Probing high scale Dirac leptogenesis via gravitational waves from domain walls

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We propose a novel way of probing high-scale Dirac leptogenesis, a viable alternative to the canonical leptogenesis scenario where the total lepton number is conserved, keeping light standard model neutrinos purely Dirac. The simplest possible seesaw mechanism for generating light Dirac neutrinos involves heavy singlet Dirac fermions and a singlet scalar. In addition to unbroken global lepton number, a discrete Z_2 symmetry is imposed to forbid direct coupling between right and left chiral parts of light Dirac neutrinos. Generating light Dirac neutrino mass requires the singlet scalar to acquire a vacuum expectation value (VEV) that also breaks the Z_2 symmetry, leading to the formation of domain walls in the early Universe. These walls, if made unstable by introducing a soft Z_2-breaking term, generate gravitational waves (GWs) with a spectrum characterized by the wall tension or the singlet VEV, and the soft symmetry breaking scale. The scale of leptogenesis depends on the Z_2-breaking singlet VEV, which is also responsible for the tension of the domain wall, affecting the amplitude of GWs produced from the collapsing walls. We find that most of the near-future GW observatories will be able to probe Dirac leptogenesis scales all the way up to 10^{11} GeV.

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I. INTRODUCTION

The observed Universe is asymmetric in its baryon content, with an excess of baryons over antibaryons, quoted in terms of the baryon-to-photon ratio as [1]

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.1 \times 10^{-10}, \tag{1}$$

based on cosmic microwave background (CMB) measurements. This observed asymmetry, which is also consistent with big bang nucleosynthesis (BBN) predictions, has been a longstanding puzzle as the standard model (SM) can not provide a viable explanation. While the SM fails to fulfill the Sakharov conditions [2] necessary for dynamically generating baryon asymmetry, several beyond-the-SM frameworks consider out-of-equilibrium decay of heavy particles, leading to baryogenesis [3,4]. One appealing alternative, known as leptogenesis [5], is to first generate such an asymmetry in the lepton sector, which later gets converted into baryon asymmetry through $(B + L)$-violating electroweak sphaleron transitions [6]. While most of the leptogenesis scenarios consider Majorana nature of light neutrinos, one equally appealing alternative is to consider Dirac nature of light neutrinos. As proposed in Refs. [7,8], one can have successful leptogenesis even with light Dirac neutrino scenarios where the total lepton number or $B - L$ is conserved, just like in the SM. Popularly known as the Dirac leptogenesis scenario, it involves the creation of an equal and opposite amount of lepton asymmetry in left-handed and right-handed neutrino sectors, followed by the conversion of left sector asymmetry into baryon asymmetry via electroweak sphalerons. The lepton asymmetries in the left- and right-handed sectors are prevented from equilibration due to the tiny effective Dirac Yukawa couplings. Various possible implementations of this idea can be found in, for example, Refs. [9–21]. In a few related works [22–24], violation of $B - L$ symmetry was accommodated in a way that preserves the Dirac nature of light neutrinos, while simultaneously generating lepton asymmetry.

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Irrespective of the Dirac or Majorana nature of neutrinos, leptogenesis in general is a high-scale phenomena with a very limited range of observational signatures. Recently, one interesting possibility for probing high-scale leptogenesis via stochastic gravitational-wave (GW) observation was pointed out in Ref. [25], and was followed by a few related works in Refs. [26–28]. These works assumed the presence of an Abelian gauge symmetry like $U(1)_{B-L}$ with a type-I seesaw framework, such that the breaking of this symmetry can lead to the formation of cosmic strings that emit GWs and also dictate the mass of heavy Majorana right-handed neutrinos, i.e., the scale of leptogenesis. For high-scale $U(1)_{B-L}$ breaking where vanilla leptogenesis is valid, the GW spectrum from cosmic strings lies within current and next-generation experimental sensitivities. While the central key assumption behind these analyses is the presence of such additional gauge symmetry, which is not necessary for the validity of type-I seesaw and high-scale leptogenesis, in this paper we consider a Dirac leptogenesis scenario where a discrete symmetry like Z_2 is necessary to validate the seesaw origin of light Dirac neutrino mass. In order to generate the light Dirac neutrino mass via the Dirac seesaw mechanism, this Z_2 symmetry gets spontaneously broken by a singlet scalar field acquiring a nonzero vacuum expectation value (VEV), which in turn also leads to the formation of topological defects known as domain walls (DWs) in the early Universe. These DWs can become metastable in the presence of an explicit Z_2-breaking term that induces a pressure difference (also known as a *bias term*) across the walls. Such metastable DWs can emit stochastic GWs whose spectrum is dependent on the singlet VEV, as well as the bias term. Since the singlet VEV also controls the Yukawa couplings and heavy neutral lepton mass in the Dirac seesaw mechanism, we get interesting correlations between the scale of Dirac leptogenesis and the GW spectrum that can be probed using several proposed GW detectors. Additionally, since the GW spectrum from a DW network is distinctly different from that generated by cosmic strings, it also provides an interesting way to distinguish Dirac leptogenesis from Majorana leptogenesis studied in earlier work [25] in the context of GW probes. This is complementary to the neutrinoless double-beta decay (NDBD) [29] probe of Majorana neutrinos. Therefore, our scenario can not only be probed at future GW experiments, but also remains falsifiable by future observations of NDBD. While the nonobservation of NDBD would not necessarily confirm the Dirac nature of light neutrinos, future observations of neutrinoless quadrupole-beta decay [30] could confirm it, providing another way of testing our setup.

II. DIRAC LEPTOGENESIS

We consider the most minimal seesaw realization of light Dirac neutrinos. The SM is extended by three copies of heavy Dirac fermions $N_{L,R}$, the right-handed counterparts of active neutrinos ν_R, and a singlet scalar η. In order to ensure the pure Dirac nature of light neutrinos, a global lepton number symmetry is assumed, which can also be remnant after some gauge symmetry breaking, not considered in this minimal setup. In order to prevent direct coupling of the SM lepton doublet L with ν_R via the SM Higgs H, a discrete Z_2 symmetry is imposed under which η, ν_R are odd, while all other fields are even. The relevant Yukawa Lagrangian then reads

$$-\mathcal{L}_Y \supset Y_L \bar{L}\,\tilde{H}\,N_R + M_N \bar{N}N + Y_R \overline{N_L}\eta\nu_R + \text{H.c.} \tag{2}$$

After the neutral components of H and η acquire the VEVs v and u, respectively, a light Dirac neutrino mass arises from the type-I seesaw equivalent for Dirac neutrinos as

$$M_\nu = \frac{1}{\sqrt{2}} Y_L M_N^{-1} Y_R v\, u. \tag{3}$$

While the net lepton asymmetry is zero due to the unbroken lepton number symmetry, one can still create equal and opposite lepton asymmetries in the left and right sectors due to CP-violating out-of-equilibrium decays $N \to LH$ and $N \to \nu_R \eta$, respectively. Throughout our analysis, the masses of the Dirac fermions N are taken to be of the same order as the mass matrix in diagonal form, $M_N = \mathrm{Diag}(M_1, 2M_1, 3M_1)$. The CP asymmetry parameter is given as [12]

$$\epsilon \simeq -\frac{1}{8\pi}\frac{M_1}{uv}\frac{\mathrm{Im}[(Y_R m_\nu^\dagger Y_L)_{11}]}{(Y_R Y_R^\dagger) + (Y_L Y_L^\dagger)}, \tag{4}$$

where $v = 246$ GeV. Now the effective neutrino mass ($\tilde{m}$) is defined as

$$\tilde{m} = [(Y_R Y_R^\dagger) + (Y_L Y_L^\dagger)]\frac{uv}{M_1}, \tag{5}$$

and without loss of generality we have assumed $Y_L \sim Y_R = y$. Now, plugging the above equation back into Eq. (4), we parametrize the CP asymmetry as

$$\epsilon = \frac{1}{8\pi} y^2 \sin(2\phi)\frac{m_\nu}{\tilde{m}} \simeq \frac{1}{8\pi} y^2 \sin(2\phi). \tag{6}$$

During the sphaleron transitions, the asymmetry in the left sector can be converted into a net baryon asymmetry. However, this depends on the condition that the asymmetries in the left and right sectors do not equilibrate with each other. Such processes leading to the equilibration of left- and right-sector asymmetries at high temperature can be approximated to be

$$\Gamma_{L-R} \sim \frac{|Y_L|^2 |Y_R|^2}{M_1^2} T^3, \tag{7}$$

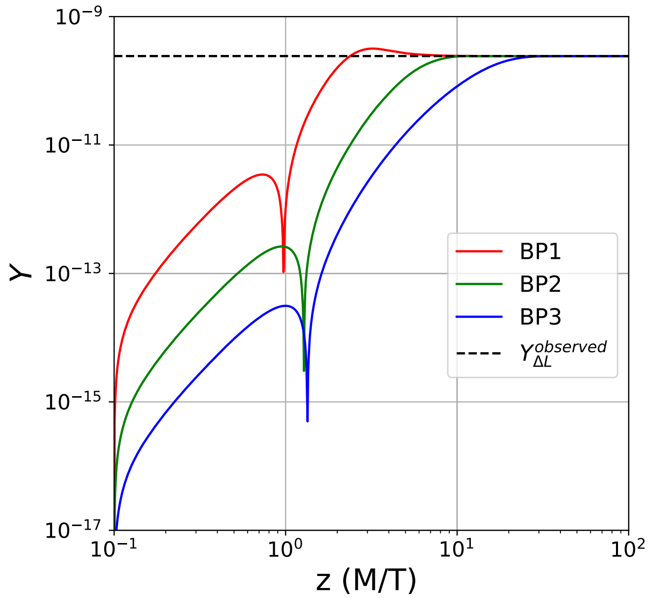

FIG. 1. Evolution of lepton asymmetry for different benchmark parameters shown in Table I. The dashed horizontal line corresponds to the required lepton asymmetry, which can be converted into the observed baryon asymmetry by sphalerons.

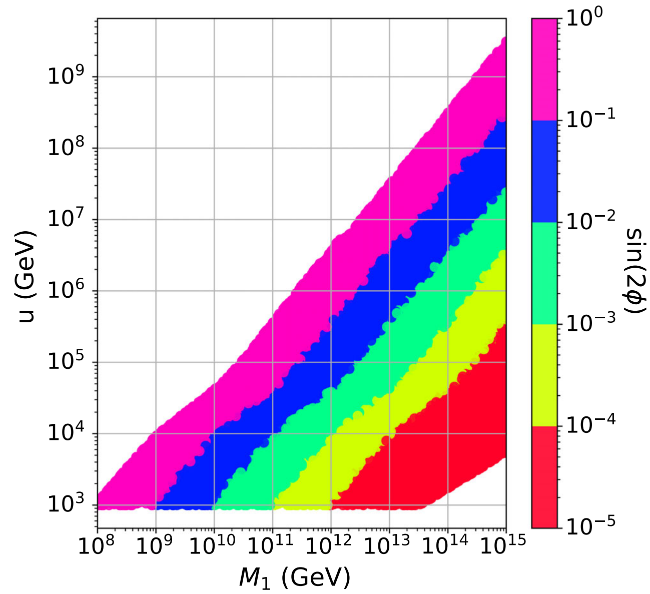

FIG. 2. Parameter space consistent with the correct baryon asymmetry.

which in turn should be less than the Hubble expansion rate during the radiation-dominated era, which is given as

$$\mathcal{H}(T) = \sqrt{\frac{8\pi^2 g_*}{90}} \frac{T^2}{M_{\mathrm{Pl}}}. \tag{8}$$

The strongest bounds comes from the high temperature when the asymmetry is produced, i.e., $z = M_1/T \simeq 1$,

$$\frac{|Y_L|^2 |Y_R|^2}{M_1} \leq \frac{1}{M_{\mathrm{Pl}}} \sqrt{\frac{8\pi^2 g_*}{90}}. \tag{9}$$

We follow the recipe outlined in Refs. [12,19] and numerically solve the relevant Boltzmann equations for calculating the final asymmetry, considering the heavy neutral fermions to be hierarchical in masses.

In Fig. 1, we show the evolution of comoving density of lepton number in either of the sectors as a function of $z = M_1/T$ for three different benchmark choices of parameters given in Table I. While the scale of leptogenesis is kept the same, variation is shown for different singlet VEV (and hence the Yukawa couplings) as required from satisfying the light neutrino mass constraints. For simplicity, the left- and right-sector Yukawa couplings are considered to be the same. Denoting the effective CP phase entering the CP asymmetry formula as $\sin 2\phi$, we perform a numerical scan for singlet VEV and the scale of leptogenesis M_1 which is consistent with the required lepton asymmetry while keeping $Y_L = Y_R$ which get restricted from light neutrino data. The viable parameter space is shown in Fig. 2. As expected, a larger value for the singlet VEV for a fixed CP phase corresponds to a larger M_1 in order to satisfy the light Dirac neutrino mass criteria. Additionally, for a fixed value of the singlet VEV, a lower value of M_1 requires a larger $\sin 2\phi$ in order to generate sufficient CP asymmetry.

TABLE I. Details of the benchmark parameters used to depict the evolution of lepton asymmetry.

	M_1 (GeV)	u (GeV)	$Y_L = Y_R$	$\sin(2\phi)$
BP1	10^{12}	10^{4}	4.51×10^{-3}	-1.12×10^{-3}
BP2	10^{12}	10^{5}	1.43×10^{-3}	-2.84×10^{-2}
BP3	10^{12}	10^{6}	4.51×10^{-4}	-0.266

III. DOMAIN WALLS AND GRAVITATIONAL WAVES

Spontaneous breaking of discrete symmetries in the early Universe can lead to the formation of topological defects like domain walls [31–33]. The energy density of domain walls, which form after spontaneous breaking of discrete symmetries, redshifts slower compared to matter or radiation and can start dominating the energy density of the Universe at some epoch. In order to prevent DWs from dominating the energy density of the Universe, the walls need to be unstable or diluted or need to be having an asymmetric probability distribution for initial field fluctuations [34,35]. In our setup with a Z_2-odd scalar singlet η having the potential

$$V(\eta) = \frac{\lambda_\eta}{4} (\eta^2 - u^2)^2, \tag{10}$$

it is possible to find a static solution of the equation of motion after imposing the boundary condition that the two vacua are realized at $x \to \pm\infty$,

$$\eta(\mathbf{x}) = u \tanh\left(\sqrt{\frac{\lambda_\eta}{2}} u x\right). \tag{11}$$

The above solution represents a domain wall extended along the $x = 0$ plane. The DW width δ is approximately the inverse of the mass of η at the potential minimum: $\delta \sim m_\eta^{-1} = (\sqrt{2\lambda_\eta} u)^{-1}$. Another key parameter for DWs known as the DW tension is given by

$$\sigma = \int_{-\infty}^{\infty} dx\, \rho_\eta = \frac{2\sqrt{2}}{3}\sqrt{\lambda_\eta} u^3 = \frac{2}{3} m_\eta u^2, \tag{12}$$

where $\rho_\eta = \frac{1}{2}|\nabla\eta|^2 + V(\eta)$ is the (static) energy density of η. For $m_\eta \sim u$, the tension of the wall can be approximated as $\sigma \sim u^3$.

The walls can be made unstable simply by introducing a pressure difference across the walls, a manifestation of a small explicit symmetry-breaking term [31,33,36,37]. Such a pressure difference or bias term ΔV should be large enough such that the DWs do not start to dominate the Universe and disappear at least before the epoch of BBN, in order not to disturb the success of standard cosmology. On the other hand, the bias term ΔV cannot be arbitrarily large due to the requirement of percolation of both the vacua (separated by DWs) whose relative population can be estimated as $p_+/p_- \simeq e^{-4\Delta V/(\lambda_\eta u^4)}$ [37]. Such unstable DWs can emit gravitational waves, the details of which have been studied in several works [38–47]. The amplitude of such GWs at peak frequency $f_{\rm peak}$ can be estimated as [38,39]

$$\Omega_{\rm GW} h^2(t_0)|_{\rm peak} \simeq 5.2 \times 10^{-20} \tilde{\epsilon}_{\rm gw} A^4 \left(\frac{10.75}{g_*}\right)^{1/3} \times \left(\frac{\sigma}{1\ {\rm TeV}^3}\right)^4 \left(\frac{1\ {\rm MeV}^4}{\Delta V}\right)^2, \tag{13}$$

with t_0 being the present time. Away from the peak, the amplitude varies as

$$\Omega_{\rm GW} \simeq \Omega_{\rm GW}|_{\rm peak} \times \begin{cases} \left(\frac{f_{\rm peak}}{f}\right) & \text{for } f > f_{\rm peak}, \\ \left(\frac{f}{f_{\rm peak}}\right)^3 & \text{for } f < f_{\rm peak}, \end{cases} \tag{14}$$

where the peak frequency reads

$$f_{\rm peak}(t_0) \simeq 3.99 \times 10^{-9}\ {\rm Hz} A^{-1/2} \times \left(\frac{1\ {\rm TeV}^3}{\sigma}\right)^{1/2} \left(\frac{\Delta V}{1\ {\rm MeV}^4}\right)^{1/2}. \tag{15}$$

In the above expressions, A is the area parameter [48,49] $\simeq 0.8$ for DWs arising from Z_2 breaking, and $\tilde{\epsilon}_{\rm gw}$ is the efficiency parameter $\simeq 0.7$ [39]. Since the GW amplitude at peak frequency increases with DW tension or, equivalently, the singlet scalar VEV, we need to consider an upper bound such that the resulting GWs do not dominate the energy density of the Universe. For example, cosmological observations from the *Planck* satellite and the corresponding CMB limits on additional effective relativistic degrees of freedom $\Delta N_{\rm eff}$ can be used to place the upper bound $\Omega_{\rm GW} h^2 \lesssim 10^{-6}$ [1,50–53]. Similar bounds can be applied from the BBN limits on $\Delta N_{\rm eff}$ as well. It should be noted that we are ignoring the friction effects between the walls and the thermal plasma [41,54], which can be significant if the field constituting the wall has large couplings with the SM bath particles like the Higgs. In the presence of such friction effects, the amplitude of GWs emitted by the collapsing walls will be smaller than that without friction discussed here. We neglect such frictional effects assuming the singlet scalar coupling with the SM bath to be tiny [43].

In Fig. 3 we show the GW spectrum arising from DWs by choosing some benchmark values of the singlet scalar VEV u while keeping the bias term fixed at $\Delta V = 500$ MeV^4. As expected, with an increase in the singlet VEV, the DW tension also increases, enhancing the GW amplitude. For the chosen benchmark points, only one of the peak frequencies remains within the experimental sensitivities, while the region of higher frequencies for all of the benchmark points remains within reach of experiments. Very large values of u for the chosen bias term are

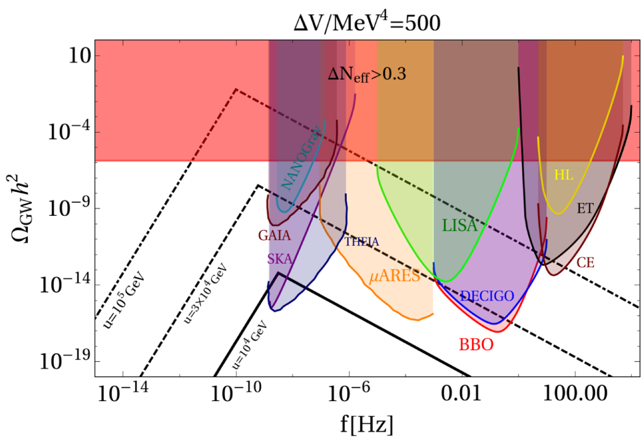

FIG. 3. Gravitational-wave spectrum from domain walls, where different straight black lines correspond to different choices of u that are consistent with baryon asymmetry, while different colored curves show the sensitivities from GW search experiments like LISA, BBO, DECIGO, HL (aLIGO), ET, CE, NANOGrav, SKA, GAIA, THEIA, and μARES. The shaded region parallel to the horizontal axis is excluded by the fact that the DW network survives long enough to dominate the energy density of the Universe before collapsing and emits a large amount of radiation, violating *Planck* bounds on $\Delta N_{\rm eff}$.

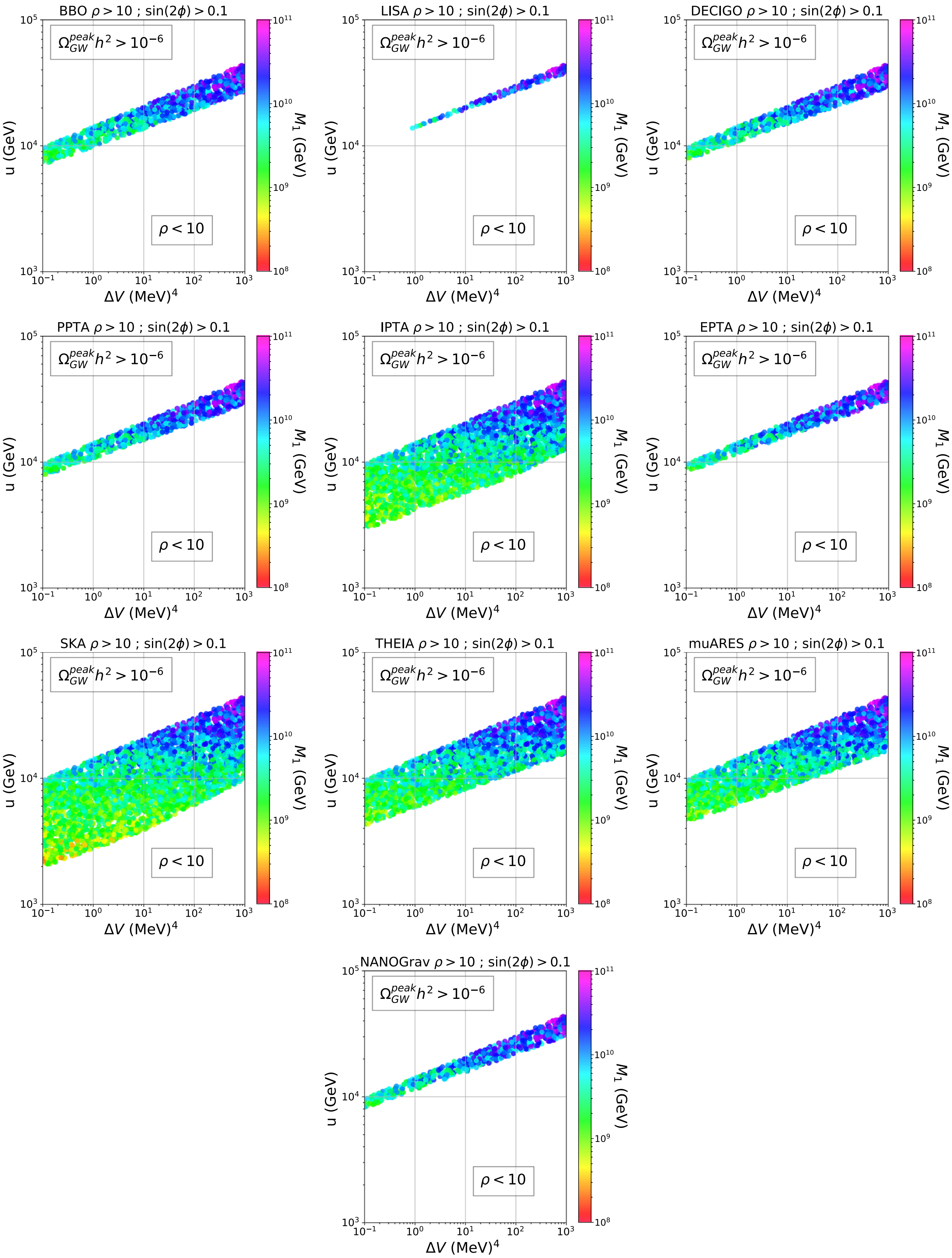

FIG. 4. Parameter space of the singlet VEV u versus the bias term ΔV, with the color code corresponding to the leptogenesis scale. The CP phase parameter $\sin 2\phi > 0.1$ and the signal-to-noise ratio for respective experiments is taken to be more than 10. The region above the colored patch is ruled out by cosmological limits from BBN as well as CMB observations, while the region below the colored patch corresponds to SNR < 10.

disfavored by the upper bound on the GW amplitude from cosmology data, shown as the pink shaded region in the uppermost region. The experimental sensitivities of NANOGrav [55], SKA [56], GAIA [57], THEIA [57], μARES [58], LISA [59], DECIGO [60], BBO [61], ET [62], CE [63], and aLIGO [64] are shown as shaded regions. Finally, we show the parameter space in singlet VEV u, bias term ΔV and scale of leptogenesis M_1 in Fig. 4 by keeping the CP phase parameter $\sin 2\phi > 0.1$. The points in these plots reflect the scale of leptogenesis shown in color code as well as the signal-to-noise ratio (SNR) at respective GW experiments to be more than 10 where the SNR is defined as [65,66]

$$\rho = \sqrt{\tau \int_{f_{\min}}^{f_{\max}} df \left[\frac{\Omega_{\rm GW}(f)h^2}{\Omega_{\rm expt}(f)h^2}\right]^2}, \qquad (16)$$

with τ being the observation time for a particular detector. In each of these plots, the regions above the colored points are ruled out by BBN as well as CMB limits on $\Delta N_{\rm eff}$. On the other hand, the regions below the colored points correspond to SNRs lower than 10. While we only show the parameter space for the GW experiments BBO [61], LISA [59], DECIGO [60], PPTA [67], IPTA [68], EPTA [69], SKA [56], THEIA [57], μARES [58], and NANOGrav [55], for remaining experiments like ET, CE, and GAIA the required SNR cannot be obtained under the assumption that all of the experiments will operate for 4 years. Thus, a larger part of the parameter space remains within reach of low-frequency GW experiments compared to the high-frequency ones, like LISA, ET, CE, etc.

IV. CONCLUSIONS

We proposed a novel way of probing Dirac leptogenesis via future observations of stochastic gravitational-wave backgrounds generated by unstable domain walls in the early Universe. Such walls arise due to spontaneous breaking of Z_2 symmetry, which needs to be imposed in the minimal Dirac seesaw model to keep unwanted terms away from the interaction Lagrangian. A soft Z_2-breaking term creates a pressure difference across the domain walls. Such a pressure difference or bias term can make the walls unstable, leading to the emission of GWs, and in the process the domain walls disappear without spoiling the success of standard cosmology. The GW amplitude depends crucially on this bias term, as well as the wall tension, which further depends on the scale of Z_2 symmetry breaking. On the other hand, in the minimal setup the scale of Z_2 symmetry breaking is the VEV of a scalar singlet, which dictates the scale of leptogenesis as it appears in the type-I Dirac seesaw relation for light neutrino masses. This leads to an interesting correlation between the scale of leptogenesis and DW tension (i.e., the singlet VEV), leading to potential GW detection prospects for several planned GW experimental facilities. We found that most of future GW experiments (such as the Pulsar Timing Array) will likely probe the parameter space of our framework corresponding to high-scale Dirac leptogenesis, with improved sensitivity. While we kept the bias term independent in our analysis, considering explicit origin of such terms like from Planck suppressed operators $\Delta V \propto \eta^5/M_{\rm Pl}$ [70] can give stronger correlation between leptogenesis favoured parameter space and GW prospects. It may also be possible to have GW probes of intermediate-scale leptogenesis, which corresponds to lower values of the singlet VEV or DW tension, especially in GW experiments sensitive to smaller strains like SKA, THEIA, and μARES. However, such low- or intermediate-scale leptogenesis will involve a more detailed analysis including lepton flavor effects, which is beyond the scope of the present work.

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