Matter and dark matter asymmetry from a composite Higgs model

M. Ahmadvand

School of Physics, Institute for Research in Fundamental Sciences (IPM), P. O. Box 19395-5531, Tehran, Iran

Abstract

We propose a low scale leptogenesis scenario in the framework of composite Higgs models supplemented with singlet heavy neutrinos. One of the neutrinos can also be considered as a dark matter candidate whose stability is guaranteed by a discrete $Z_2$ symmetry of the model. In the spectrum of the strongly coupled system, bound states heavier than the pseudo Nambu-Goldstone Higgs boson can exist. Due to the decay of these states to heavy right-handed neutrinos, an asymmetry in the visible and dark sector is simultaneously generated. The resulting asymmetry is transferred to the standard model leptons which interact with visible right-handed neutrinos. We show that the sphaleron-induced baryon asymmetry can be provided at the TeV scale for resonant bound states. Furthermore, depending on the coupling strength of dark neutrino interaction, a viable range of the dark matter mass is allowed in the model.

\(^1\)e-mail: ahmadvand@ipm.ir
1 Introduction

The Standard Model (SM) as a gauge theory for elementary particle interactions has been extremely successful in explaining many phenomena. However, some issues including the matter-antimatter asymmetry of the Universe, the Dark Matter (DM) and hierarchy problem have remained unresolved [1, 2, 3]. These shortcomings imply that the SM is incomplete and needs to be extended.

Astrophysical evidence implies the Universe is asymmetric with an overabundance of baryons relative to antibaryons [4]. Based on cosmological abundances of light nuclei and also CMB observations [5], one can characterize the baryon asymmetry by this ratio $n_B/s \sim 0.88 \times 10^{-10}$ where $n_B$ is the net baryon number density and $s$ is the entropy density of the Universe. Starting with an initial symmetric state of matter and antimatter, this ratio can be obtained in the scenario which provides three conditions [6]: baryon number violation, C and CP violation, and departure from thermal equilibrium. To achieve the baryon asymmetry, various scenarios beyond the SM, such as GUT baryogenesis [7, 8], electroweak baryogenesis [9, 10], and leptogenesis which was first proposed in the seesaw mechanism context [11, 12], have been suggested so far.

On the other hand, recent observations show that around 26% of the energy of the Universe lies in DM [5]. However, the nature of DM and its properties such as its mass and spin have not been revealed. To obtain the relic density of DM, numerous models with DM candidates have been proposed among which we can enumerate weakly interacting massive particles (WIMPs), sterile neutrinos, axions, and primordial black holes [13]. As for this problem, another notable observation is that the energy density of DM is so close to that of baryonic matter, $\Omega_{DM} \sim 5\Omega_B$. This relation may hint the dark and visible matter have a common asymmetric origin [14].

Another problem which cannot be addressed by the SM is the hierarchy problem, concerning the large corrections of UV physics to the mass of the Higgs as an elementary particle. One of the attractive solutions is Composite Higgs Models (CHMs) in which Higgs is no longer an elementary particle but a composite state of a new strongly coupled sector [15, 16]. Indeed, the Higgs is considered as a pseudo Nambu-Goldstone boson, resulted from a spontaneously broken global symmetry, so that there is a mass gap between the Higgs state and other heavier strongly interacting
bound states.

In this paper, to address the aforementioned problems, we propose a leptogenesis scenario through the possibilities of a CHM. We consider a minimal CHM supplemented with at least two singlet heavy neutrinos, where one of them can be regarded as a DM candidate. Also, in the spectrum of the strongly coupled system, large number of bound states are expected, analogous to QCD hadrons. We consider bound states which decay to Right-Handed (RH) heavy neutrinos. Due to their complex couplings, leading to a CP violation in the decay processes, the asymmetry can be generated at the compositeness scale, about TeV scale \[16\]. (Thus, we assume bound states are constituted of heavy so-called techniquarks.) Moreover, because of the interaction of visible RH neutrinos with SM leptons, the asymmetry is transferred to this sector. Then, the baryon asymmetry is generated through active electroweak sphalerons. Depending on the model parameters, for resonant bound states, we obtain the observed quantities and also find a valid range of DM masses.

Therefore, as the Higgs state interactions can be responsible for the mass generation of SM particles and the spontaneous gauge symmetry breaking, the asymmetric matter and DM may be originated from the decay of some other bound states.

In section 2 we introduce the model and obtain the parameters required for the asymmetric model. In section 3 we represent numerical examples and calculate relevant parameters. We conclude in section 4.

2 Model

Depending on the global symmetry coset, CHMs can be classified. In the minimal version with the coset SO(5)/SO(4), one pseudo Nambu-Goldstone Higgs doublet is generated due to the symmetry breaking and also the SM gauge symmetry is a subgroup of the unbroken SO(4) symmetry group. In this context, in order to introduce the interaction of the Higgs with SM fermions and also to generate their masses, the idea of partial compositeness \[18\] is expressed as \(Q_{\text{SM}}O_f\) where \(O_f\) stands for an operator composed of strong sector fermionic fields and \(Q_{\text{SM}}\) for the SM fermions.

Here, we work in the confined phase. For the sake of simplicity, we take into account two given bound states as singlet scalar fields. Moreover, we consider two singlet heavy neutrinos with their chiral components. The interaction between these

\footnote{For the sphaleron energy calculation in the context of CHMs, see \[17\].}
two sectors, actually between the bound states and RH neutrinos, is a lepton-number violating process, which may come from a four-fermi interaction in the UV theory. Therefore, the Lagrangian is given as follows
\[ \mathcal{L} \supset \frac{1}{2} \partial_{\mu} \varphi_i \partial^{\mu} \varphi_i - \frac{1}{2} M_i^2 \varphi_i^2 + \mathcal{N}_{R,\alpha} i \bar{\varphi}_i N_{R,\alpha} - m_{N_\alpha} \mathcal{N}_{L,\alpha} N_{R,\alpha} + Y_i \bar{\varphi}_i \mathcal{N}_{R,\alpha} N_{R,\alpha} + \text{h.c.} \] (1)

We consider the lepton-number of RH neutrinos as \( L(N_R) = 1 \) with the opposite sign for their antiparticles and hence the interaction gives rise to a lepton-number violation. \( N_{R,2} \) is a \( \mathbb{Z}_2 \)-odd DM candidate, while other fields are even under this symmetry. In addition, the interaction of \( N_{R,1} \) with SM leptons is necessary. This can be fulfilled via partial compositeness paradigm and leads to such Yukawa interaction \( \lambda_i \bar{\Psi}_i L H c N_{R,1} \), where \( H \) is the Higgs doublet.

### 2.1 L and CP violation

According to the interaction term, we can obtain the decay rate at the tree level as
\[ \Gamma_i \equiv \sum_\alpha \Gamma_{\alpha \alpha}^i (\varphi_i \rightarrow N_{R,\alpha} N_{R,\alpha}) = \frac{(Y_i^+ Y_i)_{ii} M_i}{16 \pi} \] (2)

where the process generates a lepton asymmetry with \( \Delta L = 2 \). However, in order to gain a net asymmetry, there should be enough CP violation in the model. In our scenario, this can be provided through the introduced complex couplings.

To obtain the CP asymmetry in \( \varphi_i \) decays, we calculate the interference of tree and one-loop level amplitudes through the following quantity
\[ \varepsilon_{\alpha \alpha}^i = \frac{\Gamma_{\alpha \alpha}^i - (\Gamma_{\alpha \alpha}^i)^c}{\Gamma_i + (\Gamma_i^c)} \] (3)

where \( c \) denotes the CP conjugate of the decay process, \( \varphi_i \rightarrow N_{R,\alpha} N_{R,\beta} \). At the one-loop level, self-energy and vertex diagrams contribute to the CP asymmetry. Since we are dealing with unstable states which cannot be described as asymptotic states by the conventional perturbation field theory, we use the resummation approach \([20, 21]\).

By focusing on the self-energy transition, \( \varphi_i \rightarrow \varphi_j \), the transition amplitude is given by
\[ T_{\varphi_i} = Y_{\alpha \alpha}^i \bar{u}_R v_R^c - i Y_{\alpha \alpha}^j \frac{\bar{u}_R v_R^c \Pi_{ji}(M_i^2)}{M_i^2 - M_j^2 + i \Pi_{jj}(M_i^2)}, \quad i, j = 1, 2, \quad i \neq j \] (4)

As for the mass generation of SM neutrinos in the model, it is required to add one more heavy neutrino as well as a Majorana mass term \([19]\).

In this case the Yukawa coupling would deviate somehow \([16]\) from the conventional Yukawa coupling, e.g., in seesaw models.
where flavor indices of spinors are not displayed for brevity. The absorptive part of the one-loop transition is expressed as

\[ \Pi_{ij}(M_i^2) = \frac{(YY^*)_{ij} M_i^2}{16\pi} = A_{ij} M_i^2. \tag{5} \]

Therefore, the transition amplitude and its CP conjugate will be

\[ T_{\phi_i} = \bar{u}_R v_c^i \left[ Y_{i\alpha \alpha} - i(Y_{j\alpha \alpha})^* A_{ji} M_i^2 \left( \Delta M_{ij}^2 - iM_i^2 A_{jj} \right) \right], \tag{6} \]

\[ \bar{T}_{\phi_i} = \bar{u}_R v_R^i \left[ (Y_{i\alpha \alpha})^* - i(Y_{j\alpha \alpha}) M_i^2 \left( \Delta M_{ij}^2 - iM_i^2 A_{jj} \right) \right], \tag{7} \]

where \( \Delta M_{ij}^2 \equiv M_i^2 - M_j^2 \). Thus, the CP asymmetry quantity is obtained as

\[ \varepsilon_{i\alpha \alpha} = \frac{\text{Im} [(Y_{\alpha i} Y_{\alpha j})_{ij}]}{8\pi (Y^* Y)_{ii}} \frac{M_i M_j (\Delta M_{ij}^2)}{(\Delta M_{ij}^2)^2 + M_i^2 M_j^2 A_{jj}^2} = \frac{\text{Im} [(Y_{\alpha i} Y_{\alpha j})_{ij}]}{(Y^* Y)_{ii} (Y^* Y)_{jj}} \frac{M_i \Gamma_j (\Delta M_{ij}^2)}{(\Delta M_{ij}^2)^2 + M_i^2 \Gamma_j^2}. \tag{8} \]

Satisfying the condition \( M_i - M_j = \Gamma_j / 2 \), the CP asymmetry can be \( |\varepsilon_{i\alpha \alpha}| \leq 1/2 \). In this case, we can neglect the vertex contribution. Additionally, resonant states may be implied to CP invariant bound states which are a mixture of \( \varphi_1 \) and \( \varphi_2 \).

### 2.2 Boltzmann equations

To obtain the number density of particles involving in the out of equilibrium processes, one can solve Boltzmann equations. We consider only decays and inverse decays of \( \varphi_i \) fields which dominantly contribute to the creation and washout of the asymmetry. Therefore, the Boltzmann equations up to \( \mathcal{O}(Y^2) \) are expressed as follows:

\[ \frac{d y_{\phi_i}}{dz} = -2z \frac{\gamma_{\phi_i}^e}{H_1 s y_{\phi_i}^e} (y_{\phi_i} - y_{\phi_i}^e), \tag{9} \]

\[ \frac{d L_\alpha}{dz} = \frac{2z}{H_1 s} \left[ \varepsilon_{i\alpha \alpha} \left( y_{\phi_i} - y_{\phi_i}^e \right) \gamma_{\phi_i}^e - \frac{L_\alpha^e y_{L_\alpha}^e}{y_{L_\alpha}^e} \gamma_{L_\alpha}^e \right] \tag{10} \]

where \( z = M_i / T, \; H_1 \equiv H(z = 1) = 1.66 \sqrt{g_* M_i^2 / M_{pl}} \) is the Hubble parameter, \( s = 2\pi^2 g_*/T^3 / 45 \) is the entropy density, \( M_{pl} = 1.22 \times 10^{19} \text{GeV} \) is the Planck mass, and \( g_* \) denotes the number of relativistic degrees of freedom at temperature \( T \). We

\textsuperscript{4}At \( \mathcal{O}(Y^4) \), \( \Delta L = 2 \) t-channel scattering, \( \varphi \varphi \leftrightarrow N_R N_R \) is induced.
also defined each density as $y_X \equiv n_X/s$ and $\mathcal{L}_\alpha \equiv y_{N_\alpha} - y_{N_\alpha}$. In Eqs. (9) (10), the thermally averaged rates are given as [12, 22] 

$$\frac{\gamma_{\phi_i}^{eq}}{n_{\phi_i}^{eq}} = \frac{K_1(z)}{K_2(z)} \Gamma_i, \quad \frac{\gamma_{L_\alpha}^{eq}}{n_{L_\alpha}^{eq}} = \frac{z^2 K_1(z)}{4\pi^2} \Gamma_{\alpha\alpha}^i. \quad (11)$$

$K_1(z), K_2(z)$ are modified Bessel functions of the second kind. In the above equations for $\alpha = 1$, beside $\Gamma_{11}$, the decay rate resulted from $N_{R,1}$ decay to the Higgs and SM leptons can be added. However, we can neglect its influence in comparison with $\Gamma_{11}$. 

For large $z$ in the strong regime [12, 23] where the final result is not sensitive to the initial abundance of $\phi_i$, we can solve the equations analytically and find the asymmetry as

$$\frac{d(y_{\phi_i} - y_{\phi_i}^{eq})}{dz} \approx 0, \quad y_{\phi_i} - y_{\phi_i}^{eq} \approx \frac{z K_2(z) H_1}{4 g_i \Gamma_i}, \quad \mathcal{L}_\alpha \approx \varepsilon_{\alpha\alpha}^i \int_{z_i}^{\infty} dz \frac{z^2 K_1(z)}{2 g_s} \exp \left( - \int_z^{\infty} dz' \frac{z'^3 K_1(z')}{2 H_1} \right) \equiv \varepsilon_{\alpha \alpha}^i \eta_{1 \alpha}. \quad (12)$$

Eventually, the resulting asymmetry of RH neutrinos is transported to the SM leptons through $N_{R,1}$ decays and then due to sphalerons which are active at the compositeness scale, the asymmetry is converted to the baryon asymmetry, $\mathcal{B} \approx -1/3 \mathcal{L}_1$ [12].

### 3 Numerical examples

Having constructed a common origin of matter and DM asymmetry based on $\phi_i$ decays, we can calculate the observed parameters. In fact, based on the baryon asymmetry and $\Omega_{DM} \sim 5 \Omega_B$ relations, parameters of the model can be constrained by the following numerical analysis.

Firstly, masses of $\phi_i$ fields should be greater than those of RH neutrinos, $M_i \gtrsim 2m_{N_{R,\alpha}}$. Taking into account the resonant effect in the CP violation parameter, we will have nearly degenerate masses of $\phi_i$s at the TeV scale. Then, using the out-of-equilibrium condition for $\phi_i$ decays, we will find $\mathcal{L}_1$ according to Eq. (13).

Assuming $M_i = 5$ TeV and $z_i = 5$, we obtain $H_1 \simeq 3.5 \times 10^{-11}$ GeV. Moreover, assuming $\phi_1$ and $\phi_2$ decay similarly, we can obtain $\mathcal{L}_1 = 3 \times 10^{-10}$ for $\Gamma_{11} \lesssim H_1$. Here, we take $g_s \sim 107$ and set Yukawa couplings $Y_{11}^i$ by three representative values of $k_1$ where $k_1 = \Gamma_{11}^i/H_1$. Then, through Eq. (13), we can determine $\varepsilon_{11}^i$, as listed in Table I

In case the imaginary and real parts of the couplings are of the same order, Eq.
\[ \varepsilon_{i11} = 5.97 \times 10^{-7} \]
\[ Y_{i11} = 5.95 \times 10^{-7} \]

| \( k_1 \) | \( \varepsilon_{i11} \) | \( Y_{i11} \) |
|--------|--------|--------|
| 1      | 5.97 \times 10^{-7} | 5.95 \times 10^{-7} |
| 0.1    | 4.94 \times 10^{-7} | 1.88 \times 10^{-7} |
| 0.01   | 4.85 \times 10^{-7} | 5.95 \times 10^{-8} |

Table 1: The values of the CP violation parameter, \( \varepsilon_{i11} \), and the Yukawa coupling, \( Y_{i11} \), associated with \( N_{R,1} \) interaction are listed for three values of \( k_1 = \Gamma_{11}/H_1 \).

\[ \varepsilon_{i11} \] values can be fulfilled for a range of values of \( Y_{i22}/Y_{i11} \) and \( \Delta M_{12} = M_1 - M_2 \) which can be about \((10^{-4} - 10^{-7}) \text{ GeV}\) as can be seen in Fig. 1.

\[ \text{Figure 1: The required mass difference of } \varphi_i \text{ fields versus } Y_{i22}/Y_{i11} \text{ is displayed for three different values of } \Gamma_{11}/H_1. \]

On the other hand, from the following relation for the asymmetric DM, one can predict the DM mass
\[ \frac{\Omega_{\text{DM}}}{\Omega_B} = \frac{n_{\text{DM}}}{n_B} \frac{m_{\text{DM}}}{m_B} \sim \frac{m_{\text{DM}} \varepsilon_{i2} \eta_{i2}}{m_p \varepsilon_{i1} \eta_{i1}} \sim 5 \] (14)

where \( m_p \sim 1 \text{ GeV} \) is the proton mass and \( m_{\text{DM}} \equiv m_{N_{R,2}} \). We assume \( m_{\text{DM}} \lesssim m_{N_{R,1}} \).

Using the obtained results and Eq. (14), we can calculate \( L_2 \) as a function of \( Y_{i22}/Y_{i11} \).

Indeed, relying on \( \Gamma_{22} = \Gamma_{11} Y_{i22} Y^{\dagger}_{i22}/(Y_{i11} Y^{\dagger}_{i11}) \) for two values of \( k_1 \), we find \( L_2 \) and thereby DM mass as a function \( Y_{i22}/Y_{i11} \), displayed in Fig. 2. Eventually, depending

\(^5\)Another range of solutions for \( \Delta M_{12} \) can be around 11 orders of magnitude smaller, not shown in Fig. (1), e.g. for \( Y_{22} = Y_{11} \).
on $Y_{i22}$ values, for example for $k_1 = 0.01$ and $0.19 \lesssim Y_{i22} / Y_{i11} \lesssim 20$, a wide range of DM masses from 10 keV to TeV can be found in the scenario.

Therefore, we can find some parameter spaces of the model compatible with the observed values of the baryon asymmetry and DM.

![Graph](image)

Figure 2: By changing $Y_{i22}$, a range of DM mass is shown for two different values of $\Gamma_{i11}/H_1$.

### 4 Conclusion

In this paper, we have tried to address two important issues, the baryon asymmetry of the Universe and DM problem, which cannot be explained by the SM. Using CHMs which are also interesting models addressing the hierarchy problem, we have proposed a model to explain these problems simultaneously. More precisely speaking, in a minimal CHM framework whose SM sector is extended by singlet heavy neutrinos, we have explored the possibility of a matter and DM asymmetric scenario. Indeed, such a model is motivated by the observed closeness of the dark and baryonic energy density.

In this scenario, from the new strongly coupled system, we have considered resonant bound states which decay to RH neutrinos. In addition, one of the RH neutrinos can play the role of DM, stabilized by a $\mathbb{Z}_2$ discrete symmetry. We obtained the decay rate of these lepton-number violating processes which should satisfy the out-of-equilibrium condition. Furthermore, as an interesting feature, the required
CP violation can be sufficiently provided in the model due to the resonant effect of bound states. We then have calculated the number densities by solving the Boltzmann equations. The generated asymmetry in the RH neutrino sector is induced to the SM leptons by their interaction with visible RH neutrinos and eventually via sphalerons it is converted to the baryon asymmetry.

By a numerical analysis, we have shown the observed baryon asymmetry and relic abundance of DM can be achieved at the compositeness scale for TeV scale bound states. As another merit which can be also experimentally interesting, depending on the strength coupling of the DM interaction with bound states, a range from 10 keV to TeV for the DM mass can be found in the model.

Acknowledgment

I would like to thank Majid Ekhterachian for helpful comments and discussions.

References

[1] A. Riotto and M. Trodden, “Recent progress in baryogenesis,” Ann. Rev. Nucl. Part. Sci. 49, 35-75 (1999) [arXiv:hep-ph/9901362] [hep-ph]; J. M. Cline, “TASI Lectures on Early Universe Cosmology: Inflation, Baryogenesis and Dark Matter,” PoS TASI2018, 001 (2019) [arXiv:1807.08749] [hep-ph].

[2] G. Bertone, D. Hooper and J. Silk, “Particle dark matter: Evidence, candidates and constraints,” Phys. Rept. 405, 279-390 (2005) [arXiv:hep-ph/0404175] [hep-ph].

[3] G. F. Giudice, “Naturally Speaking: The Naturalness Criterion and Physics at the LHC,” [arXiv:0801.2562] [hep-ph].

[4] A. G. Cohen, A. De Rujula and S. L. Glashow, “A Matter - antimatter universe?,” Astrophys. J. 495, 539-549 (1998) [arXiv:astro-ph/9707087] [astro-ph].

[5] P. A. Zyla et al. [Particle Data Group], “Review of Particle Physics,” PTEP 2020, no.8, 083C01 (2020).
[6] A. D. Sakharov, “Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe,” Sov. Phys. Usp. 34, no.5, 392-393 (1991).

[7] S. Weinberg, “Cosmological Production of Baryons,” Phys. Rev. Lett. 42, 850-853 (1979).

[8] A. Riotto, “Theories of baryogenesis,” [arXiv:hep-ph/9807454 [hep-ph]].

[9] M. Trodden, “Electroweak baryogenesis,” Rev. Mod. Phys. 71, 1463-1500 (1999) [arXiv:hep-ph/9803479 [hep-ph]].

[10] M. Ahmadvand, “Baryogenesis within the two-Higgs-doublet model in the Electroweak scale,” Int. J. Mod. Phys. A 29, no.20, 1450090 (2014) [arXiv:1308.3767 [hep-ph]]; H. Abedi, M. Ahmadvand and S. S. Gousheh, “Electroweak baryogenesis via chiral gravitational waves,” Phys. Lett. B 786, 35-38 (2018) [arXiv:1805.10645 [hep-ph]].

[11] M. Fukugita and T. Yanagida, “Baryogenesis Without Grand Unification,” Phys. Lett. B 174, 45-47 (1986).

[12] S. Davidson, E. Nardi and Y. Nir, “Leptogenesis,” Phys. Rept. 466, 105-177 (2008) [arXiv:0802.2962 [hep-ph]].

[13] T. Lin, “Dark matter models and direct detection,” PoS 333, 009 (2019) [arXiv:1904.07915 [hep-ph]].

[14] D. B. Kaplan, “A Single explanation for both the baryon and dark matter densities,” Phys. Rev. Lett. 68, 741-743 (1992).

[15] D. B. Kaplan, H. Georgi and S. Dimopoulos, “Composite Higgs Scalars,” Phys. Lett. B 136, 187-190 (1984).

[16] G. Panico and A. Wulzer, “The Composite Nambu-Goldstone Higgs,” Lect. Notes Phys. 913, pp.1-316 (2016) [arXiv:1506.01961 [hep-ph]].

[17] M. Spannowsky and C. Tamarit, “Sphalerons in composite and non-standard Higgs models,” Phys. Rev. D 95, no.1, 015006 (2017) [arXiv:1611.05466 [hep-ph]].
[18] D. B. Kaplan, “Flavor at SSC energies: A New mechanism for dynamically generated fermion masses,” Nucl. Phys. B 365, 259-278 (1991).

[19] K. Agashe, P. Du, M. Ekhterachian, C. S. Fong, S. Hong and L. Vecchi, “Hybrid seesaw leptogenesis and TeV singlets,” Phys. Lett. B 785, 489-497 (2018) [arXiv:1804.06847 [hep-ph]]; K. Agashe, P. Du, M. Ekhterachian, C. S. Fong, S. Hong and L. Vecchi, “Natural Seesaw and Leptogenesis from Hybrid of High-Scale Type I and TeV-Scale Inverse,” JHEP 04, 029 (2019) [arXiv:1812.08204 [hep-ph]].

[20] A. Pilaftsis, “CP violation and baryogenesis due to heavy Majorana neutrinos,” Phys. Rev. D 56, 5431-5451 (1997) [arXiv:hep-ph/9707235 [hep-ph]].

[21] A. Pilaftsis and T. E. J. Underwood, “Resonant leptogenesis,” Nucl. Phys. B 692, 303-345 (2004) [arXiv:hep-ph/0309342 [hep-ph]].

[22] G. F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia, “Towards a complete theory of thermal leptogenesis in the SM and MSSM,” Nucl. Phys. B 685, 89-149 (2004) [arXiv:hep-ph/0310123 [hep-ph]].

[23] W. Buchmuller, P. Di Bari and M. Plumacher, “Leptogenesis for pedestrians,” Annals Phys. 315, 305-351 (2005) [arXiv:hep-ph/0401240 [hep-ph]].