XLII Rencontres de Moriond

Electroweak Session

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Recent Issues in Leptogenesis

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March 15, 2007

3 conditions are needed to explain $Y_B \equiv \frac{n_B - \bar{n}_B}{s} \approx 8.7 \times 10^{-11}$ (Sakharov '67)

1) B violation; 2) C & CP violation; 3) Departures from thermal equilibrium.

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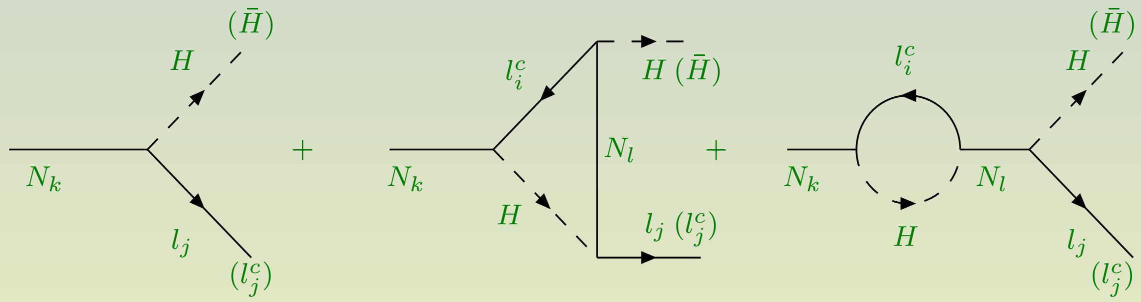

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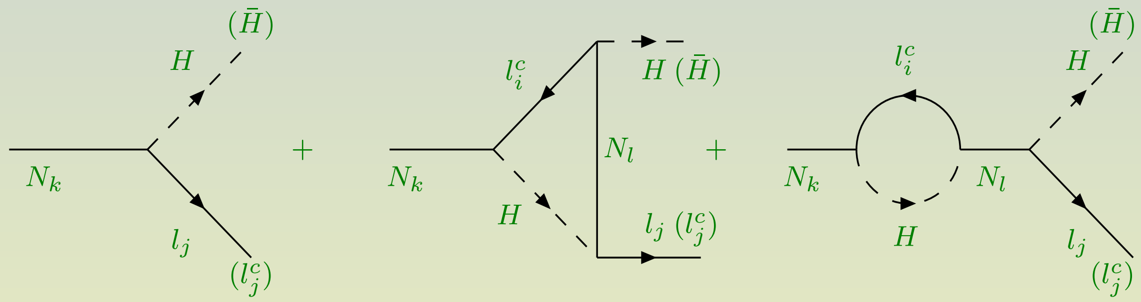

3. For a mass scale $M_N \sim 10^{11\pm3}\,\mathrm{GeV}$ deviations from thermal equilibrium in the primeval expanding Universe can occur at the time the N's decay: $(\Gamma_N(N \to \ell H) < H(T \sim M_N))$.

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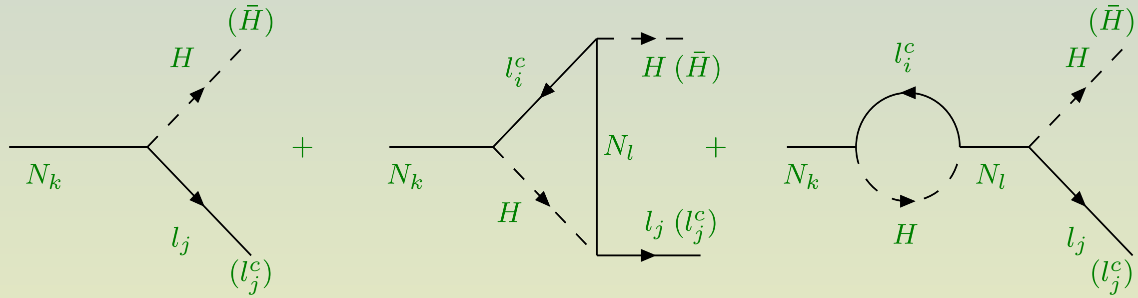

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1. $\not{B}$: The Majorana nature of the N mass is a source of lepton number violation ($\Delta L = 2$). **EW -Sphalerons** are nonperturbative SM processes that, in the EW symmetric phase, violate B and L (conserving $B - L$) and convert part of the L-asymmetry into a B asymmetry.

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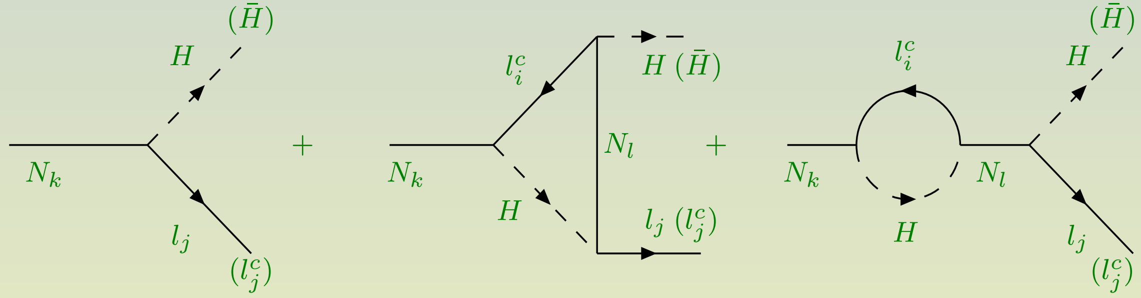

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Whether 'SM' leptogenesis is able to explain the Baryon Asymmetry of the Universe is just a quantitative question.

Brief historical review

- The general idea of LG (1986): *M. Fukugita & T. Yanagida*, *"Baryogenesis Without Grand Unification,"* Phys. Lett. B **174**, 45 (1986),
- following the discovery (1985) of fast $B+L$ violation at $T > T_{EW}$: *V. Kuzmin, Rubakov & Shaposhnikov*, *"On the anomalous Electroweak Baryon number nonconservation in the Early Universe,"* Phys. Lett. B **155**, 36 (1985).

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- Still, a few remarkable papers opened the way to *quantitative* LG: *M. A. Luty, "Baryogenesis via Leptogenesis,"* Phys. Rev. D **45**, 455 (1992); *L. Covi, E. Roulet & F. Vissani, "CP violating decays in leptogenesis scenarios,"* Phys. Lett. B **384**, 169 (1996).

- Around year 2000, a flourishing of LG studies begins:
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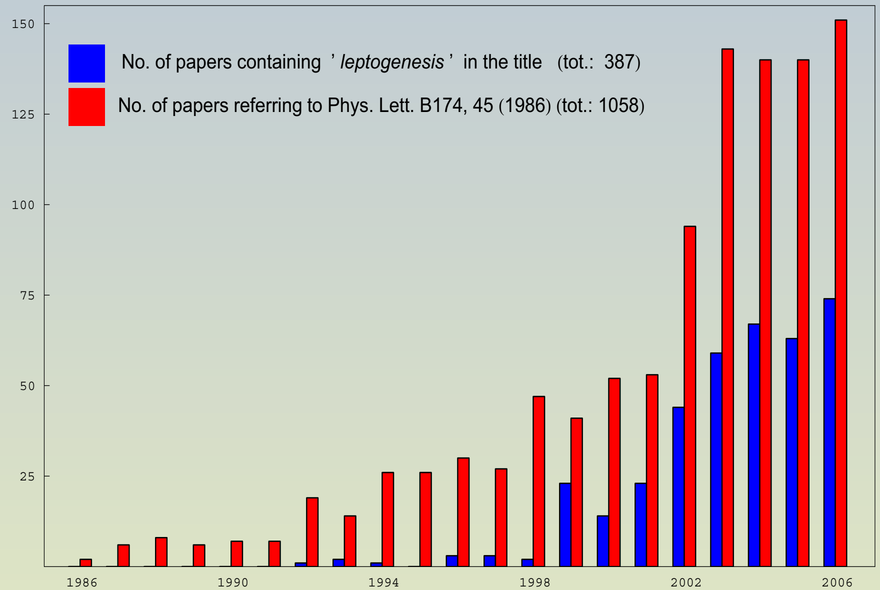

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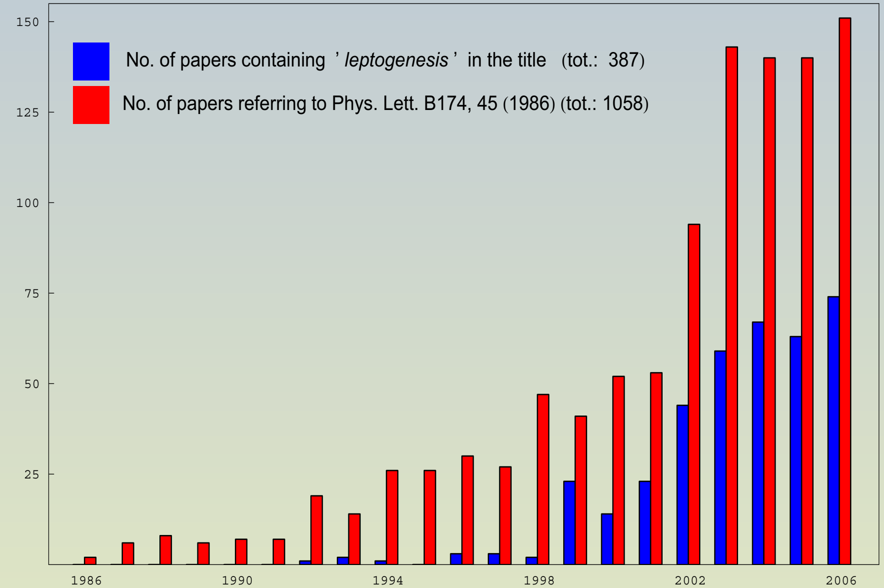

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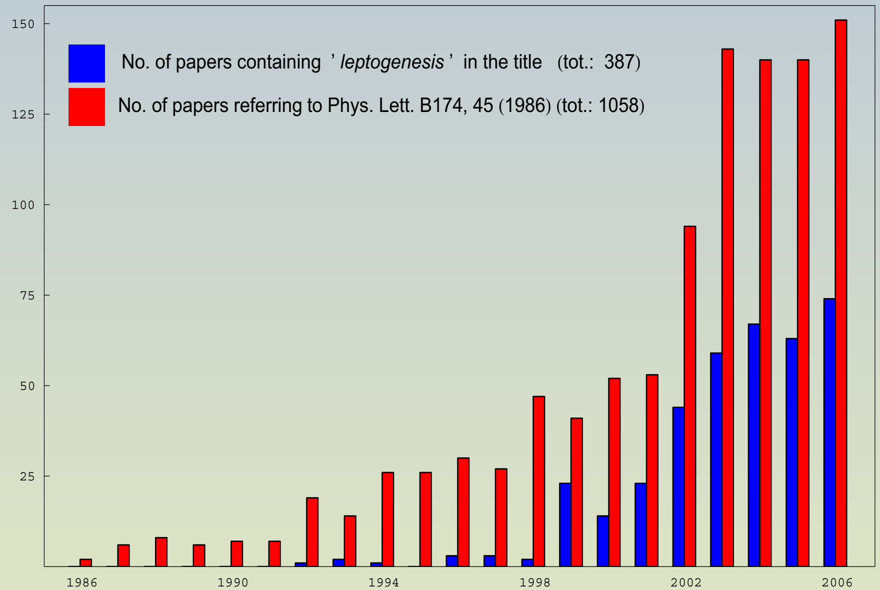

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- Indeed, additional fine effects (e.g. EW and QCD sphalerons effects, the asymmetry in the Higgs density, and various spectator reactions) were found to give at most 20%-40% corrections.
  (*see e.g. EN, Y. Nir, E. Roulet & J. Racker, "On Higgs and sphaleron effects during the leptogenesis era," JHEP* **0601**, *068 (2006); [hep-ph/0512052].*)

Two ingredients had been overlooked: Lepton flavors and $N_{2,3}$ effects

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- Dec. 2006: The asymmetry generated in the decays of the heavier $N_{2,3}$ Majorana neutrinos survives (in part) $\not{L}$ washouts at lower temperatures.
  G.Engelhard, Y.Grossman, EN & Y.Nir, "The importance of N_2 leptogenesis," [arXiv:hep-ph/0612187].

The first few terms in the leptogenesis Lagrangian

$$\mathcal{L} = \frac{1}{2}\left[\bar{N}\,(i\,\partial\!\!\!/)N \;-N^{\,T} M\,N\,\right] - (\lambda\;\bar{N}\;\ell\,H + \text{h.c.})$$

– $T \gg M_1$: $\not{L}$ violating processes are suppressed as $(M/T)^2$;

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– Relevant range: $T \sim M_1$. $\left(\tilde{m} = \frac{\lambda\lambda^\dagger v^2}{M},\; m_* \approx \frac{10^3 v^2}{M_P} \approx 1\,\text{meV}\right)$, ‘Fast’ $\not{L}$: $\tilde{m} > m_*$

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(since $\Delta m^2_\odot, \Delta m^2_\oplus > m^2_*$ the regime of 'strong washout' is the most likely one)

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- The CP asymmetry in N_1 decays: $\quad \epsilon_1 = \frac{\Gamma(N_1 \to \ell_1 H) - \bar{\Gamma}(N_1 \to \bar{\ell}_1 \bar{H})}{\Gamma_{N_1}}$
- The ℓ_1 lepton asymmetry, that is linear in ϵ_1 : $\quad Y_{\ell_1} \propto \epsilon_1 \frac{m_*}{\tilde{m}_1} \approx \eta_1 \epsilon_1$
- The lepton state ℓ_1 produced in N_1 decays: $\ell_1 = (\lambda\lambda^\dagger)^{-1}_{11} \sum_i \lambda_{1i}\,\ell_i$

  (with $\{\ell_i\}$ any orthogonal basis with well defined CP conjugation properties ($CP\{\ell_i\} = \{\bar{\ell}_i\}$))

Including Lepton Flavor Effects

(see also FX Josse-Michaux YSF-2 talk)

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- L-asymmetry enhancement: $Y_L \propto \sum_i \epsilon_1^i \frac{m_*}{K_i\, \tilde{m}_1} \approx n_f Y_L^{(n_f=1)}$

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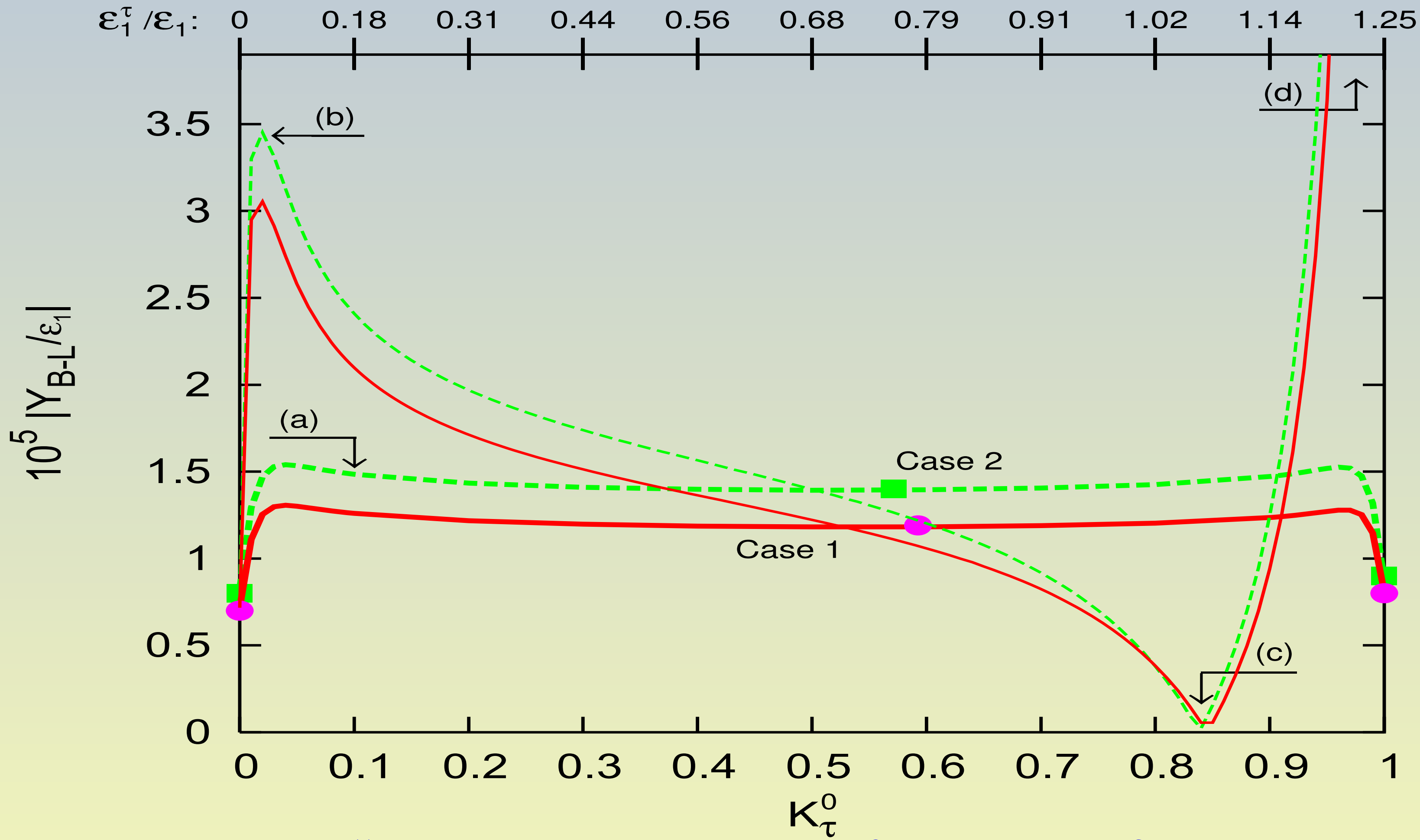
- Peculiar effect: ℓ_1 and $\bar{\ell}'_1$ have different flavor composition: $CP(\bar{\ell}'_1) \neq \ell_1$

$$\Rightarrow \; \Delta K_i \equiv K_i - \bar{K}_i \neq 0$$

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



$|Y_{B-L}|$ (in units of $10^{-5}|\epsilon|$) as a function of $K_\tau^0 \equiv |\langle \ell_\tau|\ell_1\rangle|^2$ in two 2-flavor regimes. The thick lines correspond to the special flavor cases for which $K_\tau = \bar{K}_\tau$. The thin lines give an example of the results for $K_\tau \neq \bar{K}_\tau$. The values of $\epsilon_1^\tau/\epsilon_1$ are marked on the upper x-axis.

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

$$-\mathcal{L} = \frac{1}{2} N_1^{cT} M_1 N_1^c + (\lambda_{1i}\, \overline{N_1}\, \ell_i\, H + h_i\, \overline{e}_i\, \ell_i\, H^\dagger + \text{h.c.})$$

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(O. Vives, P. Di Bari)

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At $T \gtrsim M_1$ the N_1 Yukawa processes become fast, and induce decoherence of all lepton states, projecting them onto $(\ell_1, \ell_0 \equiv \ell_{\perp_1})$. That is: $\ell_2 \to (\ell_1, \ell_0)_\perp$

⋆ The simple conditions to ensure this result are:

$$1)\ \tilde{m}_2 \not\gg m_*; \qquad 2)\ \tilde{m}_1 \gg m_*; \qquad 3)\ M_2/M_1 \gg 1.$$

⋆ Since $\ell_0 \perp \ell_1$, the component of the asymmetry Y_{ℓ_2} along the ℓ_0 direction

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⋆ In all other cases $N_{2,3}$ effects cannot be ignored in computing Y_B. Inferences and implications from N_1 leptogenesis alone are generally not reliable.

Conclusions and Outlook

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- The implications of successful leptogenesis for the low energy neutrino parameters (e.g. the upper limit on the light neutrino masses $m_\nu \lesssim 0.15\,$eV) and the lower limit on $M_1\,(\gtrsim 10^8\,\mathrm{GeV})$ should also be revised. (it is likely that they will hold only under more restrictive assumptions).

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- Any possibility of direct experimental tests? None for the moment. . . Brilliant ideas for experimental verifications of leptogenesis are most wanted.

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Assuming that R is real implies surprising results:

1: $\epsilon_1 = 0$ but $\epsilon_1^j \neq 0$ still allows for $Y_B \neq 0$

2: ϵ_1^j (and Y_B) depends on the ν-mix-matrix U

Recent attempts in this direction: Pastore *et al.*; Branco *et al.*;