# *NuFlavour Workshop*

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# Discussion: Leptogenesis

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# Baryogenesis: how to explain a single experimental number

$$\eta \equiv \frac{n_B - \bar{n}_B}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10},$$

$$Y_{\Delta B} \equiv \frac{n_B - \bar{n}_B}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

[WMAP 5yrs, BAO, SN-IA]

$$\begin{aligned} 4.7 \times 10^{-10} \leq & \quad \eta & \leq 6.5 \times 10^{-10}, \\ 0.017 \times \leq & \quad \Omega_B h^2 & \leq 0.024 \end{aligned}$$

[BBN: Light Elements Aboundances]

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For testability, one clearly needs general particle physics models that can be related also to other observables.

Leptogenesis: is a class of scenarios where the Universe baryon asymmetry $(Y_{\Delta B})$ is produced from a lepton asymmetry $(Y_{\Delta L})$ generated in the decays of the heavy singlet *seesaw* Majorana neutrinos.

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[G.C.Branco& al. NPB617,(2001); S.Davidson, J.Garayoa, F.Palorini, N.Rius PRL99,2007; JHEP0809,2008.]

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$\boxed{\text{The flavor asymmetry } \epsilon_\alpha \text{ is prop. to the imaginary part of:}}$

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

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

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Assuming that $R$ is real

EN,Nir,Roulet,Racker,JHEP0601,2006

$2$: $\epsilon_\alpha$ depends only on the $\nu$-mix-matrix $U$ !

$2$: [$\epsilon = 0$, but $\epsilon_\alpha \neq 0$, and thus $Y_{\Delta B} \neq 0$]

Dedicated studies within this scenario: Branco *et al.*; Pastore *et al.*;

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Prove vs. Disprove vs. Circumstantial evidences for LG

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## Prove vs. Disprove vs. Circumstantial evidences for LG

Direct test of LG: Produce $N$'s and measure the $CP$ asymmetry in their decays

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

The best we can hope for are *Circumstantial Evidences for LG*, by proving that (some of) the Sakharov necessary conditions are (likely to be) satisfied.

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1. $B$ violation: At $T \gtrsim \Lambda_{EW}$ **EW-Sphalerons** violate $B+L$ and connect the $B$-asymmetry and the $L$-asymmetry: $Y_{\Delta L} \sim -2 \times Y_{\Delta B}$

Does this mean that we have (at least in principle) one additional LG observable ?

At $T \gg 1\,\mathrm{GeV}$: Baryogenesis: $\Delta B \Rightarrow \Delta L$, then one expects $\Delta L_e = \Delta L_\mu = \Delta L_\tau$
If $\Delta L_e \neq \Delta L_\mu \neq \Delta L_\tau$, then necessarily $\Delta L \Rightarrow \Delta B$ i.e. Leptogenesis.

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However, today $T_\nu \sim 10^{-4}\,\mathrm{eV} < \Delta m^2_{atm,sol}$ and thus $\Delta L_{\nu_{2,3}}$ have already "evaporated".

2. $L$ 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 $L_\alpha$ differ)

Experimentally: we hope to see $0\nu 2\beta$ decays (But only if IH or if $\nu$'s are quasi degenerate)

If $m_\nu$ is measured say $\sim 0.1\,\mathrm{eV}$ (e.g. from Cosmology) and $0\nu 2\beta$ is not seen ?

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

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

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

$\cancel{CP}_L$ is observed: Circumstantial evidence for LG (and by no means a final proof)

$\cancel{CP}_L$ is not observed: LG is not disproved: Small $\delta$ phase, small $\theta_{13}$, etc. . .

4. Out of equilibrium dynamics: Is provided by the Universe expansion $H$.

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

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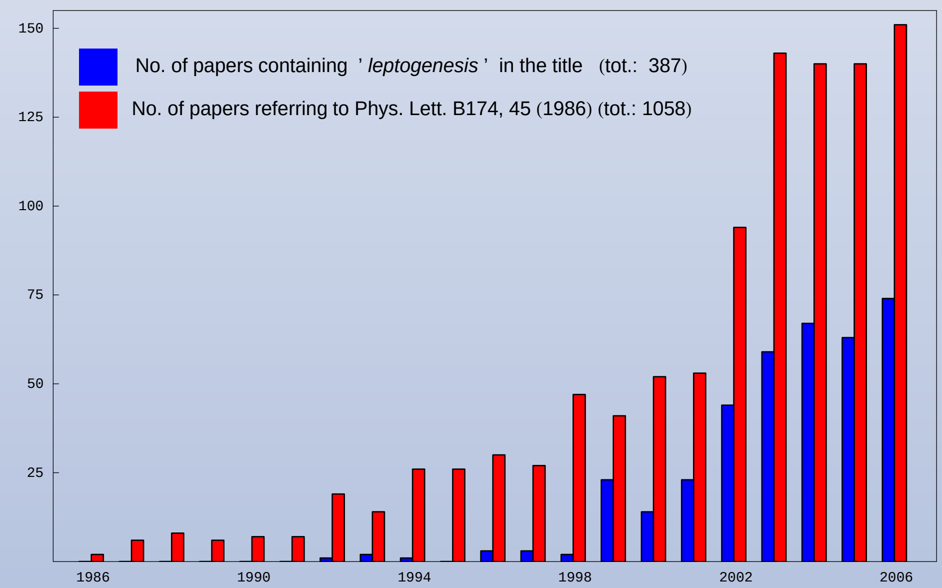


Experimental confirmation of $m_\nu \neq 0$ and in the correct mass range for LG: $\Longrightarrow$ burst of papers after Y2K.

# Summary: Proving, Disproving, Circumstantial Evidences

- Experimental detection of $0\nu 2\beta$ decays and/or $\not{CP}_L$ in the lepton sector will strengthen the case for leptogenesis – but will not prove it.

- If a quasi degenerate or IH $\nu$-spectrum is established, failure of revealing $0\nu 2\beta$-decays will strongly disfavor LG. (In the DH case no $0\nu 2\beta$ signal is expected.)

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  (However, if a sizeable $\theta_{13} \neq 0$ is established, this would pose some questions. . . .)

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  (but will certainly strengthen the case for LG).

# Summary: Proving, Disproving, Circumstantial Evidences

- Experimental detection of $0\nu2\beta$ decays and/or $\not{CP}_L$ in the lepton sector will strengthen the case for leptogenesis – but will not prove it.
- If a quasi degenerate or IH $\nu$-spectrum is established, failure of revealing $0\nu2\beta$-decays will strongly disfavor LG. (In the DH case no $0\nu2\beta$ signal is expected.)
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- Observation of low energy $\not{CP}_L$ will not result in any quantitative direct connection with the LG CP asymmetries
  (but will certainly strengthen the case for LG).
- Finally, LHC + EDM experiments will be able to establish or falsify EWB. This will indirectly determine the relevance of future LG studies.

# Can one get additional informations in the context of LFV?

Can one get additional informations in the context of flavor symmetries?

- Neutrinos: The hierarchy is milder than for charged fermions
  (the spectrum could be quasi-degenerate)
- Two mixing angles are large and one maybe maximal.
- Are these hints for a non-Abelian flavor symmetry in the $\nu$ sector?

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Non-Abelian flavor symmetry

$$\Downarrow$$

Large reduction in the number of parameters (seesaw)

$$\Downarrow$$

New connections between LE observables and HE quantities

$$\Downarrow$$

The ‘leptogenesists’ dream: compute $Y_{\Delta B}$ from measurements of LE observables

[ E.E. Jenkins, A.V. Manohar PLB668:210-215,2008: $A4$ suggests $\epsilon \sim \mathcal{O}(\theta_{13}^2)$ ]

# 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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<u>Different bases give different results.</u> 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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- With flavor $CP$ asymmetries: $\epsilon_\alpha = \frac{\Gamma(N_1 \to \ell_\alpha H) - \bar{\Gamma}(N_1 \to \bar{\ell}_\alpha \bar{H})}{\Gamma_{N_1}} = P_\alpha \epsilon$
- and flavor dependent washouts: $\tilde{m}_\alpha \sim P_\alpha\,\tilde{m}_1$
- the asymmetry is enhanced: $Y_{\Delta L} \propto \sum \frac{m_*}{\tilde{m}_\alpha}\epsilon_\alpha \approx n_f \left(\frac{m_*}{\tilde{m}_1}\epsilon\right)$

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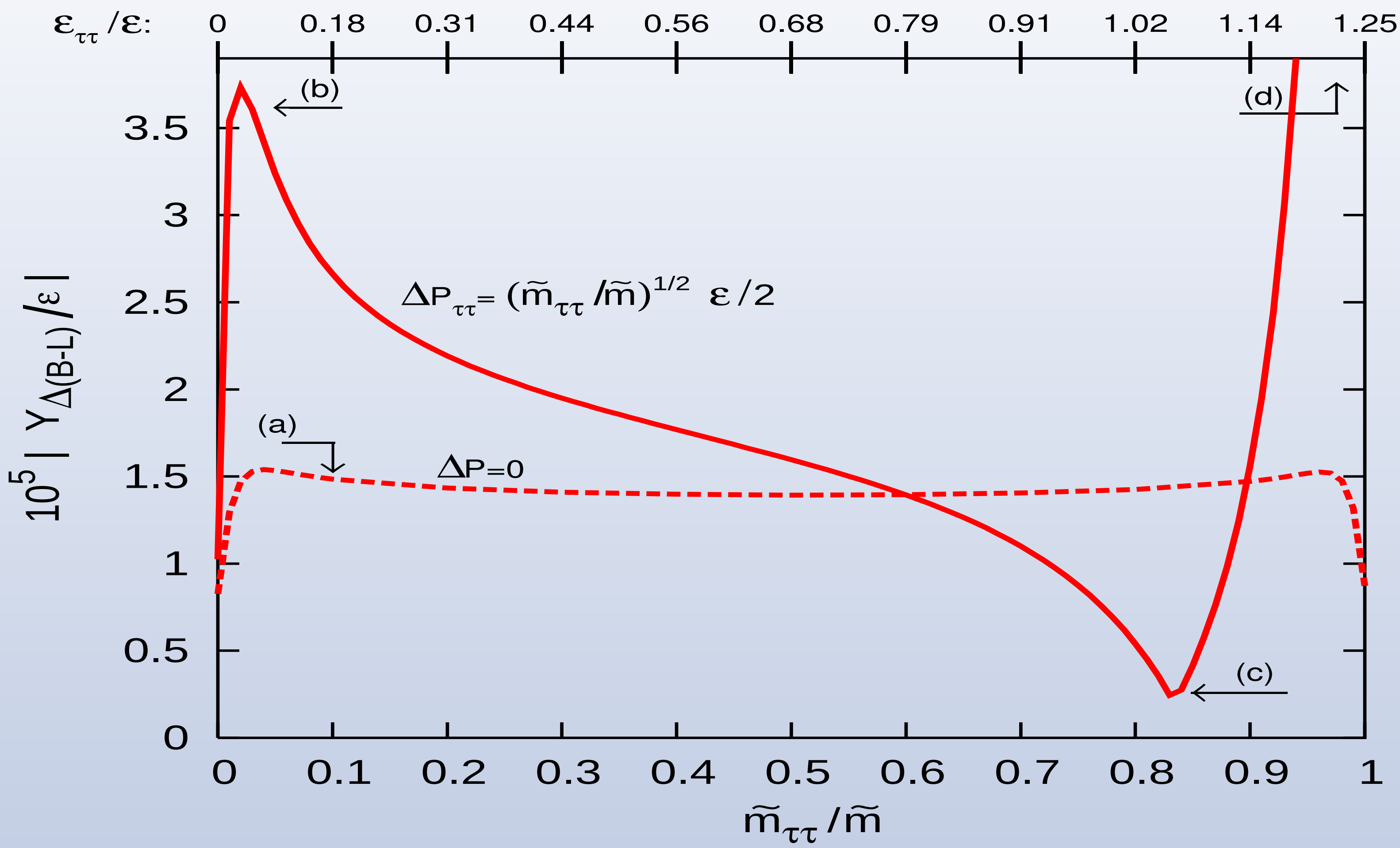
- and flavor dependent washouts: $\tilde{m}_\alpha \sim P_\alpha\, \tilde{m}_1$
- the asymmetry is enhanced: $Y_{\Delta L} \propto \sum \frac{m_*}{\tilde{m}_\alpha} \epsilon_\alpha \approx n_f \left(\frac{m_*}{\tilde{m}_1}\epsilon\right) + \frac{m_*}{\tilde{m}_1} \sum \frac{\Delta P_\alpha}{2 P_\alpha}$

The most interesting effects are due to the different flavor composition of $\ell_1$, $\bar{\ell}'_1$:

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

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




$|Y_{\Delta(B-L)}|$ (units of $10^{-5}|\epsilon|$) as a function of $P_\tau^0 \equiv |\langle \ell_\tau | \ell_1 \rangle|^2$ 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 $\epsilon_1^\tau/\epsilon_1$ (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)]**

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

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# 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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Assuming that $R$ is real implies surprising results:

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

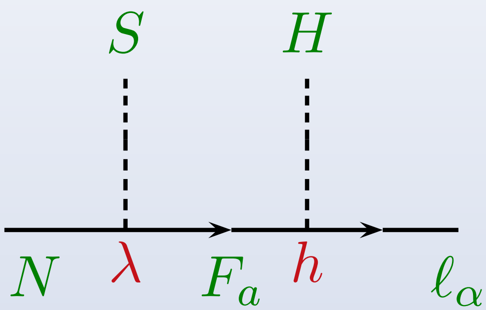
2: $\epsilon_\alpha$ depends only on the $\nu$-mix-matrix $U$ !

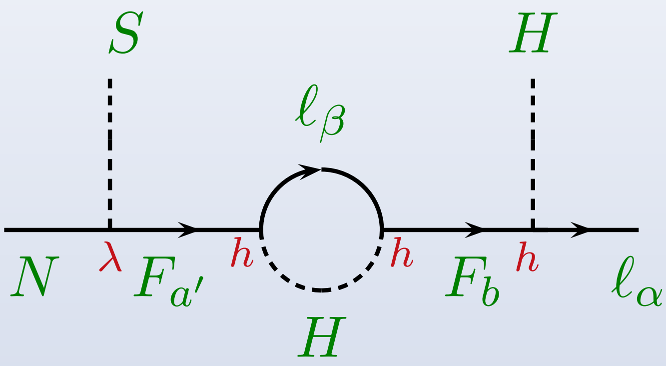
Recent studies of this scenario: Pastore *et al.*; Branco *et al.*;

# 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 $\bar{\ell} N H$ coupling,
and that the flavor symmetry is still unbroken during LG: $\langle S \rangle = 0$.




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

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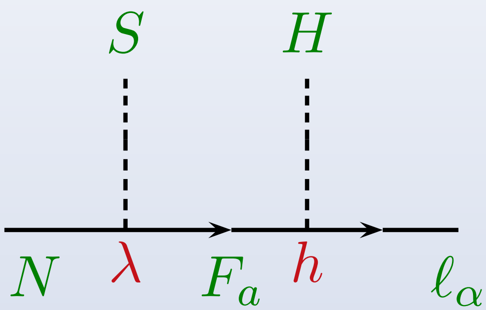
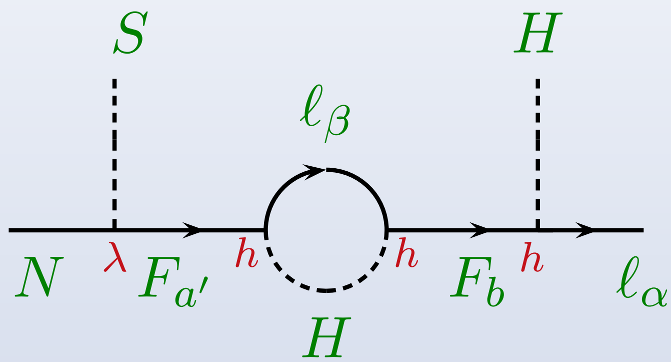
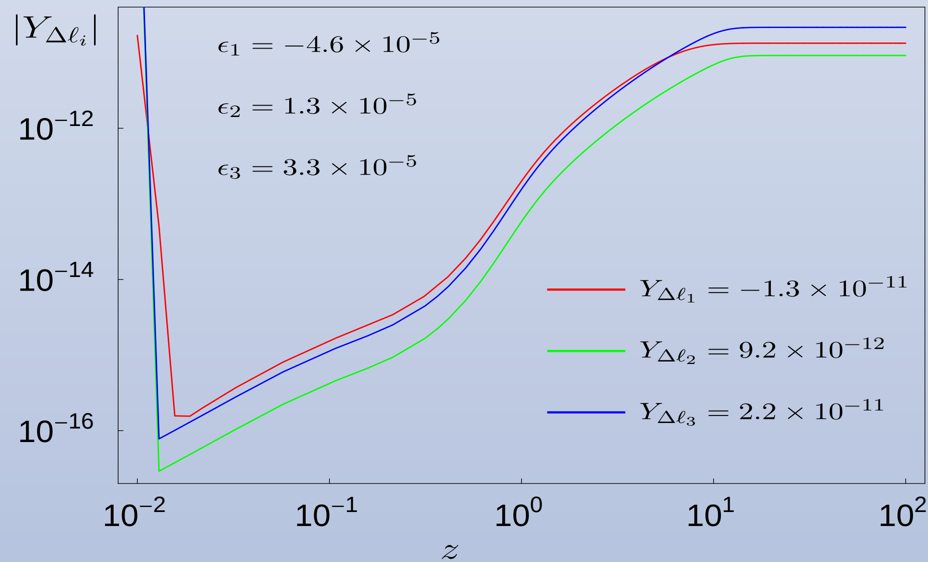



$$\tilde{\lambda}_{\alpha K} = \left( h \frac{\langle S \rangle}{M_F} \lambda^\dagger \right)_{\alpha K}; \qquad \epsilon = \sum_\alpha \epsilon_\alpha = 0$$

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

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




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

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

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

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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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$\diamond$ If the following conditions are realized, LG occurs mainly through $N_2$ effects:

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

$\star$ Since $\ell_0 \perp \ell_1$, the component of the asymmetry $Y_{\Delta\ell_2}$ along the $\ell_0$ 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

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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.