

Freeze-in leptogenesis without the need for right-handed neutrino oscillations

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(Received 14 January 2026; accepted 10 June 2026; published 13 July 2026)

We present an experimentally testable leptogenesis mechanism based on the standard type-I seesaw model that successfully operates at right-handed-neutrino (RHN) masses around the GeV scale. The mechanism takes place in a cosmological background with an asymmetry between right-handed electrons and left-handed positrons generated at high temperatures, and does not require oscillations between RHNs or any CP violation in the combined active-sterile neutrino sector. In contrast to standard leptogenesis via freeze-in, our mechanism works even in the presence of a single RHN around the GeV scale. The mechanism is illustrated for the minimal type-I seesaw with two RHNs, where we show that successful baryogenesis via leptogenesis is viable in large regions of parameter space even without a small mass splitting between the RHNs.

DOI: 10.1103/b7jy-1xh5

I. INTRODUCTION

The baryon asymmetry of the Universe (BAU) constitutes one of the most compelling indications for physics beyond the Standard Model (SM). An attractive extension of the SM capable of addressing the BAU puzzle through baryogenesis via leptogenesis (LG) [1] is the so-called type-I seesaw model [2–6], which extends the SM field content with at least two RHNs and thus provides a direct link between the BAU and the origin of tiny masses for the active neutrinos [7–9]. In its standard realization, LG can be categorized into two distinct dynamical regimes. The first, freeze-out LG (FOLG), relies on CP -violating, out-of-equilibrium decays of heavy RHNs and constitutes the traditional formulation of the mechanism [1,10–18]. The second, freeze-in LG (FILG), instead proceeds predominantly through CP -violating oscillations among RHNs in the thermal plasma of the early Universe [19,20].

FOLG provides the dominant production mechanism for RHN masses from the GUT scale down to $\mathcal{O}(100)$ GeV. For RHNs roughly heavier than the so-called Davidson-Ibarra bound [21,22], $M_N \geq 10^{9-10}$ GeV, FOLG may be realized with a hierarchical RHN mass spectrum. For lighter

RHNs, successful baryogenesis via FOLG typically necessitates either the inclusion of flavor-dependent dynamics in the lepton sector [23] or a resonant enhancement of the CP asymmetry in the RHN sector [11,12,14,17], the latter requiring a mass spectrum with very small splittings between at least two RHNs. For RHN masses of the order $\mathcal{O}(100)$ GeV, the allowed parameter space connects smoothly to the freeze-in regime [24,25], which provides the dominant production channel for even lighter RHNs. Also successful baryogenesis via FILG typically requires small mass splittings between RHNs, in particular in the minimal type-I seesaw realization with only two heavy RHNs, see, e.g., [24].

The mechanisms described so far rely on all three of Sakharov's conditions for baryogenesis [26] being satisfied in the RHN sector with sufficient efficiency and magnitude to generate the BAU. Crucially, these standard LG realizations depend on sufficient CP violation in the RHN sector, which enforces very tight constraints on mass splittings and Yukawa couplings if RHNs have masses well below the Davidson-Ibarra bound. Recently, it has been demonstrated that the stringent constraints associated with successful FOLG can be substantially alleviated if the mechanism operates in a cosmological background in which one or more of the numerous global charges that are conserved by SM interactions at high temperatures possess nonvanishing values at the time of LG. This framework, dubbed wash-in LG (WILG) [27,28], does not rely on CP violation in the RHN sector. Instead, RHNs are only needed to act as a source of $B - L$ violation that can drive the thermal plasma to an attractor solution featuring nonzero $B - L$ charge, even if $B - L$ has been

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conserved in all preceding processes throughout the history of the universe. Hence, WILG should be viewed as an effective description that requires novel CP -violating dynamics at high temperatures, which generates a non-minimal cosmological background upon which the RHNs act, see Refs. [35–38] for some realizations and [39] for related discussions. In [40], it was shown that WILG via freeze-out of RHNs with a hierarchical mass spectrum can successfully account for the BAU as long as the lightest RHN is heavier than roughly 10 TeV, which is many orders of magnitude below the Davidson-Ibarra bound.

The purpose of this paper is to demonstrate that, without imposing any additional assumptions beyond those in Ref. [40], WILG can successfully operate down to the big bang nucleosynthesis (BBN) bound on RHN masses $M_N \gtrsim 0.1$ GeV (see, e.g. Ref. [41] and references therein) if it proceeds via freeze-in of RHNs rather than freeze-out. This result is nontrivial, as WILG is most efficient when RHN interactions are efficient, and it challenges the established view that wash-in leptogenesis is strictly a high-scale mechanism ($M_N \gtrsim 10$ TeV). In this low-mass regime, the wash-in is driven primarily by scattering processes rather than the decays and inverse decays that dominate at high scales, which represents a qualitative shift in the underlying physics. In contrast to standard FILG, the WILG mechanism does not rely on RHN oscillations or

mixing, and can therefore be realized even if the RHN mass spectrum features only a single light RHN. As we will show, large regions of the neutrino-parameter space leading to successful generation of the BAU through wash-in freeze-in LG (WIFI-LG) are within reach of planned terrestrial experiments, making it a testable LG scenario.

The remainder of this paper is organized as follows. We first present the quantum kinetic equations (QKEs) governing WIFI-LG, followed by a simple parametric estimate of the resulting baryon asymmetry to build basic intuition. We then provide numerical solutions to the QKEs and identify regions of parameter space in which WIFI-LG can account for the BAU in the minimal type-I seesaw extension of the SM. Finally, we discuss potential avenues for future work and conclude. Some additional results and comparisons between standard FILG and WIFI-LG are collected in the Supplemental Material [42].

II. WIFI-LG

The equations governing the evolution of RHNs and SM particles in WIFI-LG are similar to those employed in standard FILG, which we review in the following. The standard QKEs [19,20,51–53] for FILG with an arbitrary number of RHNs takes the following form in the density matrix formalism [54],

$$\begin{aligned} \frac{T_{\text{EW}}}{M_0} \frac{dR_N}{dz} = & -i \frac{z}{T_{\text{EW}}} [\langle H \rangle, R_N] - \frac{1}{2} \frac{\langle \gamma_N^{(0)} \rangle}{T} \{F^\dagger F, R_N - 1\} + \frac{\langle \gamma_N^{(1)} \rangle}{T} F^\dagger \mu F - \frac{1}{2} \frac{\langle \gamma_N^{(2)} \rangle}{T} \{F^\dagger \mu F, R_N\} \\ & - \frac{z^2}{2T_{\text{EW}}^2} \frac{\langle S_N^{(0)} \rangle}{T} \{MF^T F^* M, R_N - 1\} - \frac{z^2}{T_{\text{EW}}^2} \frac{\langle S_N^{(1)} \rangle}{T} MF^T \mu F^* M + \frac{z^2}{2T_{\text{EW}}^2} \frac{\langle S_N^{(2)} \rangle}{T} \{MF^T \mu F^* M, R_N\}, \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{2\pi^2}{9\zeta(3)} \frac{T_{\text{EW}}}{M_0} \frac{d\mu_{\Delta_\alpha}}{dz} = & -\frac{1}{2} \frac{\langle \gamma_N^{(0)} \rangle}{T} (FR_N F^\dagger - F^* R_{\bar{N}} F^T)_{\alpha\alpha} + \frac{\langle \gamma_N^{(1)} \rangle}{T} (FF^\dagger)_{\alpha\alpha} \mu_\alpha - \frac{1}{2} \frac{\langle \gamma_N^{(2)} \rangle}{T} (FR_N F^\dagger + F^* R_{\bar{N}} F^T)_{\alpha\alpha} \mu_\alpha \\ & + \frac{z^2}{2T_{\text{EW}}^2} \frac{\langle S_N^{(0)} \rangle}{T} (F^* M R_N M F^T - F M R_{\bar{N}} M F^\dagger)_{\alpha\alpha} + \frac{z^2}{T_{\text{EW}}^2} \frac{\langle S_N^{(1)} \rangle}{T} (F M^2 F^\dagger)_{\alpha\alpha} \mu_\alpha \\ & - \frac{z^2}{2T_{\text{EW}}^2} \frac{\langle S_N^{(2)} \rangle}{T} (F M R_{\bar{N}} M F^\dagger + F^* M R_N M F^T)_{\alpha\alpha} \mu_\alpha. \end{aligned} \quad (2)$$

Here $H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{T^2}{M_P}$ denotes the Hubble rate for a standard radiation-dominated universe, $z = T_{\text{EW}}/T$ where $T_{\text{EW}} = 131.7$ GeV [55] is the temperature of sphaleron decoupling, M_N is the $n \times n$ mass matrix for the RHNs, F is the standard $3 \times n$ Yukawa coupling between the three active and n sterile neutrinos, and $M_0 = T^2/H \approx 7.12 \times 10^{17}$ GeV. The $n \times n$ matrix R_N encodes the number density matrix of the RHNs, normalized to the equilibrium number density, $R_N(T) = n_N(T)/n_N^{\text{eq}}(T)$, and the

equations for $R_{\bar{N}}$ and R_N are related via CP conjugation. The momentum-averaged effective Hamiltonian is given by $\langle H \rangle$ [52,56] and $\langle \gamma^{(i)} \rangle$ ($\langle s^{(i)} \rangle$) [51,57] denote lepton-number conserving (lepton-number violating) momentum-averaged dissipation rates. Finally, the SM is described by the following chemical potentials normalized to the temperature to have zero mass dimension $\mu = \text{diag}(\mu_\alpha) = \text{diag}(\mu_{\ell_\alpha} + \mu_\phi)$, where μ_{ℓ_α} are the flavored left-chiral lepton chemical potentials and μ_ϕ is the Higgs chemical potential. The combinations μ_α are related to lepton-flavor

asymmetries, $\Delta_\alpha = B/3 - L_\alpha$, through spectator effects. Indeed, in the literature on FILG [52], the following linear relation $\mu_\alpha = -2 \sum_\beta C_{\alpha\beta} \mu_{\Delta_\beta}$ is commonly applied, where the flavor coupling matrix $C_{\alpha\beta}$ encodes spectator process in the thermal plasma [58–60]. However, in a fully general description, the said linear relation should only be understood as a limiting case of the following affine relation

$$\mu_\alpha = 2 \left[\mu_\alpha^0 - \sum_\beta C_{\alpha\beta} \mu_{\Delta_\beta} \right], \quad (3)$$

where μ_α^0 encodes global charges (expressed in units of chemical potentials) that are approximately conserved by SM processes at high temperatures. Both μ_α^0 and $C_{\alpha\beta}$ evolve as a function of temperature, as systematically outlined in [27,29,61,62]. While the fully general relation in Eq. (3) has been mentioned in the FILG literature, see, e.g., [63], so far only the case $\mu_\alpha^0 = 0$ has been studied in this context. The novelty of our work lies in realizing that a nonzero value of μ_α^0 , respecting both theoretical and experimental bounds, can have non-negligible impact on the predictions of low-scale LG.

For the remainder of the work, we will consider the possibility that an asymmetry between right-handed electrons and left-handed positrons, $q_e = n_e - \bar{n}_e = \mu_{e_R} T^3/6$, was generated at a temperature $T \gtrsim 10^6$ GeV. The size of this asymmetry is constrained from above as [64],

$$|\mu_{e_R}| \lesssim 9.6 \times 10^{-4}, \quad (4)$$

by requiring that the primordial chiral asymmetry stored in right-handed electrons must not trigger the chiral instability of the SM plasma [65–72]. In our scenario, the affine relation Eq. (3) is given by [27]

$$\mu_\alpha^0 = \begin{pmatrix} -\frac{5}{13} \\ \frac{4}{37} \\ \frac{4}{37} \end{pmatrix} \mu_{e_R}, \quad C = \begin{pmatrix} \frac{6}{13} & 0 & 0 \\ 0 & \frac{41}{111} & \frac{4}{111} \\ 0 & \frac{4}{111} & \frac{41}{111} \end{pmatrix}, \quad (5)$$

for $T \in [T_e, 10^6 \text{ GeV}]$, where $T_e \approx 85 \text{ TeV}$ denotes the equilibration temperature of the Yukawa interaction of the right-handed electrons [64]. The validity of the above equations can be extended from T_e down to the electroweak phase transition, T_{EW} , by coupling Eqs. (1) and (2) with the evolution equation for μ_{e_R} [64]

$$\frac{d\mu_{e_R}}{dz} = -\frac{\Gamma_e}{zH} \left[\frac{711}{481} \mu_{e_R} + \frac{5}{13} \mu_{\Delta_e} - \frac{4}{37} (\mu_{\Delta_\mu} + \mu_{\Delta_\tau}) \right], \quad (6)$$

where Γ_e is the equilibration rate of right-handed electrons, see, e.g., [40] for details about Γ_e . Finally, the resulting baryon asymmetry generated via WIFI-LG is obtained by evaluating μ_{Δ_α} at T_{EW} ,

$$Y_B = c_{\text{sph}} \sum_\alpha \frac{15\mu_{\Delta_\alpha}}{2\pi^2 g_{*,s}} \Big|_{T_{EW}}, \quad (7)$$

where $g_{*,s} = 106.75$ is the number of entropic degrees of freedom and c_{sph} is the sphaleron conversion factor [73,74].

III. SIMPLE ESTIMATE

In general, the coupled system of evolution equations, Eqs. (1), (2), and (6), must be solved numerically. Before doing so, let us first present a rough parametric estimate to illustrate how various physical quantities entering the problem may affect the final asymmetry. For simplicity, the following estimate is restricted to scenarios with slow equilibration of RHNs. We set all lepton-number-violating rates, i.e., $\langle s^{(i)} \rangle$, in Eqs. (1) and (2) to zero [75], and ignore oscillations between RHNs [76]. We further approximate scattering rates as follows, $\langle \gamma^{(i)} \rangle = c_i T$, where c_i are temperature-independent constants [53,57]. Finally, let us approximate the evolution of μ_{e_R} by treating it as a constant above T_e and instantaneously equilibrated at T_e , i.e.,

$$\mu_{e_R} = \mu_{e_R}^0 \theta(T - T_e) + \mu_{e_R}^{\text{eq}} \theta(T_e - T), \quad (8)$$

where $\mu_{e_R}^{\text{eq}}$ is defined by the vanishing of the right-hand side of Eq. (6). For minimal initial conditions, $R_N(T = 10^6 \text{ GeV}) \approx \mu_\alpha(T = 10^6 \text{ GeV}) \approx 0$, the leading contribution to Eq. (2) is of the following form:

$$\frac{2\pi^2}{9\zeta(3)} \frac{T_{EW}}{M_0} \frac{d\mu_{\Delta_\alpha}}{dz} \approx \frac{\langle \gamma_N^{(1)} \rangle}{T} (FF^\dagger)_{\alpha\alpha} \mu_\alpha. \quad (9)$$

The solution can be written as

$$\mu_{\Delta_\alpha}(z_e) \approx \frac{9\zeta(3)}{\pi^2} \frac{z_e}{z_1} (\hat{F}\hat{F}^\dagger)_{\alpha\alpha} \mu_\alpha^0, \quad (10)$$

$$\mu_{\Delta_\alpha}(z_{EW}) \approx \left[\exp\left(-\frac{9\zeta(3)}{\pi^2} \frac{A}{z_1}\right) \right]_{\alpha\beta} \mu_{\Delta_\beta}(z_e), \quad (11)$$

where $\frac{1}{z_1} = c_1 \frac{M_0}{T_{EW}} \text{tr}(FF^\dagger)$, and we have defined

$$\hat{F} = \frac{F}{\sqrt{\text{tr}(FF^\dagger)}}, \quad A_{\alpha\beta} = (\hat{F}\hat{F}^\dagger)_{\alpha\alpha} C_{\alpha\beta}. \quad (12)$$

Physically, Eq. (10) represents the lepton-flavor asymmetry washed in by the RHNs during the epoch in which μ_{e_R} is still sizable, i.e., for $T \gtrsim T_e$. In contrast, for temperatures in the range $T_{EW} \lesssim T \lesssim T_e$, μ_{e_R} is rapidly depleted, and the RHNs begin to wash out lepton-flavor asymmetries in the same way as in conventional LG. Equation (11) determines the residual asymmetry at sphaleron decoupling.

To understand how our scenario may evade devastating wash-out effects, note that the right-hand side of Eq. (9) is

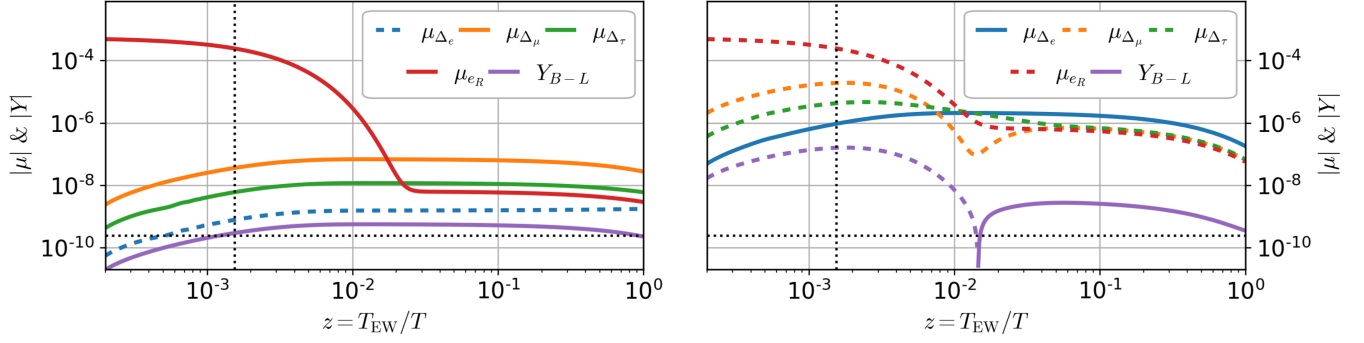


FIG. 1. Example solutions of the set of evolution equations in Eqs. (1), (2), and (6). The left (right) panel was obtained with $M = 1(1)$ GeV, $\delta M = 0.5(0.5)$, $\text{Re}\omega = \pi/4(\pi/4)$, $\text{Im}\omega = 1.6(5)$, and $\alpha_{31} = 3\pi(3\pi)$. Solid/dashed lines denote positive/negative asymmetries. The vertical black-dotted curve indicates the right-handed electron equilibration temperature, and the horizontal dotted curve shows the value of Y_{B-L} consistent with the observed BAU [83,84].

proportional to $\mu_{e_R}^0$ during wash-in and proportional to μ_{Δ} during wash-out. A hierarchy between $\mu_{\Delta_\alpha}(z_e)$ and μ_α^0 can accommodate wash-in while preventing large wash-out effects. A second point is that wash-in and wash-out are sensitive to different combinations of entries in the Yukawa matrices, implying that there can be textures that enhance wash-in while suppressing wash-out, and vice versa.

IV. NUMERICAL SOLUTIONS

We now proceed with a fully numerical analysis of the coupled system of equations in Eqs. (1), (2), and (6) [77]. For concreteness, we will henceforth consider the minimal type-I seesaw extension of the SM with two RHNs, which is the minimal setup consistent with the observed neutrino oscillations, while emphasizing that the WIFI-LG mechanism requires only a single RHN. Our analysis is carried out using the Casas-Ibarra parametrization [81], $F = \frac{1}{v} U_\nu \sqrt{m_\nu} R^T(\omega) \sqrt{M_N}$, with best-fit values for the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, U_ν , from Ref. [82]. There are five free parameters in the parametrization: Two RHN-mass parameters, $M_{1,2} \equiv M(1 \pm \frac{\delta M}{2})$, the real and imaginary components of the complex angle ω entering the orthogonal matrix R , and a Majorana phase α_{31} (α_{21}) for normal (inverted) neutrino-mass ordering.

Two example solutions of Eqs. (1), (2), and (6) are shown in Fig. 1, for a negligible initial RHN abundance and vanishing initial lepton-flavor asymmetries $R_N(T = 10^6 \text{ GeV}) = \mu_\alpha(T = 10^6 \text{ GeV}) = 0$, with CI parameters specified in the figure caption. Both panels were obtained using $|\mu_{e_R}^0| = 5 \times 10^{-4}$. The panel to the left is consistent with the simple analytical reasoning presented above: After a period of freeze-in via wash-in, there remains a large hierarchy between μ_{e_R} and μ_{Δ} at $T \sim T_e$, which prevents large subsequent wash-out of μ_{Δ} . In the panel to the right, the simple parametric estimate breaks down due to rapid equilibration of RHNs, making terms proportional to $\langle \gamma_N^{(0)} \rangle$

critical for a reliable description. In this case, the evolution of lepton-flavor asymmetries features enhanced wash-in compared to the first example, and also stronger subsequent wash-out.

V. PARAMETER SPACE

It is useful to present the LG parameter space in terms of the active-sterile neutrino mixing and the masses of the RHNs. The neutrino flavor eigenstates can be written in terms of the three light and two heavy mass eigenstates, ν_i and N_I , as $\nu_\alpha = U_{\alpha i} \nu_i + \Theta_{\alpha I} N_I^c$, where $\Theta_{\alpha I}$ denotes the mixing between active neutrinos and the RHNs. A convenient measure of the overall mixing strength is $U^2 = \sum_{\alpha, I} |\Theta_{\alpha I}|^2$. While the seesaw mechanism imposes a lower bound on this quantity, $U^2 \gtrsim \sum_i m_i/M$, the requirement of successful LG places an upper bound on U^2 [24].

In Fig. 2, the white region of parameter space, (M, U^2) , is where the observed value of the BAU can be accounted for through WIFI-LG in the minimal type-I seesaw model for fixed RHN-mass splitting $\delta M = 0.5$ and $\text{Re}\omega = \pi/4$. The generated asymmetry depends only mildly on the fixed parameters, δM and $\text{Re}\omega$, and we scan over the remaining three free parameters. The parameter space is bounded from below by the seesaw line shown by the black dashed curve. While the parameter space can be further constrained by direct searches and BBN, these bounds depend on the relative mixing pattern $U_e^2 : U_\mu^2 : U_\tau^2$ [85]. To not rule out parameter regions on the basis of these limits alone [86], we leave a detailed study of the flavor dependence of the parameter space and a careful account of constraints for future work. See, e.g., [87] and references therein for current constraints. However, note that RHN masses $M \lesssim 10^{-1}$ GeV are severely constrained by BBN irrespective of the flavor structure and therefore not considered here. Moreover, for RHN masses heavier than roughly 40 GeV, non-relativistic corrections to the rates [53,57] as well as contributions from freeze-out [24] might become

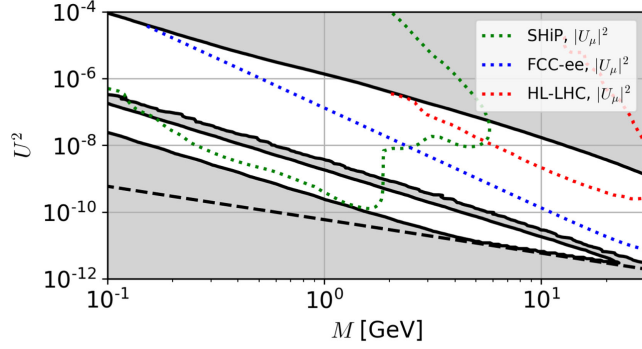


FIG. 2. Regions of parameter space where the BAU can be fully accounted for by WIFI-LG in the minimal type-I seesaw model for RHN-mass splitting $\delta M = 0.5$, $\text{Re}\omega = \pi/4$ and initial conditions respecting the bound in Eq. (4). The green, red, and blue curves display expected sensitivities of SHiP ($|U_\mu|^2$) [94], HL-LHC ($|U_\mu|^2$) [95], and FCC-ee ($|U_\mu|^2$) [96], respectively. The experimental sensitivities presented here are intended merely as a qualitative guide, as they apply only for the mixing $|U_\mu|^2$, and the large mass splitting, $\delta M = 0.5$, requires a more careful treatment of the associated constraints. See main text and Supplemental Material [42] for further details.

important requiring further investigation. The result shown in Fig. 2 was obtained assuming normal mass hierarchy for active neutrinos and the corresponding result for inverted mass hierarchy is included in Supplemental Material [42]. To contextualize the figure, note that standard FILG without wash-in cannot generate the BAU in any region of parameter space once $\delta M \gtrsim 10^{-2}$, assuming a normal-ordered neutrino mass spectrum in the minimal type-I seesaw model [24]. Meanwhile, Fig. 2 illustrates that through our mechanism, LG remains a viable explanation of the BAU even for GeV-scale RHNs with $\delta M \gg 10^{-2}$. Additional details on the visible features and a more comprehensive comparison between standard FILG and WIFI-LG can be found in Supplemental Material [42]. It is worth stressing that the WIFI-LG mechanism enables the type-I seesaw extension of the SM to account for the BAU through FILG for a mass spectrum featuring at least one RHN at the GeV scale but otherwise *arbitrary* mass splittings, even in the minimal scenario where there are only two RHNs. Intriguingly, large regions of parameter space of the minimal seesaw model will be within reach of planned experiments, as indicated by the sensitivity curves in Fig. 2, making WIFI-LG a baryogenesis scenario that will be both testable—and falsifiable—with particle-physics experiments. Finally, our numerical analysis shows that WIFI-LG remains a viable explanation of the BAU for values of $|\mu_{e_R}^0|$ as low as 6% of the upper bound in Eq. (4). As noted in Ref. [39], such an initial electron charge could be generated, e.g., by the Affleck-Dine mechanism [88–90] with a $B - L = 0$ flat direction, or axion-inflation with a strong Chern-Simons coupling [91–93].

VI. CONCLUSION AND OUTLOOK

In this paper, we have provided a framework where successful baryogenesis through FILG can be realized even with a single RHN around the GeV scale. As a proof-of-concept, we considered the minimal type-I seesaw extension of the SM with RHN masses $0.1 \text{ GeV} \lesssim M_N \lesssim 40 \text{ GeV}$ and demonstrated that the BAU can be successfully produced throughout wide regions of parameter space where the mass splitting between the two RHNs is too large for conventional FILG to be viable. This new freeze-in mechanism, which we term WIFI-LG, does not require sizable CP violation in the combined active-sterile neutrino sector and will be testable at planned intensity experiments and future colliders. Consequently, we provide a new physics case, based on the minimal type-I seesaw, for the ongoing and planned experimental searches for RHNs in the GeV range.

Our work provides many opportunities for further exploration. Although we have focused on the freeze-in contribution for RHN masses $M_N \lesssim 40 \text{ GeV}$, the analysis could—and should—be extended to heavier RHN masses. Intriguingly, by employing the formalism outlined in [24], it should be possible to unite freeze-out WILG and freeze-in WILG; we leave a detailed study of this for future work [97]. As emphasized in Supplemental Material [42], another interesting direction for future work is the extension of WIFI-LG to the type-I seesaw model with three RHNs. Moreover, the results presented in this work can be refined by improving aspects of the evolution of q_e , and they motivate dedicated analyses of the chiral plasma at temperatures $T \sim T_e$, as discussed in Ref. [40]. Last but not least, our study motivates further exploration of possible mechanisms capable of producing suitable initial conditions for WILG [35–38].

ACKNOWLEDGMENTS

We are grateful to Kai Schmitz for many valuable discussions. We would also like to thank Marco Drewes and Kai Schmitz for helpful comments on the draft. The work of M. A. M. and S. W. was supported by the Cluster of Excellence “Precision Physics, Fundamental Interactions, and Structure of Matter” (PRISMA⁺ EXC 2118/1) funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the German Excellence Strategy (Project No. 390831469). S. W. was supported by the Cluster of Excellence PRISMA⁺⁺ (EXC 2118/2, Project ID 390831469).

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [77] We solved the numerical system by suitably extending the publicly available ULYSSES code [53,78]. In our implementation, we include coherent oscillations as well as both lepton-number-conserving and lepton-number-violating interaction rates. The evolution is based on the effective Hamiltonian and on interpolated momentum-averaged dissipation rates, as provided in [53]. In [79,80] it has been shown that including the full momentum dependence in the quantum kinetic equations can change the baryon asymmetry by $\mathcal{O}(1)$. While we expect a similar level of accuracy for WIFI-LG we leave a detailed study of this for future work. Finally, in evaluating the interaction rates of the right-handed electrons, we initialize all SM couplings at their measured values at the Z pole and subsequently evolve them using their one-loop renormalization group equations up to the scale $\mu = \pi T$.
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