# BARYON ASYMMETRY OF THE UNIVERSE FROM DARK MATTER DECAY*

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We propose the baryon asymmetry of the Universe (BAU) to arise from forbidden decay of dark matter (DM) in the vicinity of a first-order phase transition (FOPT). In order to illustrate the idea, we consider the example of the minimal scotogenic model where the Standard Model is extended by three right-handed neutrinos (RHN) and a scalar doublet, all odd under an unbroken $Z_2$ symmetry. The lightest RHN is the DM candidate, which can decay in the early Universe during a first-order electroweak phase transition, leading to the origin of BAU via leptogenesis. The stochastic gravitational wave background originating from the FOPT can be probed at near-future experiments like LISA, while all new fields remain in the TeV corner offering complementary detection prospects.

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## 1. Introduction

Origins of dark matter (DM) and baryon asymmetry of the Universe (BAU) [1, 2] have been two longstanding problems in particle physics and cosmology which cannot be explained within the framework of the Standard Model (SM). BAU is quantified in terms of the baryon-to-photon ratio

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$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.2 \times 10^{-10}$ [2], while DM relic is presented in terms of its density parameter $\Omega_{\rm DM}h^2 = 0.120 \pm 0.001$ [2]. Among various new physics proposals, the weakly interacting massive particle paradigm of DM [3–5] and baryogenesis, leptogenesis [6–8] origin of BAU have been the most widely studied ones.

Here, we propose a novel scenario where the forbidden decay of DM can source the origin of BAU via leptogenesis [9, 10]. While DM is cosmologically stable, its forbidden decay in the early Universe is enabled by finite temperature effects in the vicinity of a first-order phase transition (FOPT) [9]. The finite duration of the forbidden decay, facilitated by the FOPT just before the nucleation temperature, leads to the simultaneous generation of DM relic abundance as well as baryon asymmetry. The requirement of a first-order electroweak phase transition (EWPT) keeps all the new physics particles around the TeV ballpark, within reach of experiments. The stochastic gravitational wave (GW) background arising from the FOPT offers a complementary probe in near-future experiments like LISA.

## 2. The framework

In order to illustrate the idea, we consider the minimal scotogenic model [11, 12] where the SM is extended by three right-handed neutrinos (RHN) $N_{1,2,3}$ and a scalar doublet $\eta$, all odd under an unbroken $Z_2$ symmetry. The relevant part of the Lagrangian is given by

$$-\mathcal{L} \supset \frac{1}{2} M_{ij} \bar{N}_i^c N_j + Y_{\alpha i} \bar{L}_\alpha \tilde{\eta} N_i + \text{h.c.} \tag{1}$$

Although $\eta$ does not acquire any vacuum expectation value (VEV), neutrinos acquire non-zero mass at one-loop level [12, 13]. The same scalar doublet can also assist in obtaining a first-order EWPT [14, 15].

We calculate the full scalar potential including the one-loop Coleman–Weinberg potential as well as the finite-temperature potential. After identifying the critical temperature $T_{\rm c}$, critical VEV $v_{\rm c}$, and the parameter space giving rise to a strong FOPT, we calculate the bounce-action to find the nucleation temperature $T_{\rm n}$ and relevant parameters for GW spectrum estimate. These include the duration of the FOPT $\frac{\beta}{\mathcal{H}(T)}$ (with $\mathcal{H}$ being the Hubble parameter) and the dimensionless parameter $\alpha_*$ containing the information about the latent heat released. We identify four benchmark points shown in Table 1. The heavier RHN masses are fixed at $M_2 = 2M_1, M_3 = 3M_1$.

Table 1. Benchmark model parameters along with the corresponding FOPT and GW related parameters. Here, $M_{\eta^\pm,A,H}$ denote the physical masses of charged, neutral pseudo-scalar, and neutral scalar components of $\eta$.

| | $T_c$ [GeV] | $v_c$ [GeV] | $T_n$ [GeV] | $M_1$ [GeV] | $M_{\eta^\pm} \sim M_A$ [GeV] | $M_H$ [GeV] | $\alpha_*$ | $\beta/\mathcal{H}$ |
|---|---|---|---|---|---|---|---|---|
| BP1 | 61.40 | 216.85 | 34.95 | 587.77 | 708.33 | 649.01 | 0.65 | 105.90 |
| BP2 | 62.30 | 215.31 | 43.51 | 483.32 | 555.77 | 537.32 | 0.28 | 342.37 |
| BP3 | 70.11 | 201.24 | 61.49 | 547.87 | 616.47 | 664.02 | 0.07 | 1503.81 |
| BP4 | 73.35 | 210.70 | 57.10 | 395.51 | 449.91 | 628.16 | 0.09 | 395.51 |

## 3. Results and discussion

Figure 1 shows the temperature dependence of masses of different components of scalar doublet $\eta$, lepton doublet $L$, and the lightest RHN $N_1$ plotted as a function of $z = M_1/T$ for benchmark point BP1 given in Table 1. While RHN, a gauge singlet, does not receive much thermal correction to its mass, the components of $\eta$ gets large thermal contribution to their masses at higher temperatures. While the thermal mass of scalar doublet components decreases with a decrease in temperature, after the EWPT, they all receive a large positive contribution from the SM Higgs VEV. As shown in Fig. 1, this gives rise to a finite window $T_n < T < T_s$ during which $M_1(T) > M_{\eta^\pm,H,A} + M_L$ making the decay of $N_1$ possible. At lower temperatures, $N_1$ becomes perfectly stable, giving rise to the DM.

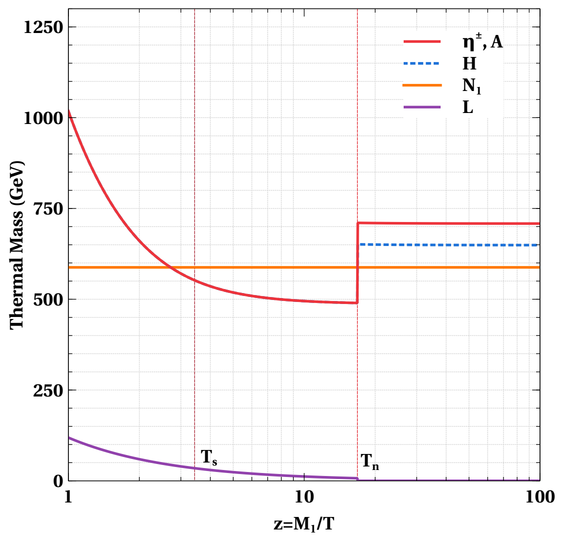


Fig. 1. Finite-temperature masses of $L, N_1$, and components of $\eta$ for BP1 shown in Table 1.

In order to find the relic abundance of DM and the baryon asymmetry, we write down the Boltzmann equations for $N_1, \eta$, and $B-L$. We then find evolution of comoving number densities $Y = n/s$ with $n, s$ being the number density of the species and entropy density of the Universe respectively. The lepton asymmetry generated from the CP-violating out-of-equilibrium decay of $N_1$ by the sphaleron decoupling epoch $T_{\rm Sph} \sim 130$ GeV gets converted into baryon asymmetry via sphaleron transitions. The final baryon asymmetry $\eta_B$ can be analytically estimated to be [16]

$$\eta_B = \frac{a_{\rm Sph}}{f}\epsilon_1\kappa\,, \tag{2}$$

where the factor $f$ accounts for the change in the relativistic degrees of freedom from the scale of leptogenesis until recombination and comes out to be $f = \frac{106.75}{3.91} \simeq 27.3$. $\kappa$ is known as the efficiency factor which incorporates the effects of wash-out processes, while $a_{\rm Sph}$ is the sphaleron conversion factor [17].

Instead of using any approximate analytical formula, we solve the coupled Boltzmann equations explicitly to calculate the abundances. Figure 2 shows the evolution of comoving number densities for BP1 in Table 1. The four different plots shown in Fig. 2 correspond to different combinations of light neutrino mass ordering and the lightest active neutrino mass. While neutrino mass ordering namely, inverted or normal, does not give rise to significant differences, the magnitude of the lightest active neutrino mass plays an important role. As the left panel plots of Fig. 2 show, larger active neutrino mass leads to a larger Dirac–Yukawa coupling of $N_1$ resulting in stronger washout. This is seen from the rise- and fall-type behaviour of $Y_{B-L}$ before getting saturated at lower temperatures. This corresponds to strong wash-out regime. On the other hand, for the smaller active neutrino mass, the asymmetry rises and then saturates, keeping us in the weak wash-out ballpark. We use the Casas–Ibarra parametrisation to relate neutrino observables with Dirac–Yukawa couplings while an arbitrary complex orthogonal matrix parametrised by complex angles $z_{ij}$ is dictating the CP-violating phases. While $\eta$ can decay at $T < T_{\rm n}$, it cannot affect baryon asymmetry as $T_{\rm n} < T_{\rm Sph}$ for BP1. Even for $T_{\rm n} > T_{\rm Sph}$, $\eta$ decay need not change lepton asymmetry if $\eta \to \eta^\dagger$ type of processes via scalar portal remains efficient. The late decay of $\eta$ can, however, change the abundance of $N_1$. However, for the chosen benchmark point BP1, such late decay contribution to DM abundance is negligible. As seen from this figure, the comoving abundance of $N_1$ saturates for $T < T_{\rm n}$ and can give rise to the observed DM abundance, depending upon the choice of benchmark parameters. It is interesting to note that decay and inverse decay are sufficient to keep $N_1$ follow the thermal equilibrium abundance before finally saturating to a constant value. The

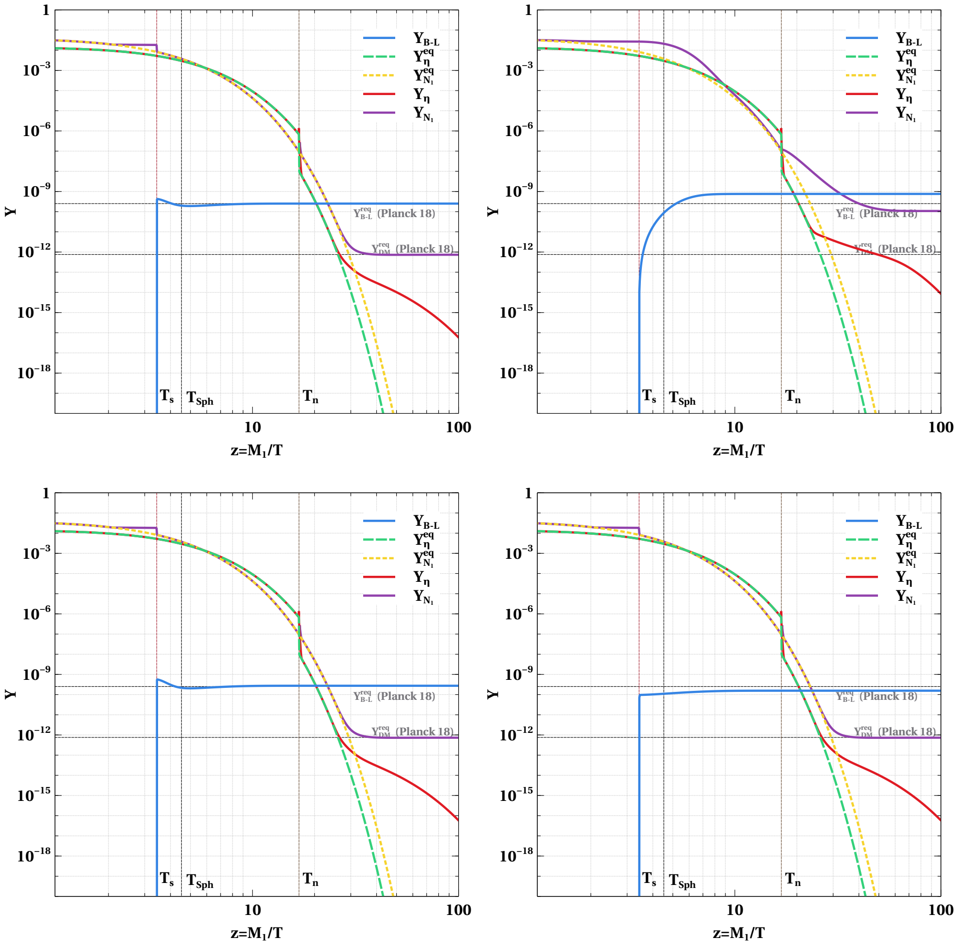


Fig. 2. Top left panel: Evolution of comoving number densities for $\eta, N_1, B-L$ for BP1 shown in Table 1 (the lightest neutrino mass is $10^{-1}$ eV in normal ordering and $z_{23} = 10.5i$). Top right panel: The same as in left panel but for the lightest neutrino mass $10^{-5}$ eV. Bottom left panel: Evolution of comoving number densities for $\eta, N_1, B-L$ for BP1 shown in Table 1 (the lightest neutrino mass is $10^{-1}$ eV in inverse ordering and $z_{23} = 10.5i$). Bottom right panel: The same as in left panel but for the lightest neutrino mass $10^{-5}$ eV. The vertical line labelled $T_s$ ($T_n$) denotes the temperature below which $N_1 \to L\eta$ decay is kinematically allowed (disallowed). The vertical line labelled $T_{\rm Sph}$ indicates the sphaleron decoupling temperature of $\sim 130$ GeV.

annihilation or coannihilation rates of $N_1$ remain suppressed due to small Dirac–Yukawa couplings required to satisfy light neutrino mass constraints in TeV scale seesaw. Although we have assumed RHN to be in the bath initially, the generic conclusions do not change even if we consider RHNs to freeze in from the bath.

The left panel of Fig. 3 shows the GW spectrum for the benchmark points given in Table 1. Sensitivities of future experiments such as LISA [18], $\mu$ARES [19], DECIGO [20], and BBO [21] are also shown as shaded regions, covering most part of the GW spectrum for our benchmark points. We also find the parameter space of the model which can be probed by these GW experiments by demanding the corresponding signal-to-noise ratio (SNR) to be more than 10. The parameter space is shown in the right panel plot of Fig. 3 with the variations in scalar and DM masses. While these points satisfy the criteria of light neutrino mass and DM relic abundance, they can also be made to satisfy the observed BAU data by appropriate variation of complex angles in the Casas–Ibarra parametrisation. Having all the new particle masses in the sub-TeV ballpark keeps other detection prospects at colliders or rare decay experiments looking for charged lepton flavour violation very promising.

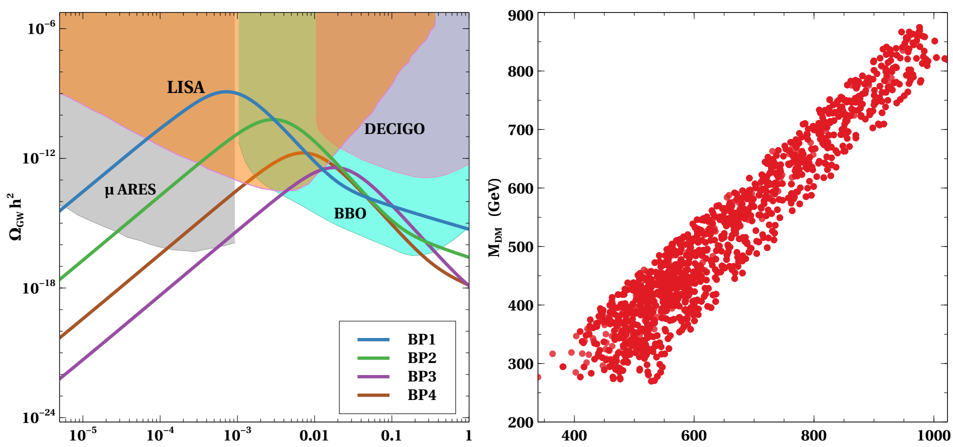


Fig. 3. Left panel: GW spectrum corresponding to the benchmark points given in Table 1. The future sensitivity of LISA, $\mu$ARES, BBO, and DECIGO are shown as shaded regions. Right panel: The parameter space in heaviest $M_{\rm DM}$−Scalar parameter space with the SNR of more than 10 in above-mentioned GW experiments. In this scan, $\mu_\eta \in (200 - 800)$ GeV, $\lambda_2 \in (1, 2)$ , the lightest neutrino mass is $10^{-3}$ eV in NO, $z_{23} = 8i$, the heavier RHN masses are fixed at $M_2 = 2M_1 and M_3 = 3M_1$. The points shown in the scan plots are consistent with DM relic criteria.

## 4. Conclusion

We have proposed a scenario where the cogenesis of baryon asymmetry and dark matter in the Universe can occur from the forbidden decay of the latter in the vicinity of a first-order phase transition. The discontinuous nature of the FOPT provides a finite temperature window over which such a forbidden decay can occur. Depending upon the model parameters, such a forbidden, CP-violating, and out-of-equilibrium decay of DM, chosen to be a singlet right-handed neutrino, can generate the required lepton asymmetry which gets converted into baryon asymmetry via electroweak sphalerons. DM becomes absolutely stable at lower temperature with its relic coinciding with the observed abundance. While the new particles in the sub-TeV ballpark can have direct signatures at laboratory experiments, the model also offers complementary detection prospects via stochastic gravitational wave background within reach of near-future experiments like LISA.

## REFERENCES

[1] P.A. Zyla *et al.*, *Prog. Theor. Exp. Phys.* **2020**, (2020).

[2] Planck Collaboration (N. Aghanim *et al.*), *Astron. Astrophys.* **641**, A6 (2020), arXiv:1807.06209 [astro-ph.CO].

[3] E.W. Kolb, M.S. Turner, «The Early Universe», 1990.

[4] G. Jungman, M. Kamionkowski, K. Griest, *Phys. Rep.* **267**, 195 (1996), arXiv:hep-ph/9506380.

[5] G. Bertone, D. Hooper, J. Silk, *Phys. Rep.* **405**, 279 (2005), arXiv:hep-ph/0404175.

[6] S. Weinberg, *Phys. Rev. Lett.* **42**, 850 (1979).

[7] E.W. Kolb, S. Wolfram, *Nucl. Phys. B* **172**, 224 (1980); *Erratum ibid.* **195**, 542 (1982).

[8] M. Fukugita, T. Yanagida, *Phys. Lett. B* **174**, 45 (1986).

[9] D. Borah, A. Dasgupta, M. Knauss, I. Saha, *Phys. Rev. D* **108**, L091701 (2023), arXiv:2306.05459 [hep-ph].

[10] D. Borah, S. Jyoti Das, R. Roshan, *Phys. Rev. D* **108**, 075025 (2023), arXiv:2305.13367 [hep-ph].

[11] Z.-j. Tao, *Phys. Rev. D* **54**, 5693 (1996), arXiv:hep-ph/9603309.

[12] E. Ma, *Phys. Rev. D* **73**, 077301 (2006), arXiv:hep-ph/0601225.

[13] A. Merle, M. Platscher, *J. High Energy Phys.* **2015**, 148 (2015), arXiv:1507.06314 [hep-ph].

[14] D. Borah *et al.*, *J. Cosmol. Astropart. Phys.* **2020**, 046 (2020), arXiv:2003.02276 [hep-ph].

[15] H. Shibuya, T. Toma, *J. High Energy Phys.* **2022**, 064 (2022), arXiv:2207.14662 [hep-ph].

[16] W. Buchmuller, P. Di Bari, M. Plumacher, *Ann. Phys.* **315**, 305 (2005), arXiv:hep-ph/0401240.

[17] J.A. Harvey, M.S. Turner, *Phys. Rev. D* **42**, 3344 (1990).

[18] LISA Collaboration (P. Amaro-Seoane *et al.*), arXiv:1702.00786 [astro-ph.IM].

[19] A. Sesana *et al.*, *Exp. Astron.* **51**, 1333 (2021), arXiv:1908.11391 [astro-ph.IM].

[20] S. Kawamura *et al.*, *Class. Quantum Grav.* **23**, S125 (2006).

[21] K. Yagi, N. Seto, *Phys. Rev. D* **83**, 044011 (2011), *Erratum ibid.* **95**, 109901 (2017), arXiv:1101.3940 [astro-ph.CO]