

Testing leptogenesis from observable gravitational waves

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(Received 9 June 2025; revised 29 January 2026; accepted 28 August 2026; published 14 September 2026)

Leptogenesis provides an elegant mechanism to explain the observed baryon asymmetry of the Universe (BAU), yet its experimental verification remains challenging due to requirements of either extremely heavy right-handed neutrinos or precisely fine-tuned mass splittings. We present a scenario where an additional scalar field, coupled to both the Higgs and right-handed neutrinos (RHNs), enhances the CP asymmetry through loop-level contributions, enabling successful leptogenesis at the electroweak scale. This same scalar sector triggers a strong first-order electroweak phase transition (EWPT), producing gravitational waves (GWs) within the reach of next-generation detectors. We demonstrate a robust correlation between the BAU and GW signal strength, providing a falsifiable prediction of leptogenesis that future GW searches can confirm or rule out.

DOI: [10.1103/69vn-4p32](https://doi.org/10.1103/69vn-4p32)

I. INTRODUCTION

The observed baryon asymmetry of the Universe (BAU) remains one of the most profound unsolved puzzles in modern particle physics and cosmology. Among the proposed explanations, leptogenesis driven by CP -violating decays of right-handed neutrinos (RHNs) stands out as a particularly compelling mechanism [1–3]. This scenario is naturally embedded within the framework of seesaw mechanisms that simultaneously address the origin of small neutrino masses [4].¹ Despite its elegance, conventional leptogenesis faces several significant challenges. In the hierarchical RHN mass regime, successful baryogenesis typically requires RHN masses $m_N \gtrsim 10^9$ GeV, known as the Davidson-Ibarra bound [22]. While this scale can be lowered to $m_N \gtrsim 10^6$ GeV when flavor effects are included [23–25], such high-scale RHNs still introduce large radiative corrections to the Higgs mass, exacerbating the electroweak hierarchy problem [26]. A promising alternative is low-scale leptogenesis with much lighter RHNs,

which avoids destabilizing the Higgs sector. Enhanced CP asymmetries can be achieved if at least two RHNs are nearly degenerate in mass, as in resonant [27,28] or Akhmedov-Rubakov-Smirnov (ARS) [29] leptogenesis, allowing RHN masses near the electroweak scale. Nevertheless, these mechanisms typically require fine-tuned mass splittings between the RHN pairs, challenging both naturalness and model simplicity.

Recent work has shown that a simple extension of the Standard Model (SM) scalar sector by an additional real singlet can enable successful leptogenesis with light RHNs without requiring strong mass degeneracy [30–35]. Simultaneously, such a singlet can couple significantly to the SM Higgs and modify the electroweak phase transition (EWPT) dynamics [36–40]. If the EWPT becomes strongly first-order, it produces stochastic gravitational waves (GWs) potentially observable at future space-based interferometers such as LISA [41,42], BBO [43], TianQin [44,45], Taiji [46], and DECIGO [47,48]. This intriguing connection suggests that the gravitational wave signature from the EWPT could serve as a probe of leptogenesis in scalar-extended scenarios.

In this work, we propose a distinct framework in which the CP asymmetry required for leptogenesis is dominantly generated via scalar-assisted processes, without fine-tuned mass degeneracy. Importantly, this mechanism is naturally accommodated within the context of seesaw models: once RHNs are introduced to generate neutrino masses, scalar-RHN couplings of the form SNN are theoretically well-motivated (representing additional contributions to

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¹For recent developments involving RHNs and seesaw mechanisms, see Refs. [5–21].

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Majorana masses), and the same scalar field can naturally induce a first-order phase transition. This generic interplay—relying on scalar-RHN interactions rather than fine-tuned RHN masses—ensures broad applicability across a wide class of beyond-the-Standard-Model (BSM) theories with extended scalar and neutrino sectors.

To demonstrate this mechanism, we adopt a minimal scalar extension of the SM as a benchmark. In this setup, a strong first-order EWPT driven by large scalar couplings induces sizable thermal corrections to the singlet mass, enabling the decay $N_2 \rightarrow N_1 S$ during the transition. This kinematically opens loop-level CP -violating contributions from both vertex and self-energy diagrams, further amplified by the same scalar interactions that strengthen the phase transition. Crucially, the baryon asymmetry η_B and the GW signal originate from a common dynamical source, exhibiting an intrinsic, approximately linear correlation.

This direct connection distinguishes our framework from existing approaches involving relativistic bubble wall dynamics [49–52], inflationary GWs [53–55], cosmic defects [56–60], or early matter-dominated eras [61,62], where the BAU and GW signals are largely independent or related with intermediate steps. Our framework thus provides a novel, testable pathway whereby future GW detectors can directly probe the mechanism behind the baryon asymmetry of the Universe, as we discuss further below. Importantly, while we focus on the singlet scalar as a benchmark, our mechanism can be broadly applicable to a wide class of scalar-extended models.

II. THEORETICAL FRAMEWORK AND THERMAL HISTORY

We consider an extension of the SM with two RHNs, $N_{1,2}$ and a real scalar singlet S . The relevant interactions are

$$-\mathcal{L} \supset h_{ai} \bar{\ell}_i N_i H + \frac{1}{2} (M_{ij} + a_{ij} S) N_i N_j + \text{H.c.}, \quad (1)$$

with $i, j = 1, 2$ and $\alpha = e, \mu, \tau$. As a benchmark, the scalar sector is minimal extended with the scalar potential given by

$$V_0(H, S) = \mu_H |H|^2 + \lambda_H |H|^4 + \frac{1}{2} \mu_S^2 S^2 + \frac{1}{4} \lambda_S S^4 + \lambda_{SH} S^2 |H|^2, \quad (2)$$

where $H = (\phi^+, \frac{\omega_h + h + i\phi^0}{\sqrt{2}})^T$, $S = \omega_s + S$ and $\omega_{h,s}$ are the vacuum expectation values (vevs) for the doublet and singlet respectively. At zero temperature, only the Higgs acquires a vev $\omega_h = v \approx 246$ GeV, while $\omega_s = 0$. There is thus no singlet-Higgs mixing, and collider constraints are avoided if $m_S > m_h$.

These interactions generate neutrino masses via the seesaw mechanism and mediate CP -violating decays

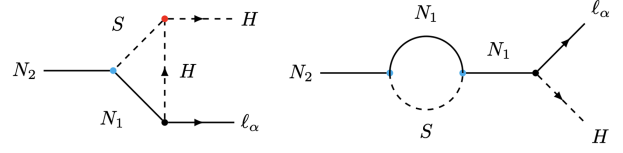


FIG. 1. The vertex correction (left) and self-energy diagrams (right) as the additional sources of CP asymmetry mediated by the scalar S in the loop level, in the decay $N_2 \rightarrow \ell_\alpha H$.

essential for leptogenesis, as shown in Fig. 1. However, the contributions from these diagrams heavily depend on the thermal history of the scalar sector that influences the scalar mass m_S and the trilinear coupling μ_{hhs} between the Higgs and the singlet.

The thermal evolution is determined by the effective potential at finite temperature. While the analytical expressions listed below use the high-temperature approximation for clarity, all numerical results employ full finite-temperature calculations with higher-order corrections following Refs. [63–67]. The potential is approximated as

$$V(\omega_h, \omega_s, T) = V_0 + \frac{1}{2} c_h T^2 \omega_h^2 + \frac{1}{2} c_s T^2 \omega_s^2, \quad (3)$$

where

$$c_h = \frac{3g^2 + g'^2 + 4y_t^2}{16} + \frac{\lambda_H}{2} + \frac{\lambda_{SH}}{12}, \quad c_s = \frac{\lambda_S}{4} + \frac{\lambda_{SH}}{3}. \quad (4)$$

The model allows four vacua: phase-O (ω_h, ω_s) = (0, 0), phase-S ($0, \omega_s$), phase-H ($\omega_h, 0$), and phase-SH (ω_h, ω_s). A strong first-order EWPT can occur via a two-step transition: $(0, 0) \rightarrow (0, \omega_s) \rightarrow (\omega_h, 0)$ when satisfying the following necessary conditions:

$$\frac{c_s}{c_h} < \frac{\mu_S^2}{\mu_H^2} < \frac{\sqrt{\lambda_S}}{\sqrt{\lambda_H}} < \frac{\lambda_{SH}}{\lambda_H}. \quad (5)$$

The scalar masses and the trilinear coupling μ_{hhs} , will evolve with temperature as

T	$[0, T_n]$	$\left[T_n, \sqrt{-\frac{\mu_S^2}{c_s}}\right]$	$\left[\sqrt{-\frac{\mu_S^2}{c_s}}, \infty\right]$
m_h^2	$-2\tilde{\mu}_H^2$	$\frac{\lambda_S \tilde{\mu}_H^2 - \lambda_{SH} \tilde{\mu}_S^2}{\lambda_S}$	$\tilde{\mu}_H^2$
m_S^2	$\frac{\lambda_H \tilde{\mu}_S^2 - \lambda_{SH} \tilde{\mu}_H^2}{\lambda_H}$	$-2\tilde{\mu}_S^2$	$\tilde{\mu}_S^2$
μ_{hhs}	0	$2\lambda_{SH} \sqrt{-\frac{\mu_S^2}{\lambda_S}}$	0,

(6)

where $\tilde{\mu}_H^2 = \mu_H^2 + c_h T^2$, $\tilde{\mu}_S^2 = \mu_S^2 + c_s T^2$, and T_n is the nucleation temperature and indicates the onset of the EWPT. During the intermediate phase, the singlet acquires nonzero vev, which induces the trilinear coupling μ_{hhs} and enables the vertex correction to the decay $N_2 \rightarrow H \ell_\alpha$. The

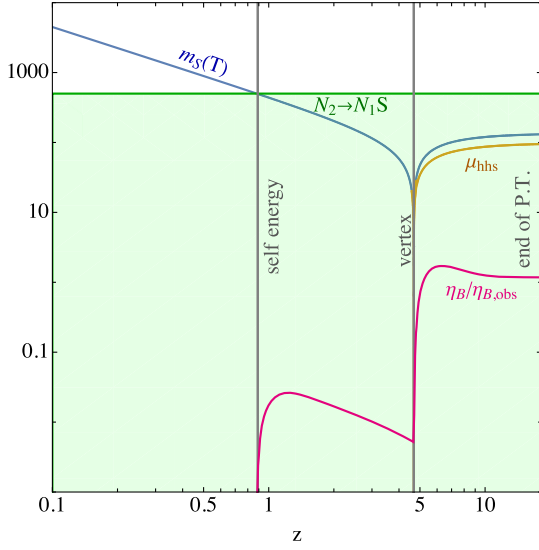


FIG. 2. Evolution of the singlet mass m_S (blue, GeV), trilinear coupling μ_{hhs} (orange, GeV), and baryon asymmetry $\eta_B/\eta_{B,obs}$ (magenta) for the benchmark $\lambda_S \approx 0.382$, $\lambda_{SH} \approx 0.317$, $|a_{21}| = 0.01$, $|a_{11}| = 10^{-4}$, $m_S(0) = 100$ GeV, $m_{N_1} = 1000$ GeV, $m_{N_2} = 1500$ GeV. The light green region marks where $m_S(T) < m_{N_2} - m_{N_1}$, enabling the $N_2 \rightarrow N_1 S$ decay.

scalar mass m_S also evolves with the temperature enabling the decay $N_2 \rightarrow N_1 S$ and switching on the CP asymmetry contributions from the RHN decays. The evolutions of the scalar mass [$m_S(T)$] and the trilinear coupling (μ_{hhs}) for one benchmark parameter point are shown in Fig. 2. The solid blue line shows $m_S(T)$; the light green shaded region indicates where it falls below the decay threshold $m_{N_2} - m_{N_1}$, enabling the enhanced CP asymmetry. The solid orange line shows $\mu_{hhs}(T)$, which is nonzero only during the first-step EWPT, so the vertex correction is active only in this window. Importantly, the GW signal from the strong EWPT depends critically on the same thermal evolution governing leptogenesis, establishing the direct connection explored below.

III. LEPTOGENESIS AND GRAVITATIONAL WAVE SIGNAL

As the Universe cools, thermal corrections to the scalar mass $m_S(T)$, induced by λ_{SH} , can make the decay $N_2 \rightarrow N_1 S$ kinematically accessible around the EWPT. This opens new sources of CP violation via self-energy and vertex corrections (cf. Fig. 1), enhancing the baryon asymmetry. The corresponding asymmetries are given by [30]

$$\varepsilon_2^v \sim \frac{|a_{21}| \mu_{hhs}}{8\pi m_{N_2}} \sqrt{\frac{m_{N_1}}{m_{N_2}}} (\mathcal{F}_{jLL}^v + \mathcal{F}_{jRL}^v), \quad (7)$$

$$\varepsilon_2^s \sim \frac{|a_{11} a_{21}|}{8\pi} \sqrt{\frac{m_{N_1}}{m_{N_2}}} (\mathcal{F}_{jLL}^s + \mathcal{F}_{jIRL}^s + \mathcal{F}_{jILR}^s + \mathcal{F}_{jIRR}^s), \quad (8)$$

where the loop functions $\mathcal{F}^{v,s}$ depend on $m_{N_{1,2}}$ and m_S . The trilinear coupling μ_{hhs} , sourced during the first step of a two-step EWPT [see Eq. (6)], directly links ε_2^v to the thermal history of EWPT. The total CP asymmetries entering the Boltzmann equations are

$$\varepsilon_1 = \varepsilon_1^0, \quad \varepsilon_2 = \varepsilon_2^0 + \varepsilon_2^v + \varepsilon_2^s, \quad (9)$$

with ε_i^0 the CP asymmetry contribution from standard type-I seesaw determined by h_{ai} in Eq. (1).

The evolution of the RHN abundances N_{N_i} and $B - L$ number N_{B-L} follows the standard Boltzmann equations with scalar-induced decays and scattering included [30],

$$\begin{aligned} \frac{dN_{N_2}}{dz} = & -(D_2 + D_{21})\Delta_2 + D_{21}\Delta_1 \\ & - \Delta_{12}S_{N_1N_2 \rightarrow HH} - \Delta_{22}S_{N_2N_2 \rightarrow HH} \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{dN_{N_1}}{dz} = & -(D_1 + D_{21})\Delta_1 + D_{21}\Delta_2 \\ & - \Delta_{12}S_{N_1N_2 \rightarrow HH} - \Delta_{11}S_{N_1N_1 \rightarrow HH} \end{aligned} \quad (11)$$

$$\frac{dN_{B-L}}{dz} = - \sum_{i=1}^2 \varepsilon_i D_i \Delta_i - W N_{B-L} \quad (12)$$

where $\Delta_i = \frac{N_{N_i}}{N_{N_i}^{\text{eq}}} - 1$ and $\Delta_{ij} = \frac{N_{N_i} N_{N_j}}{N_{N_i}^{\text{eq}} N_{N_j}^{\text{eq}}} - 1$. The decay and washout terms are

$$D_i(z) = K_i z \frac{\mathcal{K}_1(z_i)}{\mathcal{K}_2(z_i)} N_{N_i}^{\text{eq}}(z), \quad (13)$$

$$D_{21}(z) = K_{21} z \frac{\mathcal{K}_1(z_2)}{\mathcal{K}_2(z_2)} N_{N_2}^{\text{eq}}(z), \quad (14)$$

$$W(z) = \sum_i \frac{1}{4} K_i z_i^3 \mathcal{K}_1(z_i), \quad (15)$$

where $z_i = m_{N_i}/T$, $z \equiv z_1$, and $\mathcal{K}_i(z_i)$ are the i th modified Bessel function of the second kind. The decay parameters are determined by the corresponding decay width and the Hubble parameter

$$K_i \equiv \frac{\Gamma(N_i \rightarrow LH)}{H(T = m_{N_i})}, \quad K_{21} \equiv \frac{\Gamma(N_2 \rightarrow N_1 S)}{H(T = m_{N_2})}. \quad (16)$$

The baryon asymmetry freezes at the sphaleron decoupling temperature, identified with the EWPT nucleation temperature T_n , and is given by

$$\eta_B \simeq 0.013 \times N_{B-L}(T_n). \quad (17)$$

The scalar sector impacts leptogenesis in two crucial ways: (i) temperature-dependent thermal mass $m_S(T)$ determines the threshold of $N_2 \rightarrow N_1 S$ decays, controlling the onset of $\varepsilon_2^{v,s}$; (ii) the trilinear coupling $\mu_{hhs}(T)$, nonzero only during the first-step EWPT, also triggers the

contribution of ε_2^v . These are illustrated in Fig. 2, where the magenta line shows the evolution of $\eta_B/\eta_{B,\text{obs}}$.

In the absence of scalar effects, the CP asymmetry from type-I seesaw mechanism is $|\varepsilon_i^0| \lesssim 10^{-14}$ for our benchmark with light RHNs yields negligible baryon asymmetry. When scalar-induced processes are included, the evolution of η_B clearly exhibits two distinct contributions from the scalar sector discussed above. In this benchmark, near $z \approx 0.90$, $N_2 \rightarrow N_1 S$ opens, triggering $\varepsilon_2^s \sim 10^{-8}$; later, at $z \approx 4.7$, the EWPT induces $\mu_{hhs}(T)$, activating $\varepsilon_2^v \sim 10^{-5}$. This synergy enables successful low-scale leptogenesis correlated with the dynamics of the EWPT.

Crucially, the period during which $\mu_{hhs}(T)$ remains nonzero is controlled by the duration of the EWPT, terminated at T_n . A lower T_n extends this window and allows for greater accumulation of the asymmetry. Simultaneously, a lower T_n indicates a stronger first-order EWPT, resulting in more intense GW signals. This establishes a direct link between the BAU yield η_B and the detectability of GWs.

To explore this interplay, we perform a scan in the scalar sector over $(\lambda_S, \lambda_{SH})$ while fixing $m_S(T=0) = 100$ GeV. The BAU is calculated further fixing $m_{N_1} = 1000$ GeV, $m_{N_2} = 1500$ GeV, $|a_{21}| = 0.01$, $|a_{11}| = 10^{-4}$, $K_1 = 12$, and $K_2 = 20$. The conventional seesaw contribution ε_i^0 and the scattering terms are negligible in this setup. The robustness of the resulting correlation is also checked against variations of these benchmark parameters [68]. The GW spectrum is computed using lattice-calibrated fitting formulas [41,69–83] with bubble wall velocity $v_w = 0.6$ [68].

As shown in Fig. 3, the baryon asymmetry and GW SNR are strongly correlated, both scaling with $\lambda_{S,SH}$, which

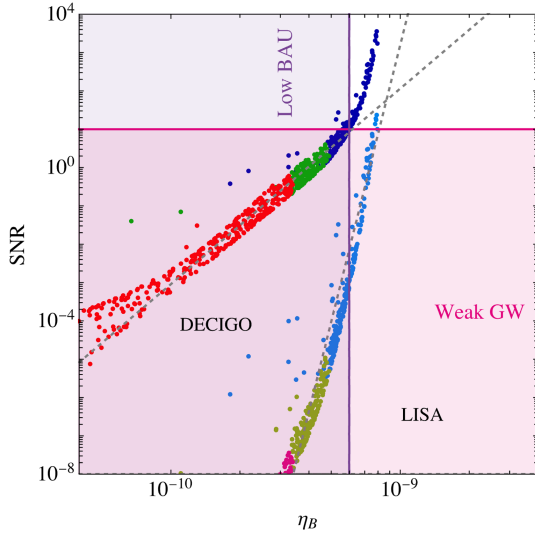


FIG. 3. Correlation between baryon asymmetry η_B and the SNR of the GW signal for both LISA (lighter points) and DECIGO (darker points). The red, green and blue points correspond to $T_c - T_n \in [0, 5]$, $[5, 10]$ and $[10, \infty]$ GeV, respectively.

governs μ_{hhs} and hence both the CP source and the strength of the EWPT. A small fraction of the points with strong enough EWPT ($T_c - T_n > 10$ GeV) yield detectable signals for LISA [41] with $\text{SNR} > 10$ and simultaneously generate sufficient η_B . The superior sensitivity of U-DECIGO [47,48] extends this coverage to more first-order EWPT points, as shown with darker markers in Fig. 3. The linear trend in the η_B -SNR plane reflects the common scalar origin of the CP asymmetry and GW productions. This tight correlation between low-scale leptogenesis and GW observables presents a unique testable framework where future GW detectors not only probe the EWPT but could also verify the mechanism behind the baryon asymmetry of the Universe.

IV. TESTING LEPTOGENESIS FROM OBSERVATION OF GRAVITATIONAL WAVES

The correlation shown in Fig. 3 demonstrates that η_B and the GW SNR move together, but does not by itself specify what a GW measurement would actually test. Future collider or displaced-vertex searches, together with neutrino oscillation data, could in principle pin down the RHN-sector parameters entering the decays $N_2 \rightarrow \ell H$ and $N_2 \rightarrow N_1 S$, namely $m_{N_{1,2}}$, a_{21} , $K_{1,2}$, and $m_S(T=0)$. However, the two scalar self-couplings λ_S and λ_{SH} that govern the EWPT dynamics are not directly fixed by these measurements; they require an independent probe of the scalar potential itself, e.g., via double/triple Higgs couplings, or via the EWPT dynamics they induce.

This is precisely where the shared origin identified above becomes a quantitative test rather than a qualitative analogy. For fixed RHN-sector parameters, the same couplings $(\lambda_S, \lambda_{SH})$ that set the strength and duration of the EWPT (and hence the GW amplitude, frequency, and SNR) also set the size and duration of the extra CP -violating sources $\varepsilon_2^{v,s}$ (and hence η_B), through the common thermal history of Eq. (6). This is illustrated in Fig. 4: requiring the observed asymmetry $\eta_{B,\text{obs}}$ selects a specific band in the $(\lambda_S, \lambda_{SH})$ plane, while the GW SNR varies systematically over the same plane. Scanning over $(\lambda_S, \lambda_{SH})$ at fixed RHN parameters, as done in Fig. 3, therefore traces out a specific correlation between the predicted η_B and the GW SNR [68].

This correlation converts a GW measurement into a direct, two-sided statement about leptogenesis in our framework, for a given, independently measured RHN sector: (i) if a future detection yields a GW SNR and spectral shape whose inferred $(\lambda_S, \lambda_{SH})$ fall inside the band reproducing $\eta_{B,\text{obs}}$, this constitutes highly nontrivial supporting evidence for the mechanism, since nothing in the theory otherwise forces the phase-transition strength and the baryon asymmetry to coincide; (ii) conversely, a null search at LISA/U-DECIGO in the relevant frequency band would exclude the region of $(\lambda_S, \lambda_{SH})$ required to reproduce $\eta_{B,\text{obs}}$ within this mechanism, thereby excluding scalar-

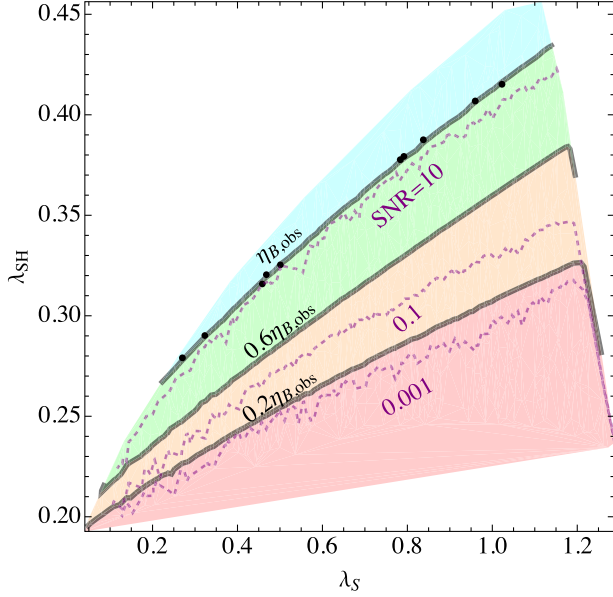


FIG. 4. Dependence of the baryon asymmetry η_B and the GW signal-to-noise ratio on the scalar couplings λ_S and λ_{SH} , for the fixed RHN-sector parameters of Fig. 2.

assisted leptogenesis as the origin of the observed asymmetry for that RHN spectrum. In either case, the GW measurement—positive or null—carries genuine, falsifiable information about the viability of leptogenesis in our framework, unlike in generic scalar-extended models where the phase-transition sector and the baryogenesis sector are mutually independent and a GW measurement carries no information about the BAU mechanism. This is the sense in which we regard GW observations as a probe, rather than merely an observational avenue, for leptogenesis.

V. CONCLUSION

We have demonstrated that scalar-assisted leptogenesis provides a compelling solution to the challenges of conventional scenarios. By extending the scalar sector with particles that couple to both RHNs and the SM Higgs, we achieve successful low-scale leptogenesis with light RHNs and without fine-tuned mass degeneracy, while simultaneously inducing a strong first-order EWPT that generates observable GW signals. Importantly, our work establishes a direct multimessenger connection: the baryon asymmetry and gravitational-wave signals originate from the same scalar-RHN dynamics, providing a novel testable pathway to probe leptogenesis through future GW observations. This represents a fundamental shift from conventional approaches where these observables are typically independent.

A key result is the intrinsic correlation between the baryon asymmetry η_B and the strength of the GW signal. Achieving detectable GWs requires a strong first-order

EWPT with a low nucleation temperature T_n , driven by large scalar couplings. The same couplings control the temperature evolution of the scalar mass and trilinear interactions, which govern the kinematics and size of the CP asymmetry during leptogenesis. Consequently, the parameter space yielding sufficient BAU is tightly aligned with that predicting observable GWs, establishing a direct experimental link between leptogenesis and gravitational wave astronomy. We stress that neither the shape of the GW spectrum in isolation, nor the discovery of the singlet scalar or the RHNs at colliders, would by itself establish a connection to leptogenesis. What makes the connection genuine and falsifiable is the bidirectional logic detailed above: for a given, independently measurable RHN sector, the same couplings required to reproduce the observed baryon asymmetry also predict a specific GW signal, so that a future detection or nondetection directly supports or excludes scalar-assisted leptogenesis as the origin of the baryon asymmetry. This constitutes a qualitatively new type of multi-messenger connection between particle cosmology and gravitational-wave astronomy, in which the same underlying dynamics is simultaneously responsible for two independently measurable cosmological observables—a connection that is particularly timely given the imminent operation of LISA, Taiji, TianQin, and DECIGO-class missions.

Our framework offers promising avenues for future exploration. In particular, scenarios with supercooled EWPTs, where prolonged transitions can further amplify both the GW signal and the baryon asymmetry, deserve detailed investigation. Studies of RHN Yukawa coupling textures and their impact on the BAU-GW correlation will be pursued in future work. Ultimately, our results demonstrate that future GW detectors such as LISA and DECIGO will provide crucial experimental verification of the leptogenesis mechanism, establishing a novel probe of the baryon asymmetry origin within the coming decade.

ACKNOWLEDGMENTS

We would like to thank Ke-Pan Xie for helpful discussion. W.L. is supported by National Natural Science foundation of China (Grant No. 12205153). Y.W. is supported by National Natural Science foundation of China under (Grant No. 12305112). The authors gratefully acknowledge the valuable discussions and insights provided by the members of the China Collaboration of Precision Testing and New Physics (CPTNP).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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