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Resonant Forbidden Leptogenesis

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S. Kanemura & Lisp, PRL **134**, 211802 (2025); arXiv: 2412.18278

Outline

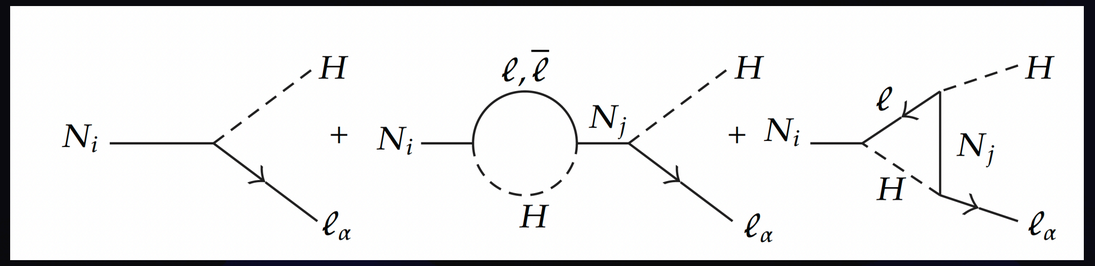
- What is forbidden leptogenesis
- Resonant forbidden leptogenesis from soft-lepton resummation
- Working regimes

Traditional v.s. forbidden leptogenesis

Traditional leptogenesis

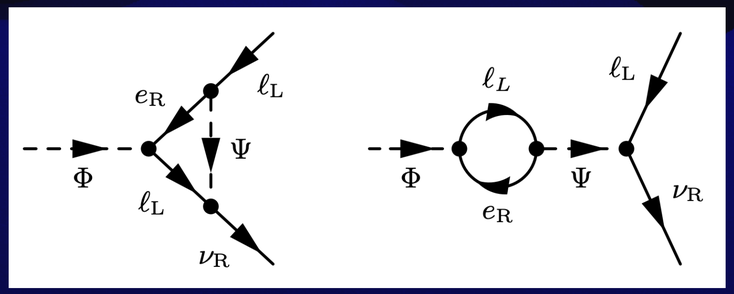
- Traditional leptogenesis from heavy neutrino decay

$$\mathcal{L}_I = \mathcal{L}_{\rm SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + \text{h.c.}\right)$$



- Traditional leptogenesis from heavy scalar decay

$$\begin{aligned}\mathcal{L} \;=\; & F(\ell_{\rm L}\cdot\Phi)\nu^c_{\rm R} + F'(\ell_{\rm L}\cdot\Phi^c)e^c_{\rm R} \\ & G(\ell_{\rm L}\cdot\Psi)\nu^c_{\rm R} + G'(\ell_{\rm L}\cdot\Psi^c)e^c_{\rm R} + \text{h.c.}\end{aligned}$$



Three ingredients from Sakharov conditions: lepton asymmetry was first generated by out-of-equilibrium decay and then converted to baryon asymmetry via non-perturbative sphaleron processes

Traditional leptogenesis

- CP-asymmetry generation in traditional leptogenesis

$$\gamma - \gamma^{CP} \propto \mathrm{Im}\left(y^4\right) \times \frac{m^2}{m_i^2 - m_j^2}$$

Mass difference: the particle with self-energy correction

Yukawa phase (CP-odd phase): complex phases from Yukawa couplings

Kinetic phase (CP-even/strong phase): imaginary contribution from on-shell loop particles, if $m_{\text{loop}} < m_{\text{external}}$

- Common practice: CP asymmetries originate from new particle mixing diagrams (neutrino/scalar)

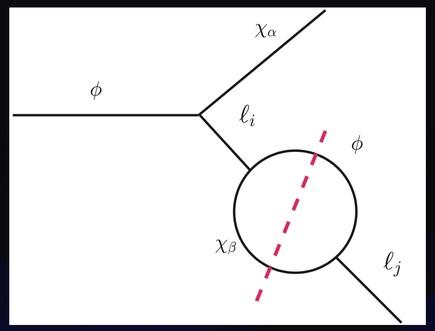
Whenever new interactions are introduced, the SM leptons usually get mixed too!

Can lepton mixing also yield CP asymmetries? → *resonant forbidden leptogenesis*

Forbidden leptogenesis

- CP asymmetry from lepton mixing—a naive perspective from $\mathscr{L} = -y'\bar{\ell}\tilde{\phi}\chi_R + \mathrm{h.c.}$

An on-shell cut in lepton self-energy diagram



- Optical theorem in *vacuum* QFT: scalar decay means $m_\phi > m_\ell + m_\chi \rightarrow$ loop particles (ϕ, χ_β) cannot go on-shell $\rightarrow$ no imaginary contribution (kinetic phase) from lepton loop $\rightarrow$ leptogenesis from lepton mixing is kinematically forbidden *in vacuum*

Leptogenesis occurs at high temperatures, does finite-temperature QFT predict leptogenesis from lepton mixing?

If positive, a naive analogy yields $\gamma - \gamma^{\mathrm{CP}} \propto \mathrm{Im}\left(y'^4\right) \times \dfrac{m_\phi^2}{m_{\ell_i}^2 - m_{\ell_j}^2}$ $\quad m_{\ell_i}^2 = \left(\dfrac{3g_2^2}{32} + \dfrac{g_1^2}{32} + \dfrac{y_{\ell_i}^2}{16}\right) T^2$ $\quad \dfrac{1}{y_\mu^2 - y_e^2} \simeq 10^7$

Resonant forbidden leptogenesis from soft-lepton resummation

Resonant Forbidden Leptogenesis

- An exemplary setup: $\mathscr{L} = -y'\bar{\ell}\tilde{\phi}\chi_R + \text{h.c.}$ with two χ flavors & total lepton number conservation $\Delta L_{\text{SM}} + \Delta L_{\chi} = 0$

  1. CP violation from complex y'
  2. Nonthermal condition from scalar decay
  3. Baryon number violation from sphaleron

- Technical treatment in finite-temperature QFT: Schwinger-Keldysh Closed-Time-Path (CTP) formalism

Kadanoff-Baym (KB) kinetic equation

$$\frac{d\Delta n_{\chi_1}}{dt} = \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\text{Tr}\left[i\Sigma^{>}_{\chi_1}(p)iS^{<}_{\chi_1}(p) - i\Sigma^{<}_{\chi_1}(p)iS^{>}_{\chi_1}(p)\right]$$

KB collision rates

Full thermal equilibrium→Kubo-Martin-Schwinger relation:
$\Sigma^{>}(p) = -e^{p_0/T}\Sigma^{<}(p)\,, S^{>}(p) = -e^{p_0/T}S^{<}(p) \rightarrow \Delta n_{\chi_1} = 0$

$\Delta n_{\chi_1} \equiv n_{\chi_1} - n_{\bar{\chi}_1}$, Tr=Dirac trace, $i\Sigma^{<,>}_{\chi_1}(iS^{>,<}_{\chi_1})$= self-energy amplitudes (propagators) of χ_1

Resonant Forbidden Leptogenesis

- Washout KB rate at one loop

$$\mathscr{W} = \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\mathrm{Tr}\left[i\Sigma^{>}_{\chi_1} iS^{<}_{\chi_1} - i\Sigma^{<}_{\chi_1} iS^{>}_{\chi_1}\right]_{1-\mathrm{loop}}$$

$$\hookrightarrow \propto f_{\chi_1} - f_{\bar{\chi}_1}$$

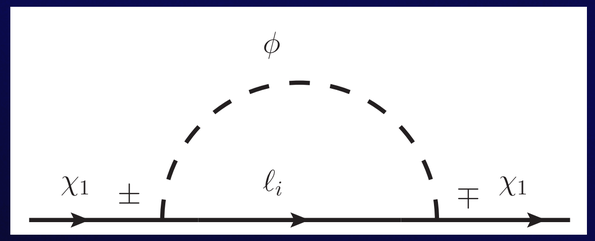
Free propagators in CTP

$$\begin{aligned}
i\$^{+-}(p) &\equiv i\$^{<}(p) = -2\pi\delta(p^2-m^2)(\not{p}+m)\left[\theta(p_0)f(p_0) - \theta(-p_0)(1-\bar{f}(-p_0))\right],\\
i\$^{-+}(p) &\equiv i\$^{>}(p) = -2\pi\delta(p^2-m^2)(\not{p}+m)\left[-\theta(p_0)(1-f(p_0) + \theta(-p_0)\bar{f}(-p_0)\right],\\
i\$^{++}(p) &\equiv i\$^{T}(p) = \frac{i(\not{p}+m)}{p^2-m^2+i\epsilon} - 2\pi\delta(p^2-m^2)(\not{p}+m)\left[\theta(p_0)f(p_0) + \theta(-p_0)\bar{f}(-p_0)\right],\\
i\$^{--}(p) &\equiv i\$^{\bar{T}}(p) = -\frac{i(\not{p}+m)}{p^2-m^2-i\epsilon} - 2\pi\delta(p^2-m^2)(\not{p}+m)\left[\theta(p_0)f(p_0) + \theta(-p_0)\bar{f}(-p_0)\right],
\end{aligned}$$

$$\begin{aligned}
iG^{+-}(p) &\equiv iG^{<}(p) = 2\pi\delta(p^2-m^2)\left[\theta(p_0)f(p_0) + \theta(-p_0)(1+\bar{f}(-p_0))\right],\\
iG^{-+}(p) &\equiv iG^{>}(p) = 2\pi\delta(p^2-m^2)\left[\theta(p_0)(1+f(p_0)) + \theta(-p_0)\bar{f}(-p_0)\right],\\
iG^{++}(p) &\equiv iG^{T}(p) = \frac{i}{p^2-m^2+i\epsilon} + 2\pi\delta(p^2-m^2)\left[\theta(p_0)f(p_0) + \theta(-p_0)\bar{f}(-p_0)\right],\\
iG^{--}(p) &\equiv iG^{\bar{T}}(p) = -\frac{i}{p^2-m^2-i\epsilon} + 2\pi\delta(p^2-m^2)\left[\theta(p_0)f(p_0) + \theta(-p_0)\bar{f}(-p_0)\right],
\end{aligned}$$

$$i\Sigma^{<}_{\chi_1} \equiv i\Sigma^{+-}_{\chi_1},\ i\Sigma^{>}_{\chi_1} \equiv i\Sigma^{-+}_{\chi_1},$$

$i\Sigma^{-+,-+}_{\chi_1} =$

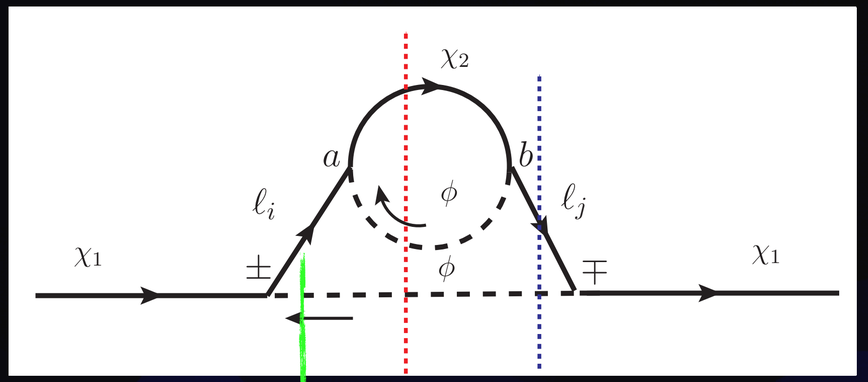


**In CTP, the time for "+" index is always earlier (less) than for "-" index, hence the symbol "<"

Resonant Forbidden Leptogenesis

- CP-violating source at two loop

$$\mathcal{S}_{\rm CP} = \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\mathrm{Tr}\left[i\Sigma^{>}_{\chi_1} iS^{<}_{\chi_1} - i\Sigma^{<}_{\chi_1} iS^{>}_{\chi_1}\right]_{2-\rm loop}$$

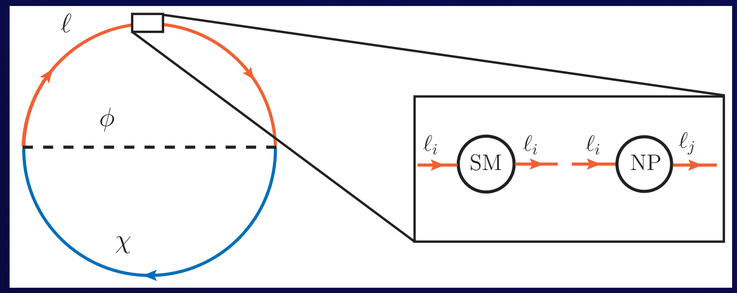


- The necessity of lepton resummation

1. Massless SM lepton propagators may lead to pinch singularity

$$\int dp\delta(p^2)\delta(p^2) \to \int dp\delta(p^2 - m_i^2)\delta(p^2 - m_j^2) = 0$$

2. Propagators are in the full form in CTP: 2PI effective action perspective

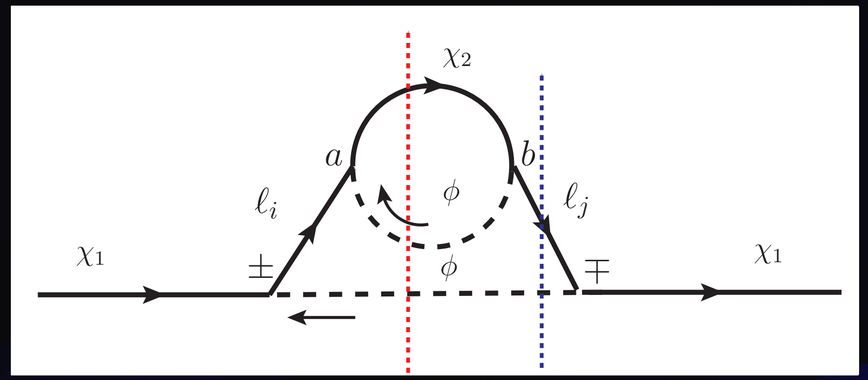


Resonant Forbidden Leptogenesis

- CP-violating source at two loop, after quite tedious calculations…

$$\mathcal{S}_{\rm CP} = \frac{\mathrm{Im}\left(y'^4\right) m_\phi^4}{256\pi^4 \underbrace{(m_j^2 - m_i^2)}} \mathcal{J}(T)$$

Resonant enhancement from resummed leptons



- Statistics function for the nature of forbidden leptogenesis

$$\mathcal{J}(T) = \int_0^\infty \frac{dp_\ell}{p_\ell} \int_{p_\ell + m_\phi^2/(4p_\ell)}^\infty dE_\phi \int_{p_\ell + m_\phi^2/(4p_\ell)}^\infty dE'_\phi \, f_\phi^{\rm eq}(E_\phi) \underbrace{\left[f_\phi(E'_\phi) - f_\phi^{\rm eq}(E'_\phi)\right]} \left[f_{\chi_2}^{\rm eq}(E'_\phi - p_\ell) + f_\ell^{\rm eq}(p_\ell) - 1\right]$$

Caveat: χ_1 alone is not sufficient to provide the nonthermal condition. Either (ϕ, χ_1) or (χ_2, χ_1) should be

Working regimes

Working Regimes

- Minimalism

1. Forbidden leptogenesis may be easily realized with a minimal particle content beyond the SM

2. The resonant enhancement by a factor of 10^7 is a SM prediction, no vacuum mass degeneracy is required to induce the resonance (traditional resonant leptogenesis developed by A. Pilaftsis)

3. It may already exist in several leptogenesis scenarios (an irreducible source), where the particle content is non-minimal (low-scale type-I leptogenesis, type-II leptogenesis, Dirac leptogenesis, scotogenic, cogenesis of dark matter…)

Working Regimes

- Low-scale leptogenesis

$$\mathcal{S}_{\rm CP} = \frac{{\rm Im}\left(y'^4\right) m_\phi^4}{256\pi^4 (m_j^2 - m_i^2)} \mathcal{J}(T) \qquad m_{\ell_i}^2 = \left(\frac{3g_2^2}{32} + \frac{g_1^2}{32} + \frac{y_{\ell_i}^2}{16}\right) T^2$$

Assumptions:

1. All SM lepton Yukawa interactions in thermal equilibrium $T \lesssim 10^5$ GeV

2. Lepton thermal masses from new-physics Yukawa couplings are suppressed

Break-down:

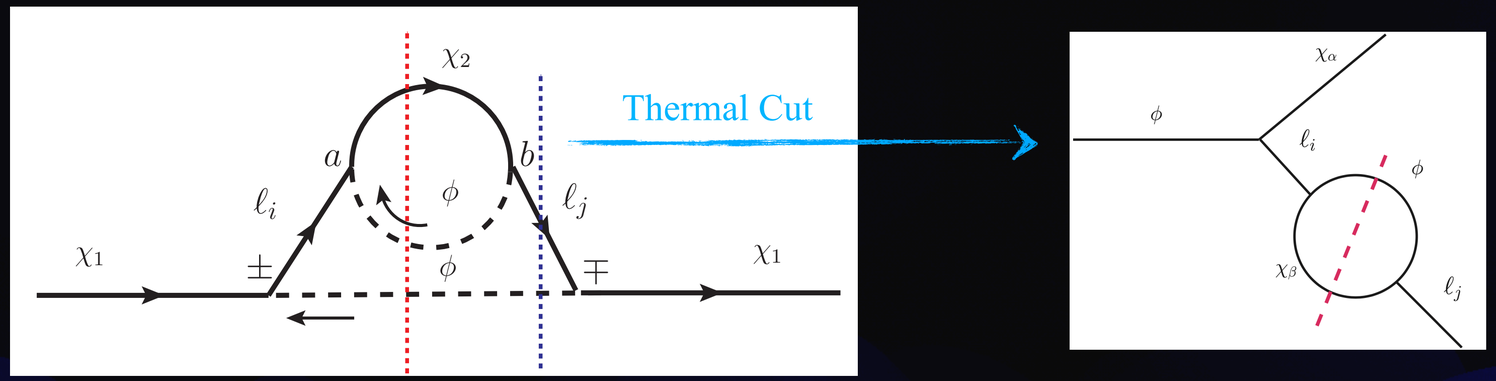
1. Applicable to high-scale leptogenesis $T \gg 10^5$ GeV, e.g., lepton flavored leptogenesis, resonant enhancement decreased (M. Beneke, *et al*, 1007.4783; B. Garbrecht, 1210.0553)

2. New-physics Yukawa couplings dominate over SM lepton Yukawa, $m_j^2 - m_i^2 \propto \mathcal{O}(y'^2) \rightarrow \mathcal{S}_{\rm CP} \propto \mathcal{O}(y'^2)$.
   Quadratic leptogenesis scenarios (an interesting project)

Working Regimes

- Nature of forbidden leptogenesis

$$\mathcal{S}_{\rm CP} = \frac{\mathrm{Im}\left(y'^4\right) m_\phi^4}{256\pi^4 (m_j^2 - m_i^2)} \mathcal{J}(T)$$



$$\mathcal{J}(T) = \int_0^\infty \frac{dp_\ell}{p_\ell} \int_{p_\ell + m_\phi^2/(4p_\ell)}^\infty dE_\phi \int_{p_\ell + m_\phi^2/(4p_\ell)}^\infty dE'_\phi \, f_\phi^{\rm eq}(E_\phi) \left[f_\phi(E'_\phi) - f_\phi^{\rm eq}(E'_\phi) \right] \left[f_{\chi_2}^{\rm eq}(E'_\phi - p_\ell) + f_\ell^{\rm eq}(p_\ell) - 1 \right]$$

Thermal statistics/background density effect from inner particles:

1. In vacuum, $f_{\chi_2}(E_{\chi_2}), f_\phi^{(\rm eq)}(E'_\phi) \to 0, \quad \mathcal{S}_{\rm CP} \to 0$

2. Kinetic phase vanishes at: $m_\phi \gg T \to \mathcal{S}_{\rm CP} = 0$

Working Regimes

- Resonance stability

$$\mathcal{S}_{\rm CP} = \frac{\mathrm{Im}\left(y'^4\right) m_\phi^4}{256\pi^4 (m_j^2 - m_i^2)} \mathcal{J}(T)$$

= modified dispersion relation + finite thermal width

$p^2 \sim m^2(T)$ $\qquad$ $\Gamma_i(T) \sim g^2 (g^2 + y_{\ell_i}^2)\, T$

$$\sim m_j^2 - m_i^2 + i\,\kappa\, g^2\, (m_j^2 - m_i^2), \quad \kappa < 1$$

$$\sim \mathcal{O}(y_\ell^2)\, T^2 + i\mathcal{O}(g^2 y_\ell^2)\, T^2$$

Summary

Why & When for forbidden leptogenesis

- A general mechanism: it aims to find out the minimal extension of the Standard Model, minimal connections to neutrino mass and dark matter origins, e.g, when you consider some neutrino/dark matter models, forbidden leptogenesis may already happen in your scenario!
- It allows TeV- and even electroweak-scale leptogenesis, allowing detection at colliders!
- Minimalism implies stronger correlations among multidisciplinary science: particle physics, cosmology, astrophysics— More detection channels from forbidden leptogenesis!

Thank you