INIFA 2010

INFN - Laboratori Nazionali di Frascati

Giugno 22-23, 2010

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]

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

[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

Recent Theoretical Advances

- They are often related with better understandings of the effects of Lepton Flavors in Leptogenesis.
  - Purely Flavored Leptogenesis (PFL) $\epsilon_{\not{CP}} = 0$
  - Flavor effects and Lepton Flavor Equilibration (LFE)
  - Relevance of Flavor effects in Soft Leptogenesis
  - Effects of anomalous symmetries present in SUSY (work in progress)
  - Soft leptogenesis via anomalous R-genesis (work in progress)
- A few considerations on experimental verifications
- Neutrino Flavor Symmetries and Leptogenesis

Flavor: the lepton basis issue

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

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

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This can be written in a more simple way by choosing a specific basis

$$-\mathcal{L}_{\rm Yukawa} = \lambda^*_1 \quad \bar{\ell}_1 \, N_1 \, H_u + \; h_{i\alpha} \, \bar{\ell}_i \, e_\alpha \, H_d \qquad (i{=}1, \perp_1, \perp_2)$$

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

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

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

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$$-\mathcal{L}_{\rm Yukawa} = \lambda^*_1 \quad \bar{\ell}_1 \, N_1 \, H_u \qquad \text{when } T \gtrsim 10^{12}\ \text{GeV}$$

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

More in detail: Lepton Flavor Effects

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

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

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$T < 10^{12}$ GeV, τ-Yukawa scatterings in equilibrium; Basis: $(\ell_\tau, \ell_{\perp_\tau})$ $\quad (n_f = 2)$

$T < 10^{9}$ GeV, μ-Yukawa in equilibrium; Basis: $(\ell_\tau, \ell_\mu, \ell_e = \ell_{\perp_{\tau\mu}})$ $\quad (n_f = 3)$

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

- With flavor CP asymmetries: $\epsilon_\alpha = \frac{\Gamma(N_1 \to \ell_\alpha H) - \bar{\Gamma}(N_1 \to \bar{\ell}_\alpha \bar{H})}{\Gamma_{N_1}} = P_\alpha \epsilon + \frac{\Delta P_\alpha}{2}$
- 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 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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The Flavor CP asymmetries:

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

[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 !

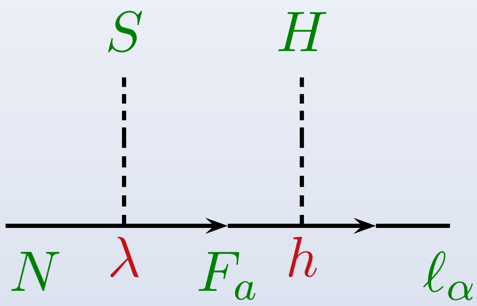
2: $Y_{\Delta B} \neq 0$ with $\epsilon = 0$, [provided $\epsilon_\alpha \neq 0$].

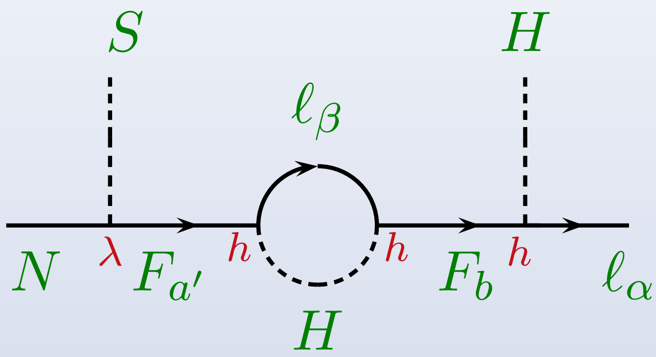
Dedicated studies within this scenario: Branco *et al.*; Petcov +Pascoli; Molinaro; Pastore; Riotto. . .

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 $\bar{\ell} N H$ couplings, and that the flavor symmetry is still unbroken during LG, when L number is violated.





For $M_F \gg M_N$: effective seesaw Yukawa couplings: $\tilde{\lambda}_{\alpha K} = \left(h \frac{\langle S \rangle}{M_F} \lambda^\dagger \right)_{\alpha K}$;

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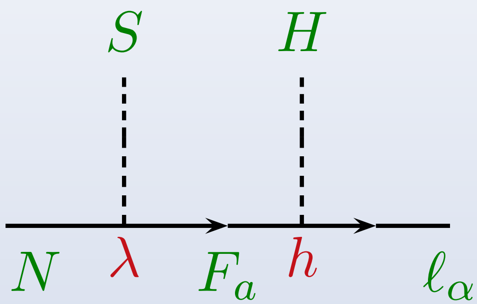

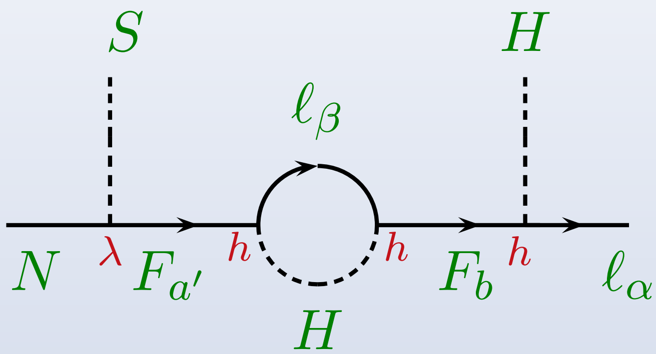

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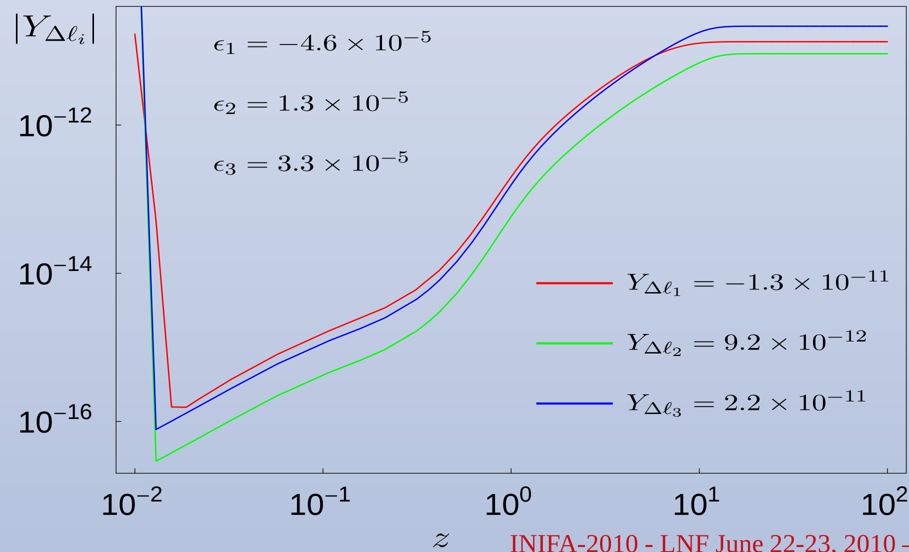
CP Asymmetries:

$$\epsilon = \sum_\alpha \epsilon_\alpha = 0; \qquad \epsilon_\alpha \neq 0$$

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

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



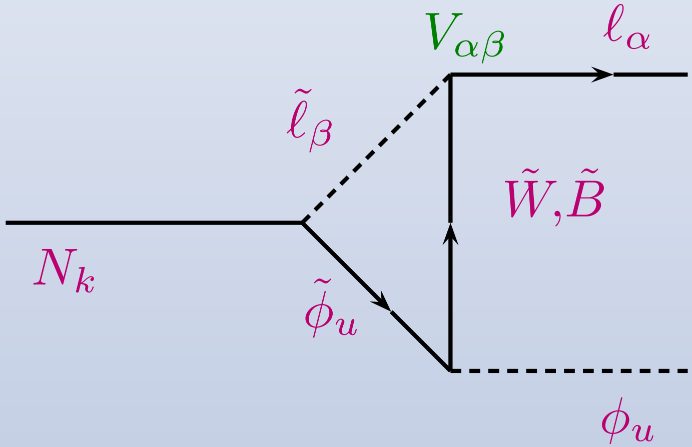
Flavor Effects and Lepton Flavor Equilibration

[D. Aristizabal, M. Losada, EN, JCAP 0912:015 (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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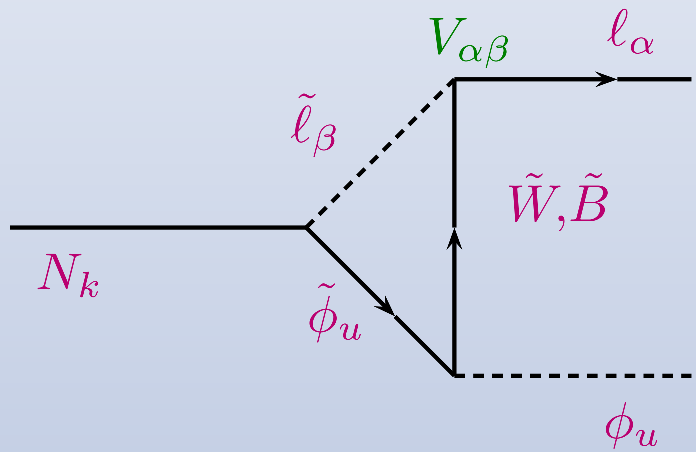

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In general, models of new physics have new sources of LFV. In studying leptogenesis it should be checked if flavor effects survive or not!

Higher Dimensional Contributions and Leptogenesis

[**S. Antusch, S. Blanchet, M. Blennow, E. Fernandez-Martinez, arXiv:0910.5957 JHEP 1001:017, (2010)**]

Computation of ϵ_α (vertex and *self-energy* contributions) yields $(x_j = M_j^2/M_1^2)$:

$$\epsilon_\alpha = \frac{-1}{8\pi(\lambda\lambda^\dagger)_{11}} \sum_{j\neq 1} \mathrm{Im}\left\{ \lambda_{j\alpha}\lambda^*_{1\alpha} \left[\underbrace{\frac{3}{2\sqrt{x_j}}(\lambda\lambda^\dagger)_{j1}}_{\not L:\ D_5=(\ell\phi)^2} + \underbrace{\frac{1}{x_j}(\lambda\lambda^\dagger)_{1j}}_{L:\ D_6=(\bar\ell\phi^*)\not\partial(\ell\phi)} \right] \right\}$$

$D_5 \Rightarrow$ light neutrinos (Majorana) masses; $D_6 \Rightarrow$ non unitarity in lepton mixing.

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$D_5 \Rightarrow$ light neutrinos (Majorana) masses; $D_6 \Rightarrow$ non unitarity in lepton mixing.

- Impose a lepton number-like global $U(1)$ to suppress D_5 (but not D_6).
- this enforces PFL: $\epsilon_\alpha \neq 0$ with a strong suppression of $\sum \epsilon_\alpha \simeq 0$.
- Flavor asymmetries are independent of m_ν and can be large at low scales.

However, for moderate $N_{1,2,3}$ hierarchies (as is needed to keep D_6 sizeable), there is too much $N_{2,3}$-mediated lepton flavor violation $\left(\ell_\alpha\phi \longleftrightarrow \ell_\beta\phi\right)$.

Eventually, for $M_1 \lesssim 10^8$ GeV flavor equilibration effects suppress too much the final baryon asymmetry. **LFE enforces a lower limit on M_1.**

Enhanced flavor effects and LFE in soft-leptogenesis

[C.S. Fong, M.C. Gonzalez-Garcia, JHEP 0806:076; C.S. Fong, M.C. Gonzalez-Garcia, EN, J.Racker arXiv:1004.5125]

(Assuming no LFE) flavor effects combined with the temperature dependent CP asymmetries (characteristic of soft leptogenesis)

$$\epsilon = \epsilon_0 \cdot \Delta_{BF}(T); \qquad \Delta_{BF}(z) \sim \frac{2e^{z/2}(e^z - 2)}{e^{2z} - 3e^z + 4} \qquad (z{=}T/M):$$

can yield large enhancements of the efficiency, up to $\sim \mathcal{O}(100)$. (Also when $\Delta P = 0$).

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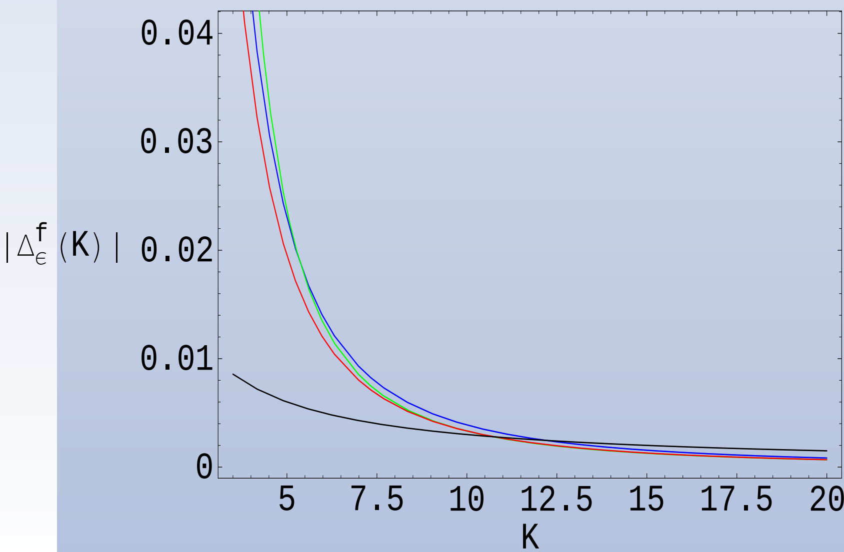
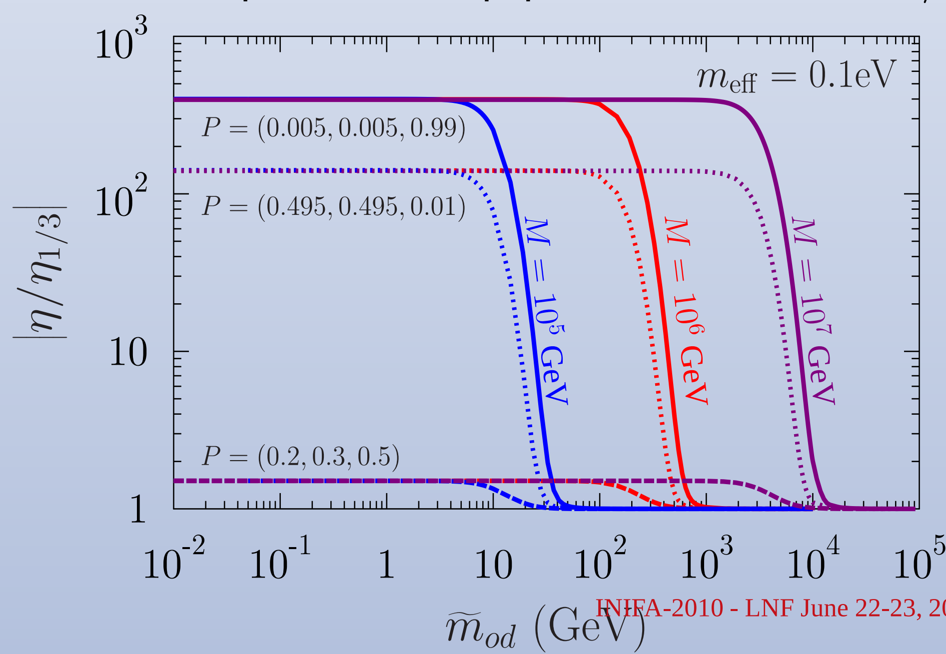
Soft-leptogenesis effective efficiency $\Delta^f_\epsilon(K)$ compared with the constant ϵ case yielding an efficiency $\eta \sim 1/K$



The dependence of the efficiency on the off-diagonal soft slpeton masses m_{od} (normalized to the lepton flavor equipartition case $P_\alpha = 1/3$)



Proving vs. Disproving vs. Circumstantial Evidences for LG

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

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

Indirect tests: Reconstruct the complete seesaw model

$$18 \text{ parameters } \; vs. \; 3m_\nu + 3\theta_{ij} + \delta, \alpha_1, \alpha_2 = 9 \text{ observables} \qquad \underline{\text{Not possible!}}$$

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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 at some $T \gg m_\nu$: $\Delta L_e = \Delta L_\mu = \Delta L_\tau$

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. 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)

If m_ν 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:

Experimentally, we hope to see $\not{CP}_L$ (e.g. with ν SuperBeams – Dirac phase only).

If $\not{CP}_L$ is observed: Circumstantial evidence for LG (but by no means a final proof)

If $\not{CP}_L$ 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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Symmetries $\Rightarrow$ Large reduction in number of parameters !

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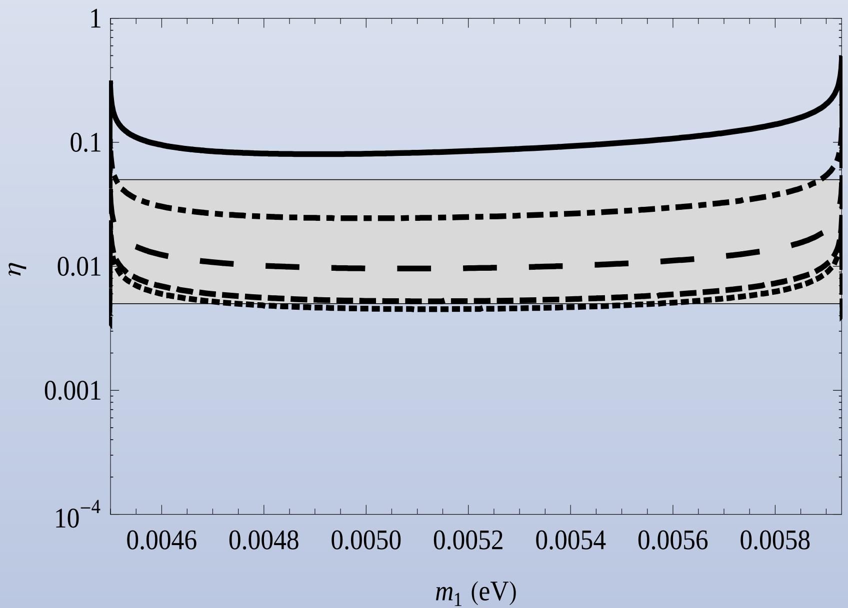
In the $A_4 \times Z_3$ model for TBM [Altarelli & Feruglio NPB720 (2005)], as long as the symmetry is unbroken: $\epsilon = \epsilon_\alpha = \theta_{13} = \theta_{23} - \frac{\pi}{4} = 0$ [Jenkins, Manohar PLB668, 2008]

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



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

THANK YOU !