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Recent Developments in Leptogenesis

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Baryogenesis: explaining a single experimental number:

$$\eta \equiv \frac{n_B - \bar{n}_B}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}, \quad \left[Y_{\Delta B} = \eta \, \frac{n_\gamma}{s} = (8.75 \pm 0.23) \times 10^{-11} \right]$$

[WMAP 5yrs, BAO, SN-IA]

$$4.7 \times 10^{-10} \leq \eta \leq 6.5 \times 10^{-10}, \qquad \left[0.017 \times \leq \Omega_B h^2 \leq 0.024 \right]$$

[BBN: Light Elements Aboundances]

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For testability, one needs general particle physics models that can be related to other observables independent of η.

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 Majorana neutrinos of the *seesaw*.

Baryon Asymmetry $\Leftrightarrow$ Neutrino Physics

Topics

- First recall the effects of Lepton Flavors in Leptogenesis. Then, I will address more recent issues:
  - Purely Flavored Leptogenesis (PFL)
  - Lepton Flavor Equilibration (LFE)
  - Relevance of LFE in Soft Leptogenesis
- A few considerations on experimental verifications
- Flavor Symmetries and Leptogenesis

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:

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

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

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

More in detail: Lepton Flavor Effects

$$-\mathcal{L}_{\text{Yukawa}} = \lambda_1 \;\; \bar{N}_1 \, \ell_1 \;\, H_u + \text{h.c.}$$

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The ℓ_1 ($\bar{\ell}'_1$) flavor content becomes important: $P_\alpha = |\langle \ell_\alpha | \ell_1 \rangle|^2$ $\left(\bar{P}_\alpha = |\langle \bar{\ell}_\alpha | \bar{\ell}'_1 \rangle|^2\right)$

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- and flavor dependent washouts: $\tilde{m}_\alpha \sim P_\alpha\,\tilde{m}_1$
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The most interesting effects are due to the different flavor composition of ℓ_1, $\bar\ell'_1$:

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

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

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

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

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$$\epsilon_\alpha = \mathrm{Im}\left\{F\left[m_\nu, M, R\right]_{ji} \times U_{j\alpha}U^*_{i\alpha}\right\}$$

[Phases of U 'unrelated' to η_B - Davidson, Garayoa, Palorini, Rius PRL99,2007; JHEP0809,2008.]

The Total CP asymmetry:

$$\epsilon = \frac{M_1 M_K}{v^4}\mathrm{Im}\left\{\left(\sum_i m_{\nu_i} R^*_{i1} R_{iK}\right)^2\right\}$$

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Assuming that R is real

(No well justified way to enforce this!!)

EN,Nir,Roulet,Racker,JHEP0601,2006

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

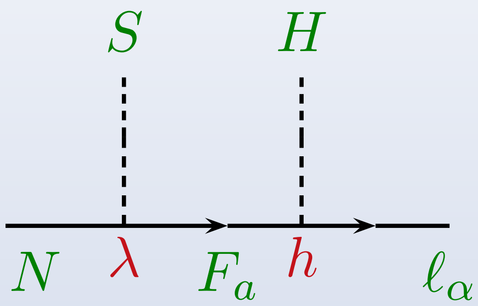
2: $Y_{\Delta B} \neq 0$ with $\epsilon = 0$, [provided $\epsilon_\alpha \neq 0$].

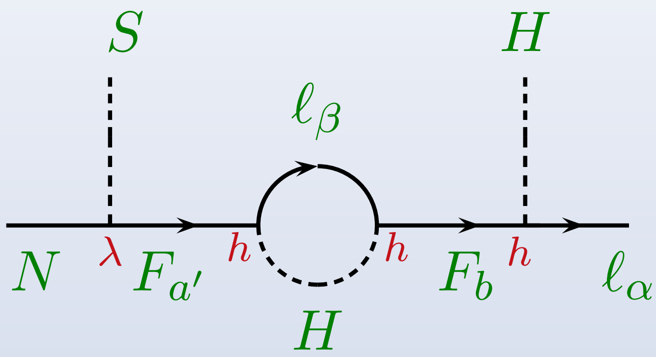
Dedicated studies within this scenario: Branco *et al.*; Petcov +Pascoli; Molinaro; Pastore; Riotto. . .

By studying L-number vs. Flavor Symmetry Breaking: $\Rightarrow$ PFL

[D. Aristizabal, M. Losada, EN, PLB659 (2008);D. Aristizabal Sierra, L.A. Munoz, EN PRD80 (2009)]

Assume a Flavor $U(1)_F$ symmetry (FN) forbidding direct $\bar{\ell}NH$ couplings,
and that the flavor symmetry is still unbroken during LG, when L number is violated.





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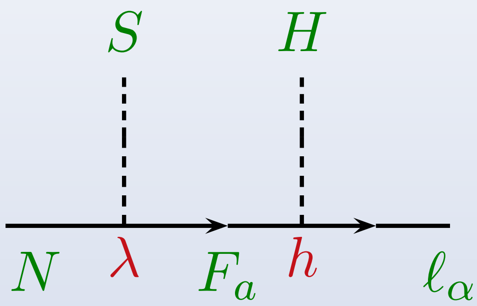

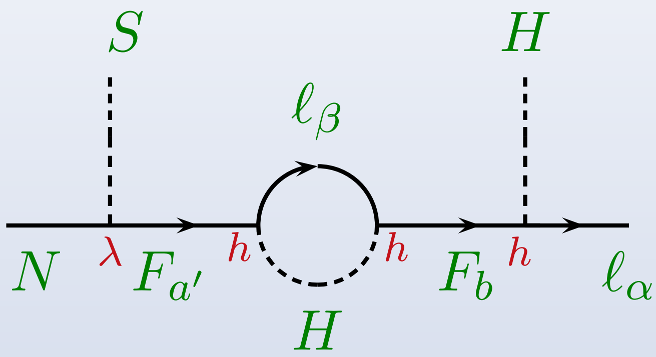

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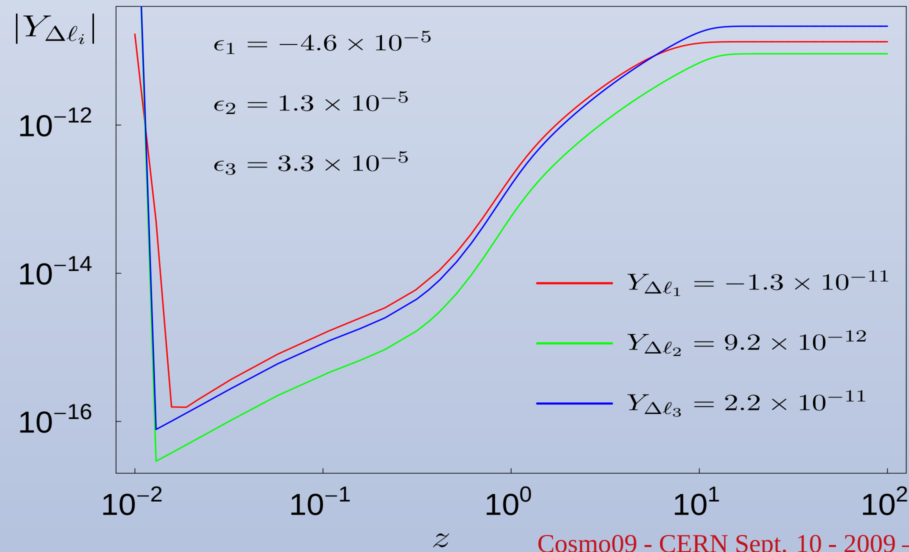
CP Asymmetries:

$$\boxed{\epsilon = \sum_\alpha \epsilon_\alpha = 0; \qquad \epsilon_\alpha \neq 0}$$

$\epsilon_\alpha \sim \mathcal{O}(h^2)$; $\qquad \tilde{m}_\alpha \sim \mathcal{O}(\tilde{\lambda}^2)$;

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



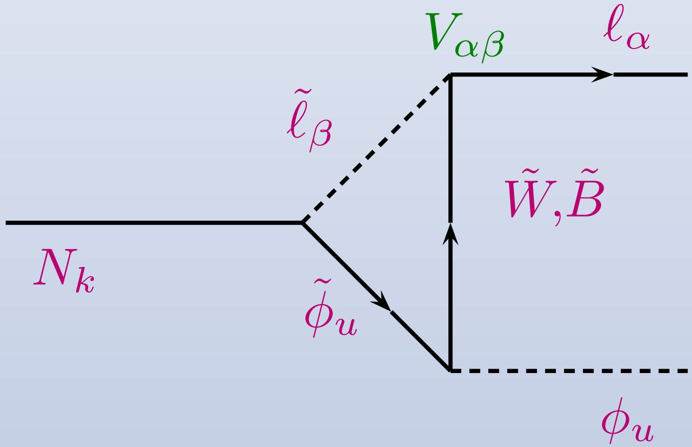
Lepton Flavor Equilibration

[D. Aristizabal, M. Losada, EN, arXiv:0905.0662 (2009)]

In the presence of LFV, (e.g. from SUSY soft $m^2_{\alpha\beta}$ terms), fast $\ell_\alpha \leftrightarrow \ell_\beta$ transitions 'kill' effectively all dynamical flavor effects.

Soft Leptogenesis: as long as $m^2_{\alpha\beta} > 1$ GeV and $M_N < 100$ TeV, a one flavor approximation with $\epsilon = \sum_\alpha \epsilon_\alpha$ describes correctly leptogenesis.

New soft LFV diagrams that could give rise to PFL:



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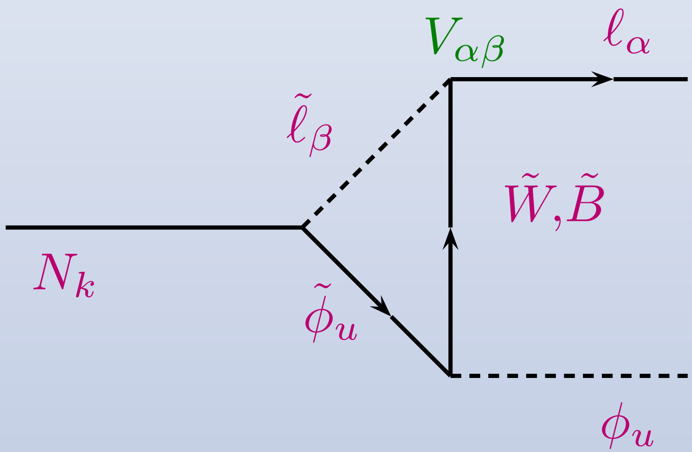

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In general, models of new physics have new sources of LFV. In studying leptogenesis it should be checked if flavor effects survive or not!

Proving vs. Disproving vs. Circumstantial Evidences for LG

Direct tests: Produce N's and measure the CP asymmetry in their decays

$$m_\nu \sim \frac{\lambda^2 v^2}{M_N} \sim \left(\frac{\lambda}{10^{-6}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_N}\right) \sqrt{\Delta m^2_{atm}} \qquad \text{Not possible!}$$

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

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

Condition 1. is (optimally) satisfied for $\widetilde{m}_1 \sim 10^{-3} \div 10^{-1}\,\mathrm{eV}$

$\widetilde{m}_1 \sim \sqrt{\Delta m^2_\odot}, \sqrt{\Delta m^2_{atm}}$ would ensure that the N's decay out-of-equilibrium.

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

NOTE: Baryogenesis: $\Delta B \Rightarrow \Delta L$, implies that $\Delta L_e = \Delta L_\mu = \Delta L_\tau$
If $\Delta L_e \neq \Delta L_\mu \neq \Delta L_\tau$, then necessarily $\Delta L \Rightarrow \Delta B$: that is *Leptogenesis.*

[However, today $T_\nu \ll \Delta m^2_{atm,sol}$ and for non-relativisitc ν's $\Delta L_{\nu_{2,3}}$ has "evaporated".]

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2b. $\underline{L}$ violation: Is provided by the Majorana nature of the N's: $\ell_\alpha \phi \leftrightarrow N \leftrightarrow \bar{\ell}_\beta \bar{\phi}$

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

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3. $\underline{C \text{ \& } CP \text{ violation:}}$

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

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

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

Any possible alternative strategy ? Maybe yes. . .

- The neutrino mass hierarchy is milder than for charged fermions
  (the spectrum could be quasi-degenerate)
- Two mixing angles are large and one maybe maximal.
- Is this the outcome of a non-Abelian flavor symmetry?

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An interesting example: [E.Bertuzzo, P.Di Bari, F.Feruglio, EN [arXiv:0908.0161]]

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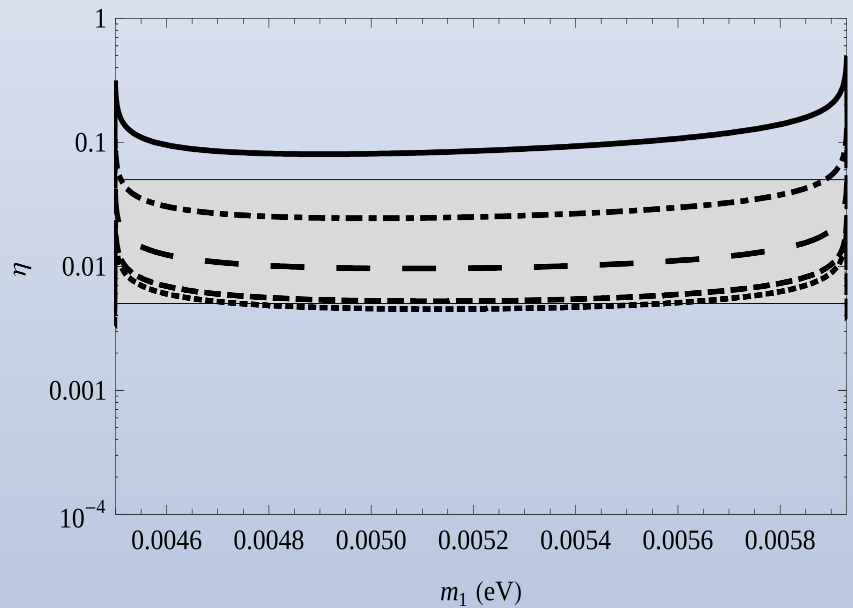
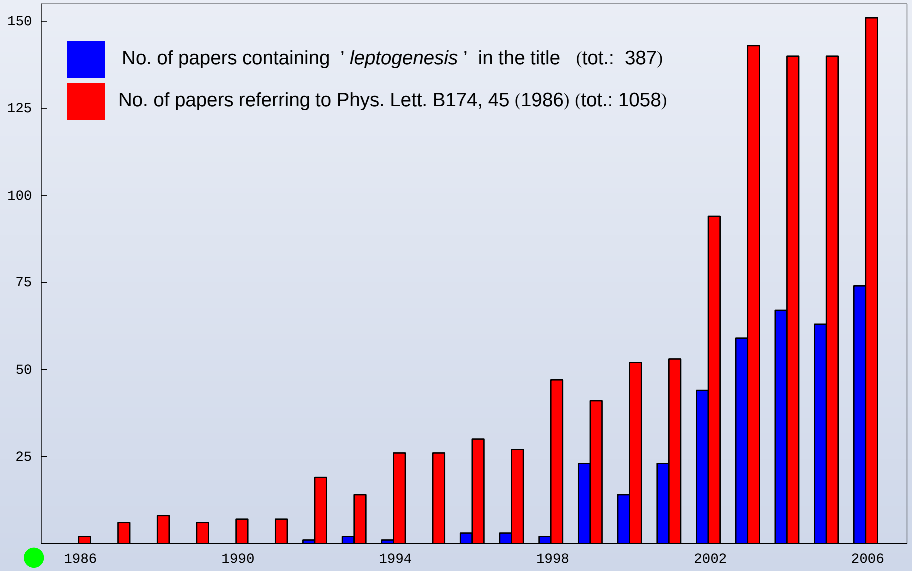
In the $A_4 \times Z_3$ model for TBM [Altarelli & Feruglio NPB720 (2005)], as long as the symmetry is unbroken: $\boxed{\epsilon = \epsilon_\alpha = \theta_{13} = \theta_{23} - \frac{\pi}{4} = 0}$ [Jenkins, Manohar PLB668, 2008]

We can estimate the amount of symmetry breaking required by leptogenesis ($\epsilon \neq 0$), and from this derive $\sin^2\theta_{13} \approx 0.005 \div 0.06$.



During Aug. 09 other similar studies appeared: Hagedorn, Molinaro, Petcov [arXiv:0908.0240]; D.Aristizabal Sierra et al., [arXiv:0908.0907]; Gonzalez Felipe & Serodio, [arXiv:0908.2947].

THANK YOU !



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 ν-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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- Failure of revealing $\not{CP}_L$ will not disprove LG.

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

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Summary: Proving, Disproving, Circumstantial Evidences

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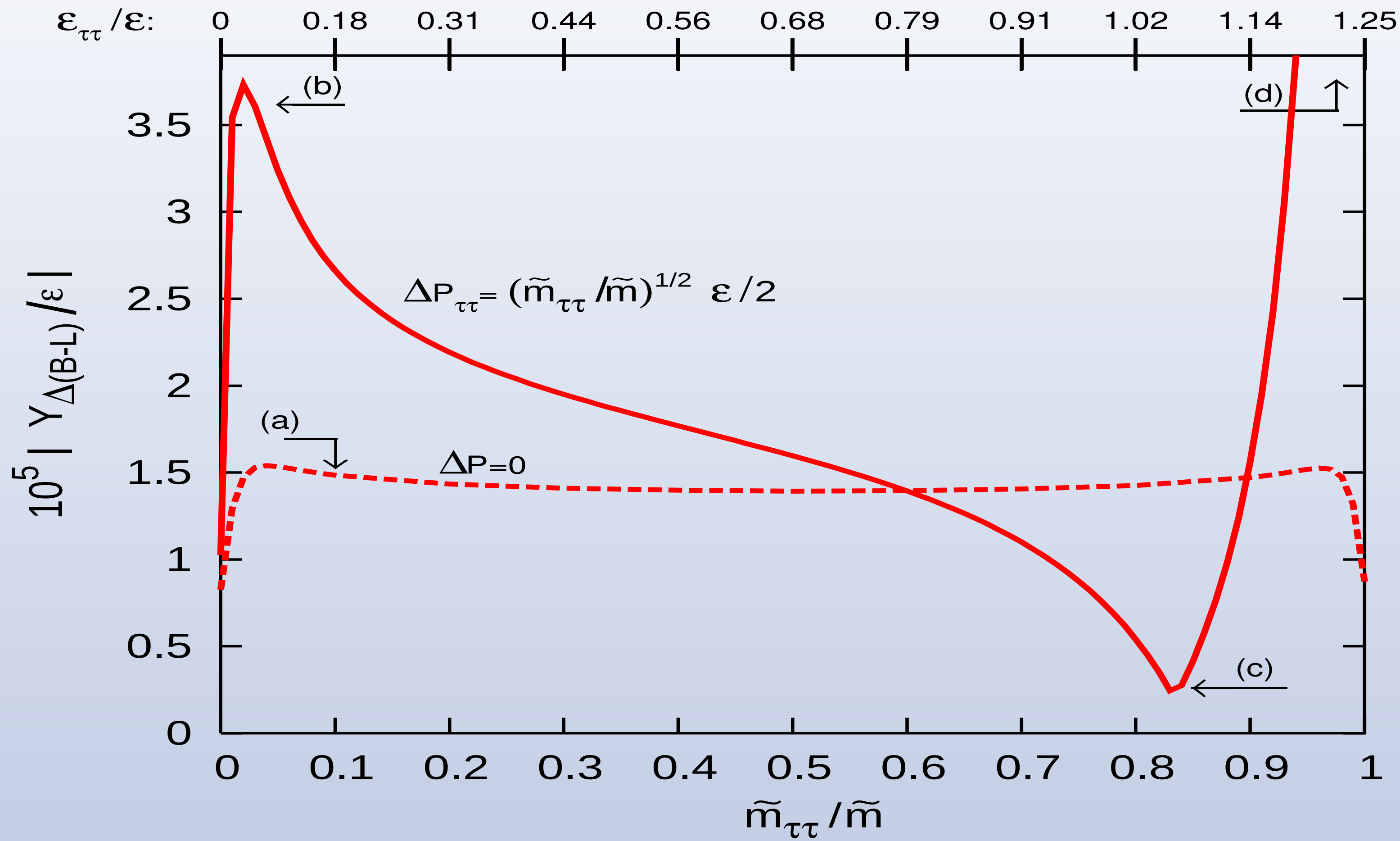
- Finally, LHC + EDM experiments will be able to establish or falsify EWB. This will indirectly determine the relevance of future LG studies.

Two-flavor case: $\ell_\tau, \ell_{\perp_\tau}$ ($10^9\,\mathrm{GeV} < T < 10^{12}\,\mathrm{GeV}$): $|Y_{\Delta(B-L)}|$ 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 $\epsilon_1^\tau/\epsilon_1$ (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)]**

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

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

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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.*;

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

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

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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.

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