lambda_{x\chi}^2 \sin^2\theta (m_1^2 + m_2^2 - 8m_\chi^2 + s) (-2\sqrt{2} \lambda_{x\chi} v_b^2 (\cos^3\theta - 2\cos\theta \sin^2\theta) (m_1^2 - m_2^2) + \]
\[ 2\lambda_{x\chi} m_\chi \sin\theta v_b (m_1^2 + m_2^2 - 3\sqrt{2}\cos\theta m_\chi^2 (\cos^2\theta m_1^2 + m_2^2 \sin^2\theta)) \]
\[ \log \frac{m_1^2 + s}{m_1^2 - s} \left( \frac{(s-4m_\chi^2)(m_1^4-2m_2^2(m_2^2+s)+(m_2-s)^2)}{s^3} - 1 \right) + m_2^2 \right) \] 
\[ (A.10) \]

For \( \chi \to h_2 h_2 \), we have
\[ \sigma_{22} = \frac{F_{22}^1 + F_{22}^2 + F_{22}^3 + F_{22}^4}{64\pi (-4m_\chi^2 + (-2m_\chi^2 + s)^2)} \] 
\[ (A.11) \]

where \( F_{22}^1, F_{22}^2, F_{22}^3, F_{22}^4 \) are defined by
\[ F_{22}^1 = \frac{(4m_\chi^2 - s) \sqrt{(-4m_\chi^2 + s)^2} \sin^4\theta}{2m_\chi^2 v_b^2} \left( -\frac{\sin^4\theta}{(m_\chi^2 - s)^2} \left( \frac{3\sqrt{2} \cos^2\theta m_\chi^2 (\cos^2\theta m_1^2 + m_2^2 \sin^2\theta) +}{(m_1^2 - s) v_b^2} \\
\]
\[ 2\sqrt{2} \lambda_{x\chi} v_b^2 (\cos^4\theta - 2\cos^2\theta \sin^2\theta) (m_1^2 - m_2^2) - 2\cos\theta \lambda_{x\chi} m_\chi \sin\theta v_b (m_1^2 + 2m_2^2) \right)^2 \\
\]
\[ \frac{6\cos^2\theta \sin^2\theta}{(m_\chi^2 - s)^2} \left( -\frac{\sin^4\theta}{(m_\chi^2 - s)^2} \right) \left( -\frac{\sin^4\theta}{(m_\chi^2 - s)^2} \right) \left( -\frac{\sin^4\theta}{(m_\chi^2 - s)^2} \right) \right)^2 \\
\]
\[ (A.12) \]
\[ F_{22}^2 = \frac{4\cos^3\theta \lambda_{x\chi}^2}{(m_\chi^2 - s) v_b^2} \left( \cos^3\theta m_\chi^2 (\cos^2\theta m_1^2 + m_2^2 \sin^2\theta) + \sqrt{2} \lambda_{x\chi} m_\chi \sin^3\theta v_b + 2\cos\theta \lambda_{x\chi} m_\chi \sin^3\theta v_b + \sqrt{2} \cos^4\theta \sin^2\theta (m_1^2 m_\chi^2 + 2\lambda_{x\chi} (m_2^2 - m_1^2) v_b^2) \right)^2 \\
\]
\[ (A.13) \]
\[ F_{22}^3 = 8 \cos^4 \theta \lambda_{\alpha z}^4 \left( (m_2^2 - 8m_\chi^2 - s) \log \left( \frac{\left( \sqrt{\frac{(s - 4m_\chi^2)}{(s - 4m_\chi^2) - s}} + 2m_\chi^2 \right)}{2m_\chi^2 - \sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) + s}} \right) \right) \]
\[ \frac{\sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) (2(m_2^2 - 6m_\chi^2 + s)}{m_\chi^2 - 4m_\chi^2 m_\chi^2 + s} \right) \right) \]

\[ F_{22}^4 = 8 \cos^4 \theta \lambda_{\alpha z}^4 \left( -\sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2)} + \frac{1}{m_\chi^2 + m_\chi^2 - s} (m_2^4 - m_1^4 s + m_2^2 s - 16m_\chi^4 + 4m_\chi^2 s) \right) \]
\[ \log \left( \frac{2m_2^4 + \sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) - s}}{2m_2^4 - \sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) + s}} \right) \right) + (m_2^4 + 4m_\chi^2 (s - 4m_\chi^2)) \right) \]
\[ \log \left( \frac{\left( \sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) - s} + 2m_\chi^2 \right)}{2m_\chi^2 - \sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) + s}} \right) \right) \right) \] (A.14)

\[ \log \left( \frac{2m_2^4 + \sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) - s}}{2m_2^4 - \sqrt{(s - 4m_\chi^2) (s - 4m_\chi^2) + s}} \right) \right) \right) + (m_2^4 + 4m_\chi^2 (s - 4m_\chi^2)) \right) \] (A.15)

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