Neutrino Frontiers – 2008

TPI – University of Minnesota

Leptogenesis

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Brief historical review

Leptogenesis: is a class of scenarios where the Universe baryon asymmetry $Y_{\Delta B} \equiv \frac{n_B - \bar{n}_B}{s} \approx 8.7 \times 10^{-11}$ is produced from a lepton asymmetry $(Y_{\Delta L})$ generated in the decays of heavy singlet Majorana (seesaw) neutrinos.

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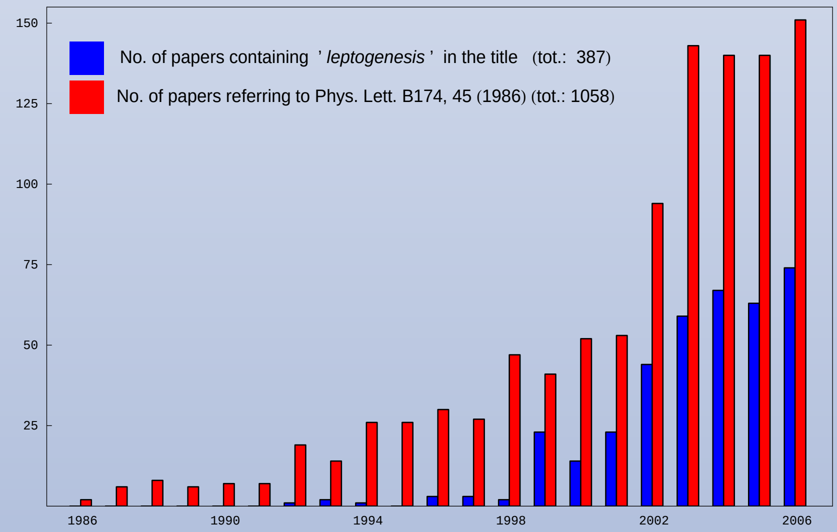

Experimental confirmation of $m_\nu \neq 0$
$m_\nu \ll m_f \Rightarrow$ hints to the seesaw ?
(there is a stronger reason - see below).

Quantitative LG in the one-flavor approximation:

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"Towards a complete theory of thermal leptogenesis in the SM and MSSM," *NPB***685***, 89 (2004).*

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Beyond the one-flavor approximation: Lepton flavors (and $N_{2,3}$) effects

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- Quantitative and qualitative differences from 1-flavor approx. (Jan. 2006):

  A. Abada, S. Davidson, F.X. Josse-Michaux, M. Losada, A. Riotto,
  "Flavour issues in leptogenesis," JCAP **0604**, *004 (2006); [hep-ph/0601083].*

  EN, Y. Nir, E. Roulet & J. Racker,
  "The importance of flavor in leptogenesis," JHEP **0601**, *164 (2006); [hep-ph/0601084].*

- The asymmetry generated in the decays of the heavier $N_{2,3}$ Majorana neutrinos can also give sizeable contributions to $Y_{\Delta B}$ (Dec. 2006).

  G.Engelhard, Y.Grossman, EN & Y.Nir,
  "The importance of N_2 leptogenesis," Phys. Rev. Lett. **99** *(2007) 081802.*

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$$m_\nu \sim \frac{\lambda^2 v^2}{M_N} \sim \left(\frac{\lambda}{10^{-6}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_N}\right) \sqrt{\Delta m^2_{atm}} \qquad \text{Impossible!}$$

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1. B violation: In the EW symmetric phase, **EW-Sphalerons** violate $B+L$ and convert part of any existing L-asymmetry into a B-asymmetry.

Experimentally: we can predict $-Y_{\Delta L} \sim \mathcal{O}(Y_{\Delta B})$. [More precisely: $Y_{\Delta\nu} \sim -3Y_{\Delta B}$]
(However, since $L_\nu \leftrightarrow \nu$-helicity, at $T_\nu \sim 10^{-4}$ eV $\Delta\nu$ has already "evaporated")

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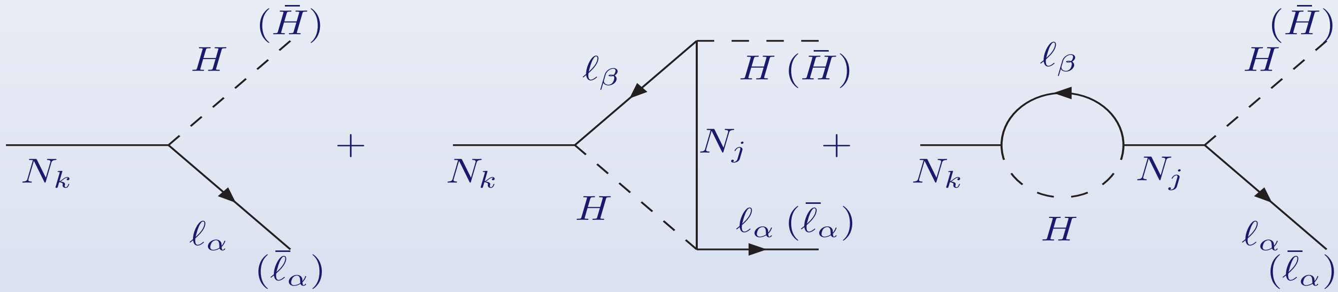
L violation: Is provided by the Majorana nature of the N's: $\ell_\alpha\phi \leftrightarrow N \leftrightarrow \bar\ell_\beta\bar\phi$

(Important: generically, the rates for violation of individual L_α differ)

Experimentally: we hope to see $0\nu2\beta$ decays (But only if IH or if ν's are quasi degenerate)

2. <u>C & CP violation:</u> From interference between tree and 1-loop amplitudes, due to complex Yukawa couplings $(\lambda^*_{\alpha k}\bar{\ell}_\alpha H^* N_k)$.

The CP-asymmetry between $\Gamma_\alpha \equiv \Gamma(N \to \ell_\alpha H)$ and $\bar{\Gamma}_\alpha \equiv \Gamma(N \to \bar{\ell}_\alpha \bar{H})$ decays



$$\text{Necessary condition}: \ \epsilon_\alpha = \frac{\Gamma_\alpha - \bar{\Gamma}_\alpha}{\Gamma_N} \neq 0 \qquad \left(\text{but } \epsilon \equiv \sum_\alpha \epsilon_\alpha \neq 0 \quad \text{is not necessary}\right)$$

Experimentally, we hope to see $\cancel{CP}_L$ (e.g. with ν SuperBeams – Dirac phase only).

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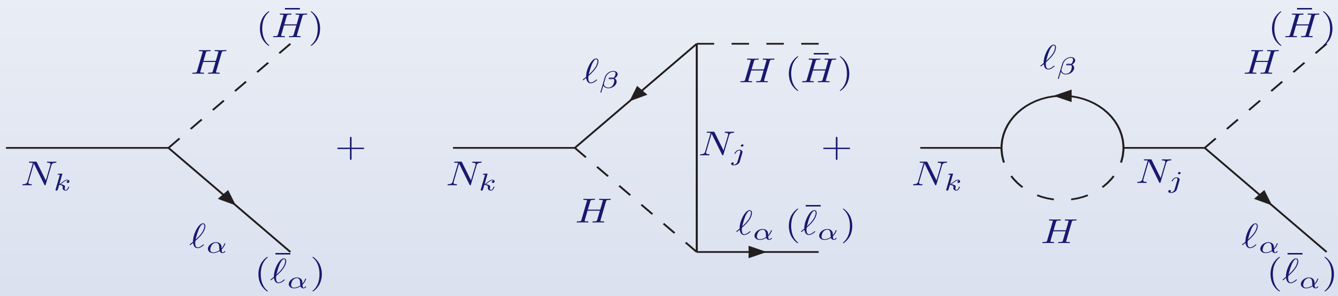

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3. Out of equilibrium dynamics: Is provided by the Universe expansion rate H.

$$\Big[\Gamma_{N_1} \sim H\Big]_{T=M_{N_1}} \times \frac{8\pi v^2}{M^2_{N_1}} \quad \Rightarrow \quad \frac{(\lambda^\dagger\lambda)_{11}}{M_{N_1}} v^2 \equiv \ \tilde{m}_1 \sim m_* \ \simeq 10^{-3}\,\text{eV}$$

Condition 3. is (optimally) satisfied for $\tilde{m}_1 \sim \sqrt{\Delta m^2_\odot} - \sqrt{\Delta m^2_{atm}}$ ($\tilde{m}_1 > m_{\nu_1}$ always)

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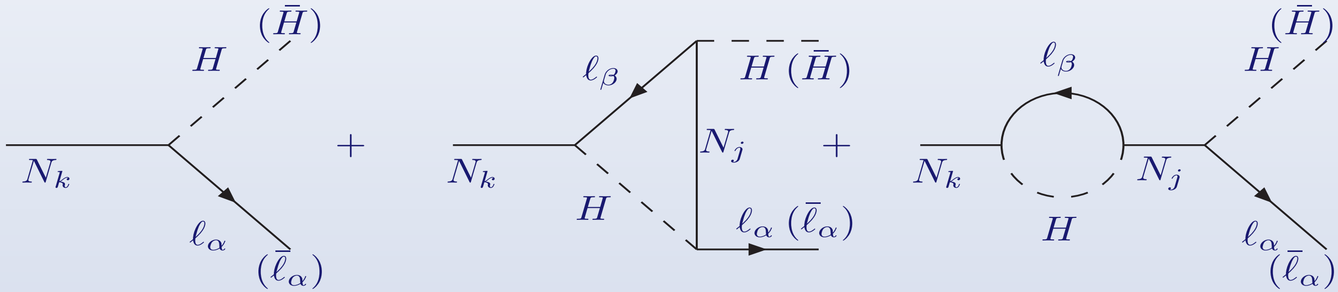

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Other considerations (sufficient amount of CPV, perturbativity of λ couplings) suggest a mass scale $M_{N_1} \sim 10^{11\pm 2}\,\text{GeV}$ – the seesaw scale.

Flavor: the lepton basis issue

To simplify: neglect $N_{2,3}$ except for their effects in the loops (CP asymmetry)

$$\boxed{-\mathcal{L}_{\rm Yukawa} = \lambda^*_{\alpha 1}\bar{\ell}_\alpha\, N_1\, H_u \;+\; h_{\alpha\beta}\,\bar{\ell}_\alpha\, e_\beta\, H_d \;+\; h.c.}$$

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Different bases give different results. The approx. solution of the BE for LG:

$$\boxed{Y_{\Delta B} \approx 10^{-3} \;\times\; \eta_\ell \,\cdot\, \epsilon_\ell \qquad \eta_\ell \sim \frac{m_*}{\tilde{m}_\ell}\ \text{(strong washout);} \qquad \tilde{m}_\ell \propto \lambda^*_{\ell 1}\lambda_{\ell 1}}$$

$$Y_{\Delta B} \approx 10^{-3} \times \begin{cases} \sum \eta_\alpha \cdot \epsilon_\alpha & \textit{flavor regime} \\ \sum \eta_\alpha \;\cdot\; \sum \epsilon_\alpha \;\equiv\; \eta \cdot \epsilon & \textit{one flavor approximation} \end{cases}$$

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The physical basis is determined dynamically at each T by the h-reaction rates.

More in detail: Lepton Flavor Effects

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$T \gg 10^{12}$ GeV, no charged lepton Yukawa scattering has occurred yet $(n_f = 1)$

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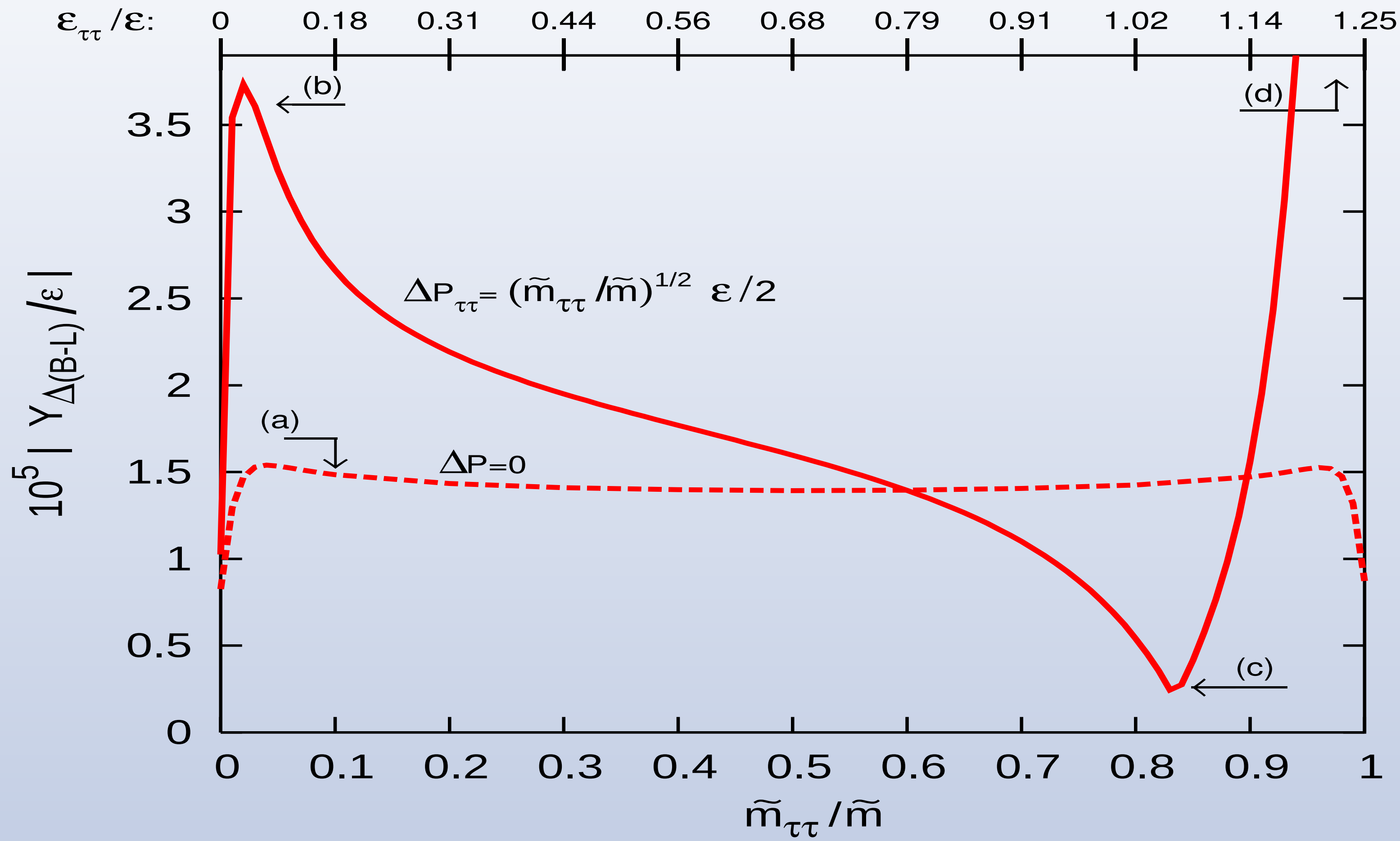
The most interesting effects are due to the different flavor composition of ℓ_1, $\bar{\ell}'_1$:

$$CP(\bar{\ell}'_1) \neq \ell_1 \quad \Rightarrow \quad \Delta P_\alpha \equiv P_\alpha - \bar{P}_\alpha \neq 0$$

Two-flavor case: ℓ_τ, $\ell_{\perp_\tau}$ ($10^9\,\mathrm{GeV} < T < 10^{12}\,\mathrm{GeV}$): $|Y_{\Delta(B-L)}|$ versus P^0_τ



$|Y_{\Delta(B-L)}|$ (units of $10^{-5}|\epsilon|$) as a function of $P^0_\tau \equiv |\langle \ell_\tau | \ell_1 \rangle|^2$ in the 2-flavor regime. Dashed: special case in which $P_\tau = \bar{P}_\tau$. Solid: typical behavior when $P_\tau \neq \bar{P}_\tau$. The value of $\epsilon^\tau_1/\epsilon_1$ (that can be > 1) is marked on the upper x-axis.

Purely Flavored Leptogenesis ($\epsilon = 0$): SM+seesaw

Casas-Ibarra parameterization for the N Yukawa couplings **[NPB618 (2001)]**

$$\lambda_{\alpha K} = \frac{1}{v}\left[U^{\dagger}\sqrt{m_\nu}\,\cdot\, R\sqrt{M_N}\right]_{\alpha K}; \qquad R = \frac{v}{\sqrt{m_\nu}}\cdot U^T\cdot\lambda\cdot\frac{1}{\sqrt{M_N}}$$

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The flavor asymmetry ϵ_α (leading term) $\propto$ the imaginary part of:

$$\lambda^*_{\alpha 1}\lambda_{\alpha K}\left(\lambda^\dagger\lambda\right)_{1K} = \frac{M_1 M_K}{v^4}\left(\sum_i m_{\nu_i} R^*_{i1} R_{iK}\right)\left(\sum_{i,j}\sqrt{m_{\nu_j} m_{\nu_i}}\, R^*_{j1} R_{iK}\, U_{j\alpha} U^*_{i\alpha}\right)$$

The total asymmetry $\epsilon \propto \mathrm{Im}$: $(\lambda^\dagger\lambda)^2_{1K} = \dfrac{M_1 M_K}{v^4}\left(\sum_i m_{\nu_i} R^*_{i1} R_{iK}\right)^2$

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Assuming that R is real implies surprising results:

1: $\epsilon = 0$, but $\epsilon_\alpha \neq 0$, and thus $Y_{\Delta B} \neq 0$

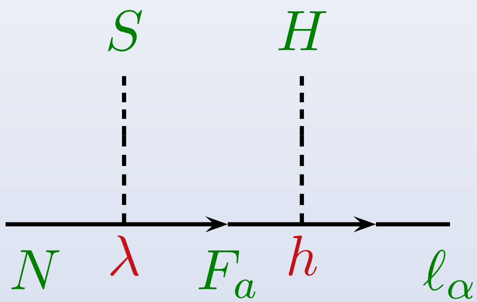
2: ϵ_α depends only on the ν-mix-matrix U !

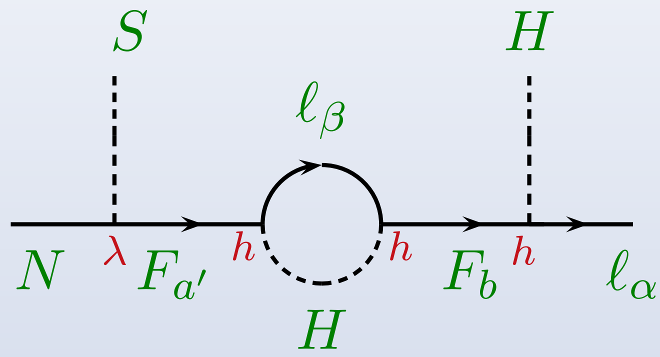
Recent studies of this scenario: Pastore *et al.*; Branco *et al.*;

Purely Flavored Leptogenesis: Beyond the SM+seesaw

[**D. Aristizabal, M. Losada, EN, PLB659 (2008)**]

Assume a $U(1)_F$ (flavor) symmetry that forbids a direct $\bar{\ell}NH$ coupling,
and that the flavor symmetry is still unbroken during LG: $\langle S\rangle = 0$.





$$\tilde{\lambda}_{\alpha K} = \left(h \frac{\langle S\rangle}{M_F} \lambda^\dagger\right)_{\alpha K};$$

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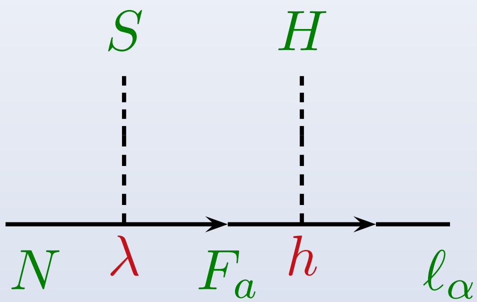
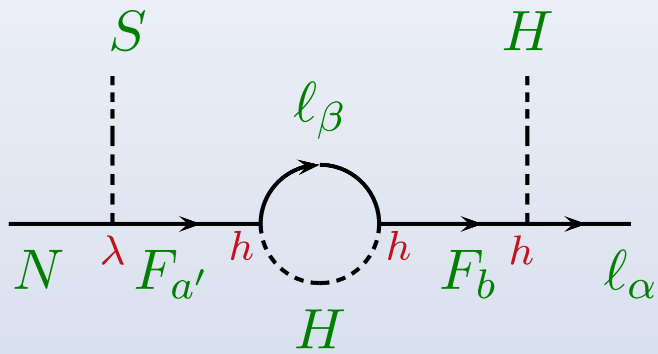
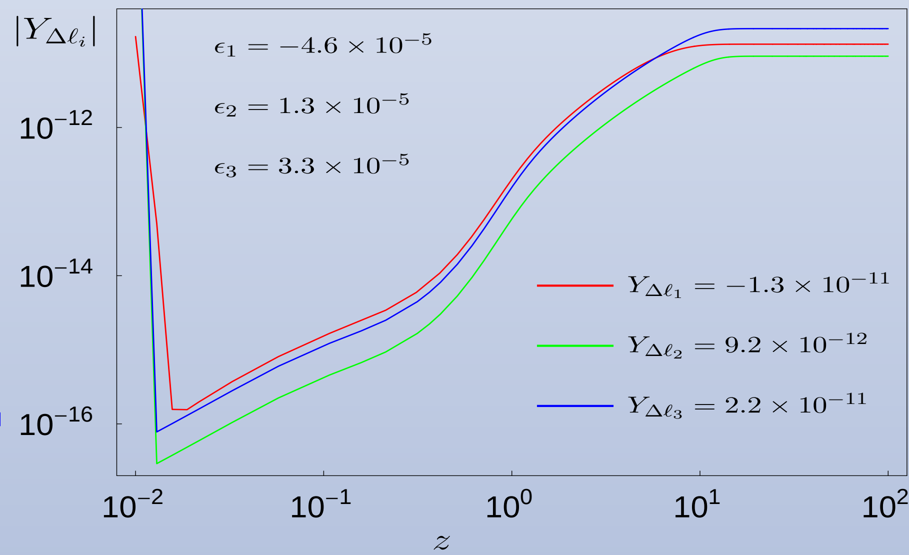




$$\tilde{\lambda}_{\alpha K} = \left(h\frac{\langle S\rangle}{M_F}\lambda^\dagger\right)_{\alpha K}; \qquad \epsilon = \sum_\alpha \epsilon_\alpha = 0$$

$$\epsilon_\alpha = \frac{3}{128\pi}\frac{\mathbb{I}m\sum_\beta\left[\left(hr^2h^\dagger\right)_{\beta\alpha}\tilde{\lambda}_{1\beta}\tilde{\lambda}^*_{1\alpha}\right]}{\left(\tilde{\lambda}\tilde{\lambda}^\dagger\right)_{11}} \sim \mathcal{O}(h^2);$$

$$\tilde{m}_\alpha \sim \mathcal{O}(\tilde{\lambda}^2); \qquad m_\nu \sim \frac{\tilde{\lambda}^2 v^2}{M_N} \sim \mathcal{O}(\tilde{\lambda}^2)$$



By decoupling ϵ_α from $\tilde{m}_\alpha, m_\nu$ the LG scale can be lowered: $M_N \sim$ few TeV.

Including the effects of the Heavier Neutrino $N_{2,3}$

$$-\mathcal{L}_{\rm Yukawa} = \lambda_{\alpha 1}\overline{N_1}\,\ell_\alpha\,H_u\, + h^*_\alpha\,\overline{e}_\alpha\,\ell_\alpha\,H_d + \text{h.c.}$$

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- $\tilde{m}_1 \sim m_*$: 'moderate' washouts, $Y_{\Delta \ell_2}$ in part survives. It contributes to $Y_{\Delta B}$.

- $\tilde{m}_1 \gg m_*$: 'very strong' washout regime, $Y_{\Delta \ell_2}$ in part survives, and it can be the main responsible for $Y_{\Delta B}$ (contrary to common belief).

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◇ If the following conditions are realized, LG occurs mainly through N_2 effects:

$1)\ \eta_2 \cdot \epsilon_2 \neq 0;$ $\qquad 2)\ \tilde{m}_1 \gg m_*;$ $\qquad 3)\ M_2/M_1 \gg 1.$

⋆ Since $\ell_0 \perp \ell_1$, the component of the asymmetry $Y_{\Delta\ell_2}$ along the ℓ_0 direction: $Y_{\Delta\ell_0} = |\langle \ell_0 | \ell_2 \rangle|^2\, Y_{\Delta\ell_2}$ is protected from N_1 washouts and survives.

Conclusions and Outlook

- Leptogenesis is a very attractive scenario to explain $Y_{\Delta B}$.

  Recent developments showed that *quantitative* and *qualitative* estimates of $Y_{\Delta B}$ have to take into account the detailed flavor structure of the seesaw parameters.

- Implications for the low energy neutrino parameters established in the one-flavor approximation, (e.g. $m_\nu \lesssim 0.15$ eV) do not hold in general (or hold only under much more restrictive assumptions).

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  (However, if a sizeable $\theta_{13} \neq 0$ is established, it would disfavor it.)

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- Finally, LHC + EDM experiments will be able to establish or falsify EWB. This will indirectly determine the relevance of future LG studies.