Neutrino Oscillation Workshop

Conca Specchiulla (Otranto, Lecce, Italy)
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Leptogenesis and Neutrino Masses

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Baryogenesis: explaining one 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, BAO, SN-IA]

$$4.7 \times 10^{-10} \leq \quad \eta \quad \leq 6.5 \times 10^{-10},$$

$$0.017\times \leq \quad \Omega_B h^2 \quad \leq 0.024$$

[BBN: Light Elements Abundances]

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Particle physics models for baryogenesis relate $Y_{\Delta B}$ 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 $SU(2)$ singlet *seesaw* Majorana neutrinos.

Baryon Asymmetry $\Leftrightarrow$ Neutrino Physics

THE SM WITH THE SEESAW

Minimal extension of the SM: add $n = 3$ singlet neutrinos

$$-\mathcal{L} = \frac{1}{2} M_{N_i} \bar{N}_i^c N_i^c + \lambda_{i\alpha} \overline{N}_i \ell_\alpha \widetilde{H}^\dagger \; + \; h_\alpha \overline{e}_\alpha \ell_\alpha H^\dagger + \text{h.c.}$$

Basis: $M_N = \mathrm{diag}(M_1, M_2, M_3)$; diagonal charged lepton Yukawas h_α

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In terms of the diagonal light ν mass-matrix: $m_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$:

$$\lambda_{j\alpha} = \frac{1}{\langle H \rangle} \left[\sqrt{M_N} \cdot R \cdot \sqrt{m_\nu} \cdot U^\dagger \right]_{j\alpha}$$

(where $R^T R = 1$ and $UU^\dagger = 1$)

[Casas Ibarra **NPB618 (2001)**]

The seesaw model has 18 independent parameters (3 M_i plus 3 + 3 from complex angles in R; 3 m_{ν_i} plus 3 angles and 3 phases in U). 3+6 parameters can be measured (in principle) at low energy, 3+6 are confined to high energy.

The SM+seesaw satisfies all the Sakharov conditions ('67)

1. $\not{L}$: Majorana masses M_N imply lepton number violation ($\Delta L \neq 0$)
   $\not{B}$: EW-Sphalerons are SM processes that at $T \gg M_W$ violate $B + L$ (conserving $\Delta_\alpha = B/3 - L_\alpha$) and convert part of ΔL into ΔB.

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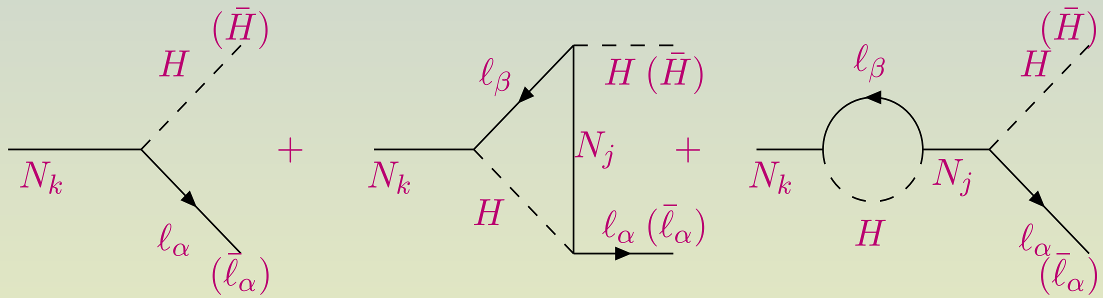

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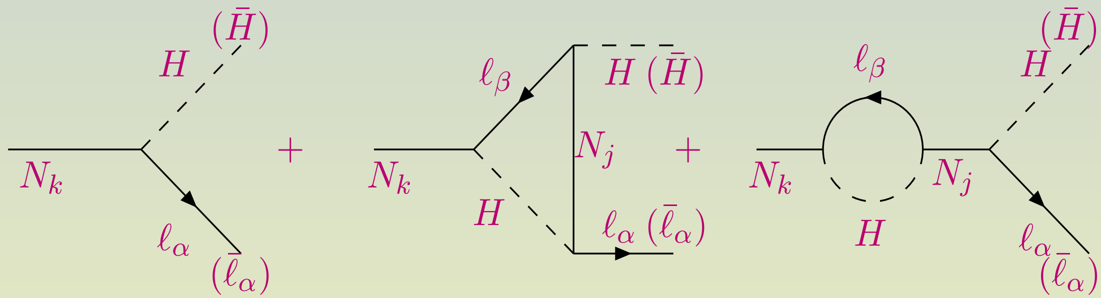

3. Deviations from thermal equilibrium: If $\tau_N \sim t_U(T \sim M_N)$ the N's decay out-of-equilibrium. And since $t_U \sim H^{-1}$ the condition is: $\Gamma_N \sim H\big|_{T\sim M_N}$.

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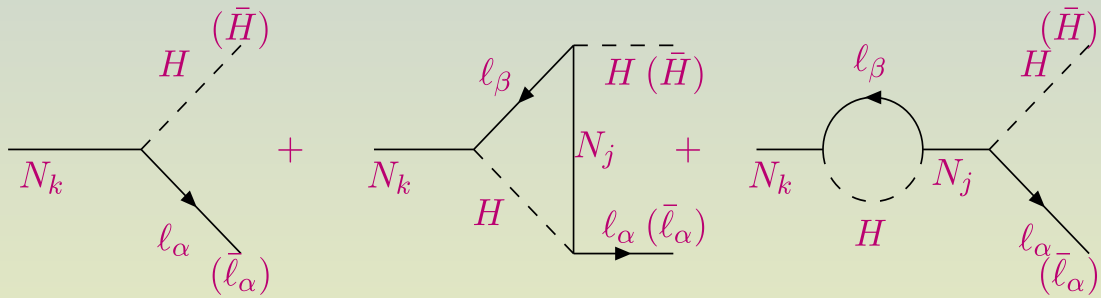

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Whether leptogenesis can explain the baryon asymmetry of the Universe, is basically a quantitative question.

No asymmetry can be generated in thermal equilibrium

[**S. Weinberg, PRL42 (1979), p.850 (2009)**]

Consider the one-family SM: $Q = \binom{u_L}{d_L},\ u,\ d,\ \ell = \binom{\nu_L}{e_L},\ e,\ H,\ N$

We can have 6 chemical potentials: $Q \equiv \mu_Q = \mu_{u_L} = \mu_{d_L};\ u \equiv \mu_{u_R};\ \ldots$
since for Majorana neutrinos the chempot vanishes: $M_N \neq 0 \Rightarrow \mu_N = 0$

Yukawa reactions can give 3 chemical equilibrium conditions:

$$\boxed{Q + H = u} \qquad \boxed{Q - H = d} \qquad \boxed{\ell - H = e}$$

Plus 1 from sphaleron chemical equilibrium (effective operator $\mathcal{O}_{EW} = QQQ\ell$)

$$(B+L)_{SU(2)} = 0 \qquad \Rightarrow \qquad \boxed{3Q + \ell = 0}$$

Plus 1 constraint from hypercharge conservation (global neutrality):

$$\mathcal{Y}_{\rm tot} = \sum_\phi \Delta n_\phi y_\phi = \text{const} \qquad \Rightarrow \qquad \boxed{\sum_f g_\phi \mu_\phi y_\phi = 0}$$

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Adding N Yukawa chemical equilibrium: $\ell + H = 0 \quad \Rightarrow \quad Q, u, d, \ell, e, H = 0\,!$

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Chemical equilibrium $\Leftrightarrow$ conservation law: $h_e \to 0 \quad \Leftrightarrow \quad \Delta n_e = 0$
$\Gamma_{sphal} \to 0 \quad \Leftrightarrow \quad \Delta B = 0$

At each temperature, one chempot (ℓ) is sufficient to describe the asymmetries.

Open parenthesis: Supersymmetric Leptogenesis

[C.S. Fong, M.C. Gonzalez-Garcia, EN, J. Racker, arXiv:1009.0003]

Leptogenesis can only proceed at temperatures $T \gg 10^8\,\mathrm{GeV}$ where:

$$\Gamma_{m_{\tilde{g}}} \sim m_{\tilde{g}}^2/T \ll H \quad \Rightarrow \quad m_{\tilde{g}} \to 0 \quad \Rightarrow \quad \tilde{g} \neq 0, \qquad U(1)_R$$

$$\Gamma_\mu \sim \mu^2/T \ll H \quad \Rightarrow \quad \mu_{H_u H_d} \to 0 \quad \Rightarrow \quad H_u + H_d \neq 0, \qquad U(1)_{PQ}$$

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Both these new symmetries have mixed $SU(2)$ and $SU(3)$ anomalies:

[Ibañez & Quevedo: PLB 283, 261 (1992)]

$$\mathcal{O}_{EW} \quad \Rightarrow \quad \widetilde{\mathcal{O}}_{EW} = \Pi_\alpha (QQQ\ell_\alpha)\ \tilde H_u \tilde H_d \tilde W^4 \qquad \mathcal{A}(R_3) = \mathcal{A}(R - 3PQ) = 0$$

$$\mathcal{O}_{QCD} \quad \Rightarrow \quad \widetilde{\mathcal{O}}_{QCD} = \Pi_i (QQu^c d^c)_i\ \tilde g^6 \qquad \mathcal{A}(R_2) = \mathcal{A}(R - 2PQ) = 0$$

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We end up with a leptogenesis picture quite different from the usual one:

- Particle sparticle non-superequilibration: $\mu_{\tilde\psi} = \mu_\psi \pm \tilde g$
- A new global charge neutrality condition $(\mathcal{R} = \frac{5}{3}B - L + R_2)$ $\Delta\mathcal{R} = 0$
- The sneutrino density asymmetry $\Delta_{\tilde N} = n_{\tilde N} - n_{\tilde N^*}$
  joins the leptonic asymmetries $\Delta_\alpha = \frac{B}{3} - L_\alpha$ as a new independent quantity

[. . . admittedly, with no striking numerical consequences . . .]

Coming back to neutrino masses . . .

Sakharov III: The N lifetime Γ_N^{-1} should be of the order of the Universe lifetime H^{-1} at the time when $T \sim M$.

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$$\Gamma_N = \frac{M}{16\pi}\left(\lambda\lambda^\dagger\right)_{11} \quad \text{by rescaling} \quad \widetilde{m} \equiv 16\pi\frac{v^2}{M^2} \times \Gamma_N = \frac{v^2}{M}\left(\lambda\lambda^\dagger\right)_{11}$$

$$H = \sqrt{\frac{8\pi G_N \rho}{3}} \simeq 1.7\sqrt{g_*}\frac{T^2}{M_P} \qquad m_* \equiv 16\pi\frac{v^2}{M^2} \times H(M) \approx 10^{-3}\text{eV}$$

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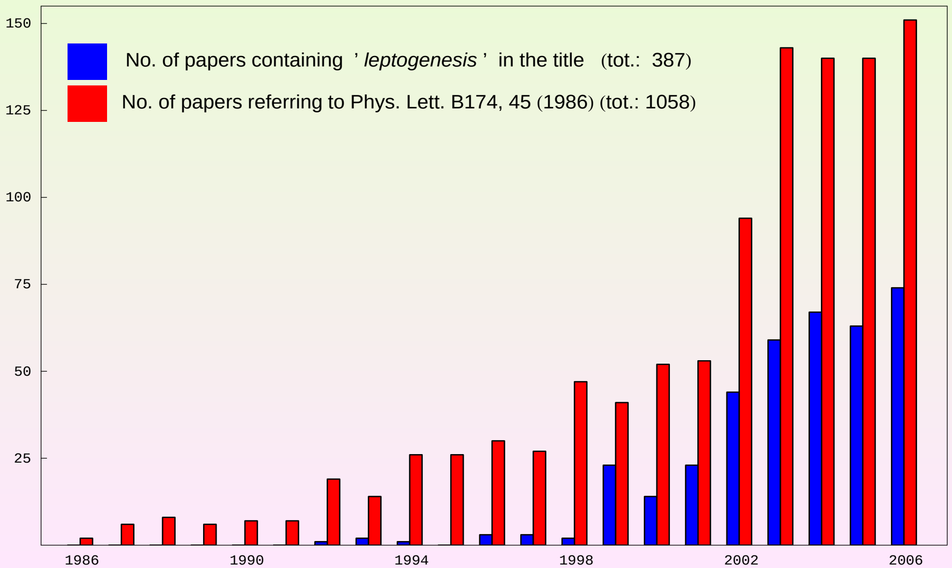

Experimental confirmation of $m_\nu \neq 0$ in the correct mass range for LeptoG:
$\Longrightarrow$ burst of lepto-papers around Y2K.

Do we have a limit on m_ν from LeptoG ? The DI bound:

[S. Davidson & A. Ibarra, PLB 535 (2002)]

[W. Buchmüller, P. Di Bari& M. Plümacher; S. Blanchet & P. Di Bari;]
[T. Hambye,Y. Lin, A. Notari, M. Papucci & A. Strumia; ...]

Computation of $\epsilon_\alpha = \frac{\Gamma_{\ell_\alpha} - \Gamma_{\bar{\ell}_\alpha}}{\Gamma_N}$ (*vertex* + *self-energy*) yields :

$$\epsilon_\alpha = \frac{-1}{8\pi(\lambda\lambda^\dagger)_{11}} \sum_{j\neq 1} \mathrm{Im}\left\{ \lambda_{j\alpha}\lambda^*_{1\alpha} \left[\underbrace{\frac{3M_1}{2M_j}(\lambda\lambda^\dagger)_{j1}}_{\not{L}:\ D_5=(\ell\phi)^2} + \underbrace{\frac{M_1^2}{M_j^2}(\lambda\lambda^\dagger)_{1j}}_{L:\ D_6=(\bar{\ell}\phi^*)\not{\partial}(\ell\phi)} + \underbrace{\frac{5M_1^3}{6M_j^3}(\lambda\lambda^\dagger)_{j1}}_{\not{L}:\ D_7=(\ell\phi)\partial^2(\ell\phi)} + \ldots \right.\right.$$

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DI: $\left|\epsilon^{(D_5)}\right| = \left|\sum_\alpha \epsilon_\alpha^{(D_5)}\right| \leq \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1) \xrightarrow{m_3\approx m_1} \left|\epsilon^{(D_5)}\right| \leq \frac{3}{16\pi}\frac{\Delta m^2_\oplus}{2v^2}\frac{M_1}{m_3}$

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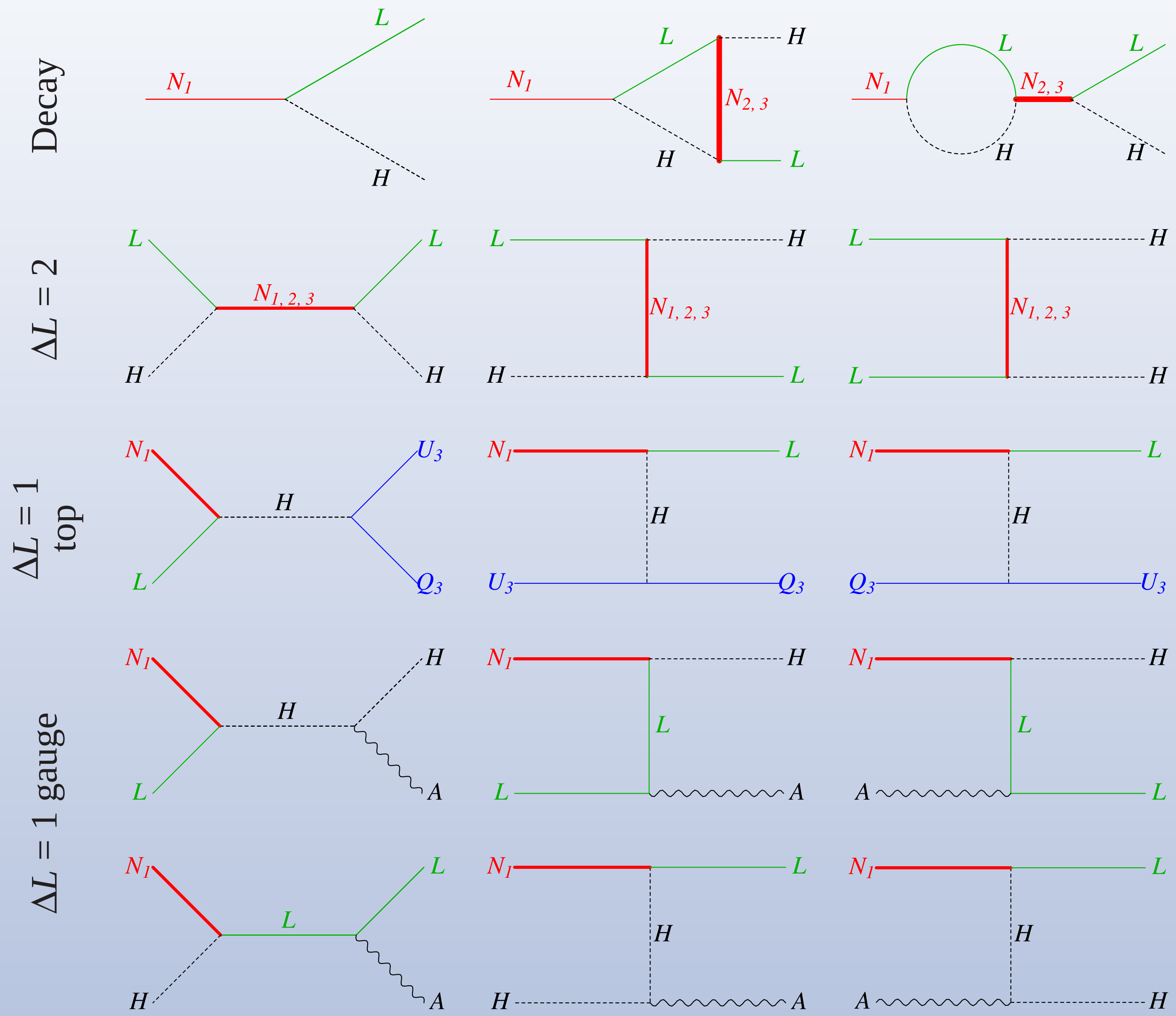
- Holds only for large hierarchies $M_1 \gg M_{2,3}$. (D_7 can dominate when $m_3 - m_1 \approx 0$).
- Applies only in the unflavored regime $T \gtrsim 10^{12}\,\mathrm{GeV}$. (No DI for flavored ϵ_α.)
- Applies only if leptogenesis is N_1 dominated. (No DI for the heavier sneutrinos $\epsilon_{2,3}$.)

Still, if $m_\nu^{\rm obs} > m_\nu^{\rm max}$ (cosmology?) one of the above conditions is not realized.

What is the Limit? – (CP asymmetry and collision diagrams)

[L.A.Muñoz, EN & J.Noreña, unpublished]



Network of (unflavored) Boltzmann equations

$$1.\quad \dot{Y}_N = -\left(\frac{Y_N}{Y_N^{eq}}-1\right)(\gamma_D + 2\gamma_{Ss} + 4\gamma_{St}),$$

$$2.\quad \dot{Y}_{\Delta L} = \left(\frac{Y_N}{Y_N^{eq}}-1\right)\epsilon_1\,\gamma_D - \left[2y_\ell + (y_t - y_{Q_3})\left(\frac{Y_N}{Y_N^{eq}}+1\right)\right]\gamma_{St}$$

$$- \left(\frac{Y_N}{Y_N^{eq}}y_\ell + y_t - y_{Q_3}\right)\gamma_{Ss} - 2\,(y_\ell + y_H)\,(\gamma_{Ns} + \gamma_{Nt}) \;+ \dot{Y}_{\Delta L}^{EW}$$

$$3.\quad \dot{Y}_{\Delta B} = \dot{Y}_{\Delta B}^{EW} \qquad \underline{\text{But sphalerons conserve } B-L:} \qquad \dot{Y}_{\Delta B}^{EW} - \dot{Y}_{\Delta L}^{EW} = 0$$

Eliminate the sources $Y_{L,B}^{EW}$ subtracting $2.$ from $3.$ and express all asymmetries in terms of $B-L$:

$$y_\ell \equiv -c_\ell \frac{Y_{B-L}}{Y^{eq}}; \qquad y_H \equiv -c_H \frac{Y_{B-L}}{Y^{eq}}$$

using also: $y_t - y_{Q_3} = \frac{y_H}{2}$

$$\dot{Y}_{B-L} = -\left(\frac{Y_N}{Y_N^{eq}}-1\right)\left[\epsilon_1\,\gamma_D + \left(c_\ell\,\gamma_{Ss} + \frac{c_H}{2}\,\gamma_{St}\right)\frac{Y_{B-L}}{Y^{eq}}\right] -$$

$$\left[(2\,c_\ell + c_H)\left(\gamma_{St} + \frac{1}{2}\gamma_{Ss}\right) + 2\,(c_\ell + c_H)\,(\gamma_{Ns} + \gamma_{Nt})\right]\frac{Y_{B-L}}{Y^{eq}}$$

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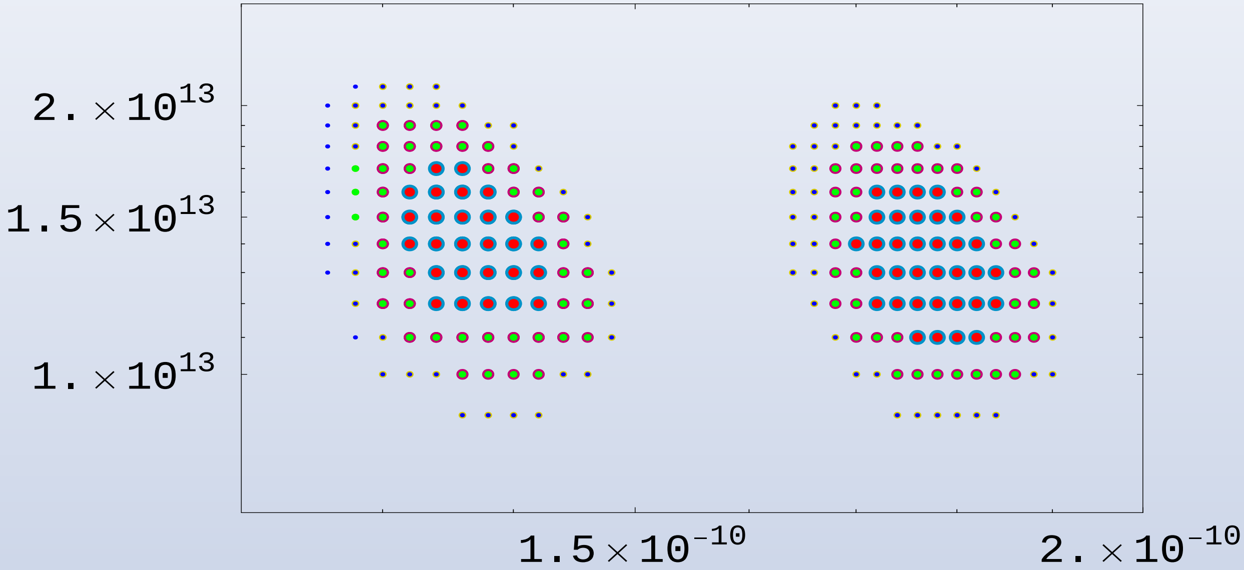
The leptogenesis limit on m_{ν_3}. (Relevance of Higgs effects)

[L.A.Muñoz, EN & J.Noreña, unpublished]

– Vertical axis: the lightest heavy neutrino mass M_1 (GeV);

– Horizontal axis: the "washout parameter" $\tilde{m}_1 = v^2 \frac{(\lambda\lambda^\dagger)_{11}}{M_1}$ (GeV).



M_1-$\tilde{m}_1$ values yielding successful leptogenesis, for different values of m_{ν_3} (3-σ)

- Right picture: Effects of the Higgs asymmetry neglected $(c_H = 0)$.
  Small, medium, large points: $m_{\nu_3} = 0.161,\ 0.162,\ 0.163$ eV.
- Left picture: Effects of the Higgs asymmetry included $(c_H = -1/3)$.
  Small, medium, large points: $m_{\nu_3} = 0.130,\ 0.131,\ 0.132$ eV.

$$m_{\nu_3}^{\max} = 0.13\,\mathrm{eV}$$

$$\tilde{m}_1^{\max} = 0.28\,\mathrm{eV}$$

Recap: Mass limits in Basic Leptogenesis (Seesaw type I):

- The One Flavor Regime ($T \gtrsim 10^{12}$ GeV): Constraints
  - If N's are strongly hierarchical, the DI limit on the maximum CP asymmetry for N_1 holds, and $m_\nu^{\max} = 0.13\,\mathrm{eV}$.
  - If light N's are only mildly hierarchical or degenerate, there is NO BOUND on m_ν from the requirement of successful leptogenesis!
- Leptogenesis with flavors:
  - Additional sources of CP violation: it can easily be $\epsilon_\alpha > \epsilon$.
  - We can have successful leptogenesis also for degenerate light neutrinos and for a wider range for the washout parameter $\tilde{m}_1$.
  - There is NO BOUND on absolute scale of light neutrinos.
- Leptogenesis with heavy flavors N_2 and N_3 can be successful with:
  - N_1 in the decoupled regime $\epsilon_1 \approx 0, \;\; \tilde{m}_1 \ll m_*$. $\epsilon_{2,3}$ dominate.
  - N_1 in a strongly coupled regime, if $\ell_{2,3}$ are strongly misaligned with ℓ_1.
  - In both cases there is NO BOUND on absolute scale of light neutrinos.

Beyond SM + type 1 seesaw, and beyond the seesaw

- SUSY Leptogenesis
  - The SUSY seesaw model gives a qualitatively different (but quantitatively similar) realization of leptogenesis.
  - Alternative mechanisms: Soft Leptogenesis can be successful at much lower scale, because has new sources of $\not{CP}$.
  - Alternative mechanisms: Affleck-Dine
- Different types of Seesaw:
  - Type I seesaw (standard: $SU(2)_L$ singlets Majorana neutrinos)
  - Type II seesaw ($SU(2)_L$ scalar triplet)
  - Type III seesaw ($SU(2)_L$ fermion triplet)
- Dirac Leptogenesis
  - Leptogenesis without lepton number violation

Leptogenesis: proving vs. disproving.

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

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

Not possible!

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A direct proof: At $T \gtrsim \Lambda_{EW}$ sphalerons relate B and L: $\Delta L \approx -2 \times \Delta B$

Baryogenesis: $\Delta B \Rightarrow \Delta L$ thus necessarily $\Delta L_e = \Delta L_\mu = \Delta L_\tau$

Leptogenesis. $\Delta L \Rightarrow \Delta B$: almost unavoidably $\Delta L_e \neq \Delta L_\mu \neq \Delta L_\tau$ $(T \ggg m_\nu)$

However, for non-relativistic Majorana neutrinos the ΔL information is lost, and since today $T_\nu \sim 10^{-4}\,\mathrm{eV} \ll \Delta m^2_{atm,sol} \ldots$ Not possible !

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Not possible !

Indirect tests: Reconstruct the complete seesaw model

18 parameters *vs.* 9 observables : $3m_\nu + 3\theta_{ij} + \delta, \alpha_1, \alpha_2$

Not possible!

Can theory help? *yes… if nature is kind to us*

- Neutrinos: The hierarchy is milder than for charged fermions

  (the spectrum could be quasi-degenerate)
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Non-Abelian flavor symmetry

$\Downarrow$

Large reduction in the number of (seesaw) parameters

$\Downarrow$

New connections between LE observables and HE quantities

$\Downarrow$

New information on crucial HE leptogenesis parameters

[See S. Morisi talk (Monday, Branch V)]

Recent works: Jenkins & Manohar; E. Bertuzzo, P. Di Bari, F. Feruglio, EN; Hagedorn, Molinaro & Petcov; D. Aristizabal Sierra, F. Bazzocchi, I. de Medeiros Varzielas, L. Merlo, S. Morisi,; Gonzalez Felipe & Serodio.

About future experiments? *We can hope for circumstantial evidences...*

by proving that (some of) the Sakharov conditions are (likely to be) satisfied:

1. $\underline{L}$ 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 (requires IH or quasi degenerate ν's)
[Iachiello & Giuliani talks, and afternoon's Branch I]

If m_ν is measured $@\,0.2\,\mathrm{eV}$ (Cosmology? - Cooray, Melchiorri) and $0\nu 2\beta$ is not seen?

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3. Out of equilibrium dynamics in the early Universe: (apparently the most difficult)

We have seen that can be satisfied for $\widetilde{m}_1 \sim 10^{-3} \div 10^{-1}\,\text{eV}$ (optimal values)

This could well be the first circumstantial evidence !

Conclusions and Outlook

- Leptogenesis is a very attractive scenario to explain $Y_{\Delta B}$.
- Recent developments have shown that *quantitative* and *qualitative* estimates of $Y_{\Delta B}$ have to take into account lepton flavors and the heavier Majorana neutrinos.
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- If $m_\nu \gtrsim 0.1\,\mathrm{eV}$ is established, failure of revealing $0\nu 2\beta$-decays will seriously endanger the Majorana ν hypothesis and strongly disfavor LG.
- Finally, LHC + EDM experiments will be able to establish or falsify EWB. This will indirectly determine the relevance of future LG studies.

Under what conditions low & high eng. $\not{CP}$ can be connected?

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

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Assuming that R is real

EN,Nir,Roulet,Racker,JHEP0601,2006

1: ϵ_α depends only on the ν-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.*;

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

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

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

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

More in detail: Lepton Flavor Effects

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

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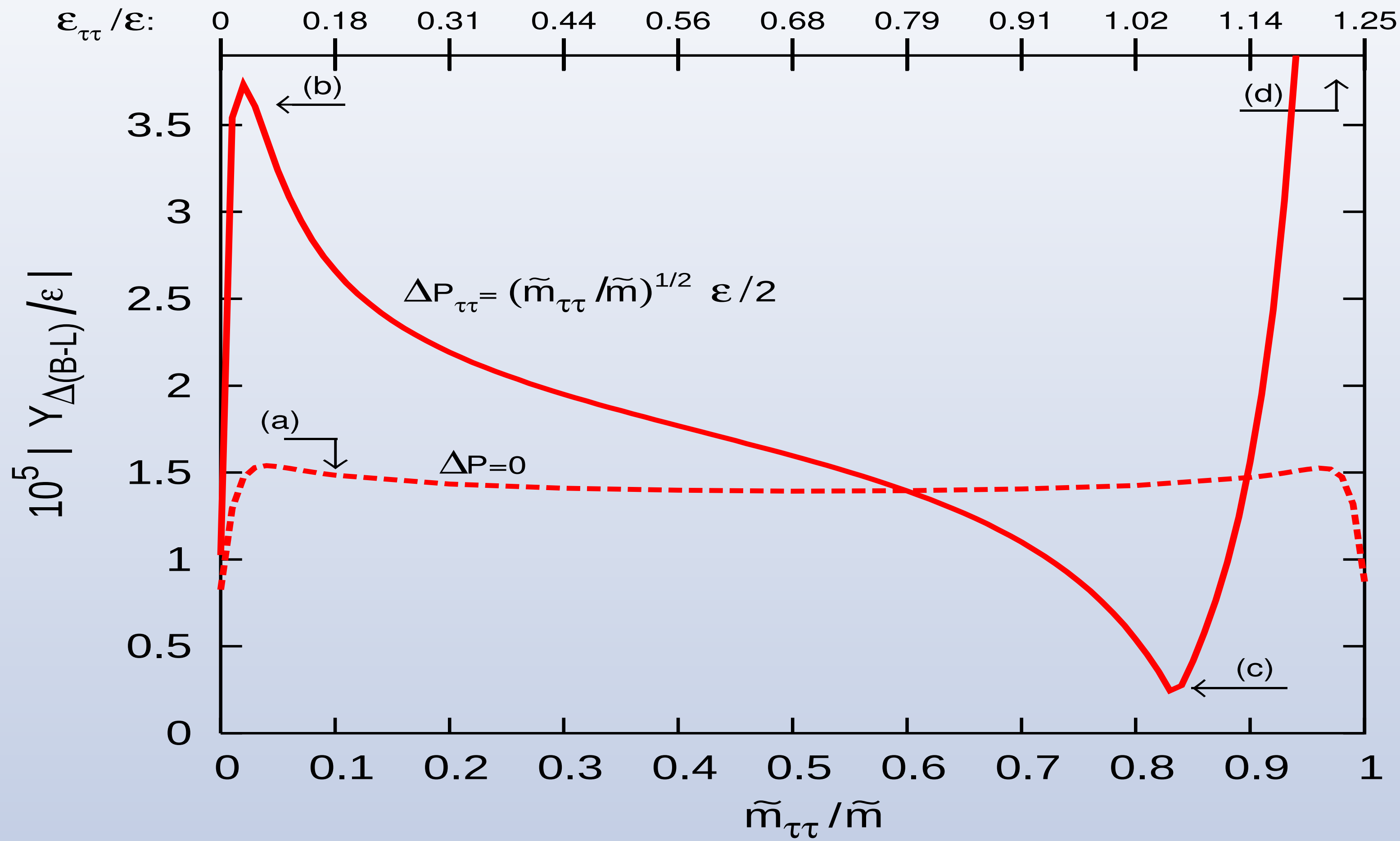
The most interesting effects are due to the different flavor composition of ℓ_1, $\bar{\ell}'_1$:

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

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

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Assuming that R is real implies surprising results:

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

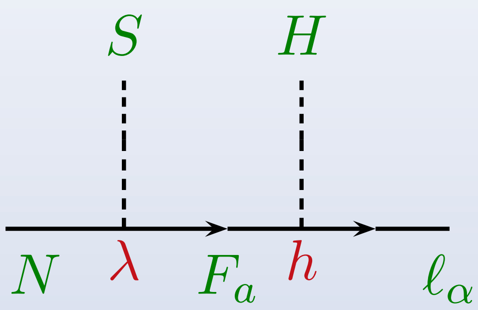
2: ϵ_α depends only on the ν-mix-matrix U !

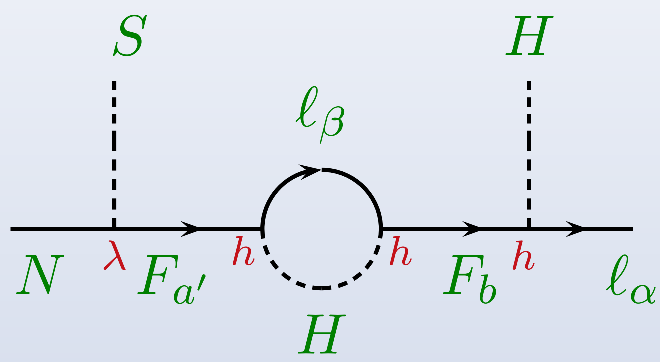
Recent studies of this scenario: Pastore *et al.*; Branco *et al.*;

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



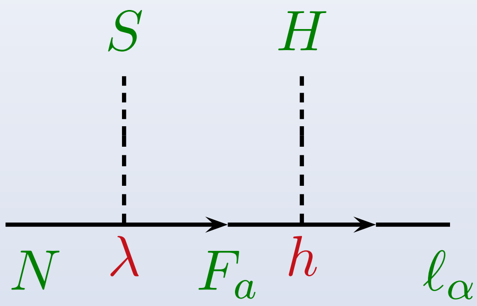


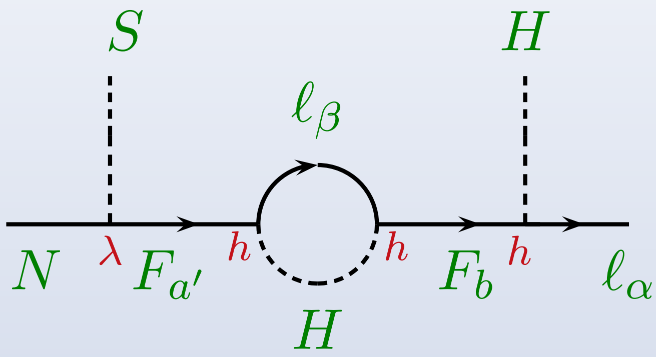
$$\tilde{\lambda}_{\alpha K} = \left(h \frac{\langle S \rangle}{M_F} \lambda^\dagger \right)_{\alpha K}; \qquad \epsilon = \sum_\alpha \epsilon_\alpha = 0$$

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: $\langle S\rangle = 0$.





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

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

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

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