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Leptogenesis and neutrino masses

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That is the cosmic excess of baryons over antibaryons

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1. Light Elements Abundances [D, ^{3}He, ^{4}He, ^{7}Li] $vs.$ 3ν-BBN predictions ($T \lesssim 1$ MeV)

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2. CMB anisotropies [WMAP7, BAO, SN-IA, HST] (Recombination: $T \lesssim 1$ eV)

$$\Omega_B\, h^2 \equiv \frac{\rho_B}{\rho_{\rm crit}} \left(\frac{H_0}{100\,\mathrm{km/sec/Mpc}} \right)^2 = \left(2.258^{+0.057}_{-0.056}\right) \times 10^{-2} \quad (68\% \text{ c.l.}),$$

[WMAP7 + ΛCDM: D. Larson *et al.*, A.J.Suppl. 192, 16 (2011)]

[Same quantity: $10^{10}\,\eta = 274\,\Omega_B\, h^2$]

A third way to express the same quantity: $\boxed{Y_{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{s}}$

[Normalization with the entropy density $s/n_\gamma|_0 = 7.04$ gives a quantity conserved in the Universe evolution.]

$$\boxed{Y_{\Delta B}^{BBN} = (8.10 \pm 0.85) \times 10^{-11}, \qquad Y_{\Delta B}^{CMB} = (8.79 \pm 0.44) \times 10^{-11}.}$$

The impressive consistency between $Y_{\Delta B}^{BBN}$ and $Y_{\Delta B}^{CMB}$ determined at different epochs $T_{BBN}/T_{CMB} \approx 10^6$: We know the BAU with less than 10% uncertainty.

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We have one well determined experimental number, that represents *Physics Beyond the SM*. No other related quantity ("LAU") is measurable.

Particle physics models for baryogenesis must relate $Y_{\Delta B}$ to other types of observables.

There are different scenarios for baryogenesis

Leptogenesis: is a class of scenarios where the Universe baryon asymmetry (ΔB) is produced from a lepton asymmetry (ΔL) generated in the decays of the heavy $SU(2)$ singlet *seesaw* Majorana neutrinos.

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Electroweak Baryogenesis: is a class of scenarios where the out-of-equilibrium condition for generating ΔB is provided by a 1^{st} order EW phase transition.

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Affleck-Dine Baryogenesis: is a class of scenarios where ΔB arises from large squarks and/or sleptons expectation values generated in the early Universe when $H > m_{\text{susy}}$ ($T \sim 10^{10}$ GeV).

Baryon Asymmetry $\Leftrightarrow$?? (m_ν ?)

(Spontaneous Baryogenesis, etc....)

With respect to the three Sakharov conditions ('67)

1. $\cancel{B}$ & $\cancel{B\text{-}L}$ | 2. $\cancel{C}$ & $\cancel{CP}$ | 3. Deviations from thermal equilibrium

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A-D$^{(*)}$	$V''(\phi) \sim -H^2$ when $m_{\rm soft} \ll H$	enough spontaneous CP violation at $T \gg M_W$	Relations(?) with low energy parameters: ($m_\nu < 10^{-5}$ eV)

$^{(*)}$ I. Affleck & M. Dine, NPB**249** (1985); M. Dine, L. Randall, S. Thomas, NPB**458**, (1996)

The SM plus the SEESAW $\Rightarrow$ LeptoG

Minimal extension of SM: add $n = 2, 3, \ldots$ singlet neutrinos

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

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

This explains nicely the suppression of ν masses: $\mathcal{M}_\nu = - \, \lambda^T \frac{\langle H \rangle^2}{M_N} \lambda$

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

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

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

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

The $n = 3$ 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.

Thermal Leptogenesis: the experimental connections

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

- If $\tau_N \gg \tau_U(M_N)$ no time to produce N's before $e^{-\frac{M_N}{T}}$ Boltzmann suppression
- If $\tau_N \ll \tau_U(M_N)$ fast decays *and* fast inverse decays $\Rightarrow$ chemical equilibrium.

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

$$H\Big|_M = \sqrt{\frac{8\pi G_N\,\rho(M)}{3}} \simeq 17 \cdot \frac{M^2}{M_P} \qquad m_* \equiv 16\pi\frac{v^2}{M^2} \cdot H(M) \approx 10^{-3}\mathrm{eV}$$

$$\boxed{\text{Condition: } \tilde{m} \sim m_* \ (\times 10^{\pm 2})}$$

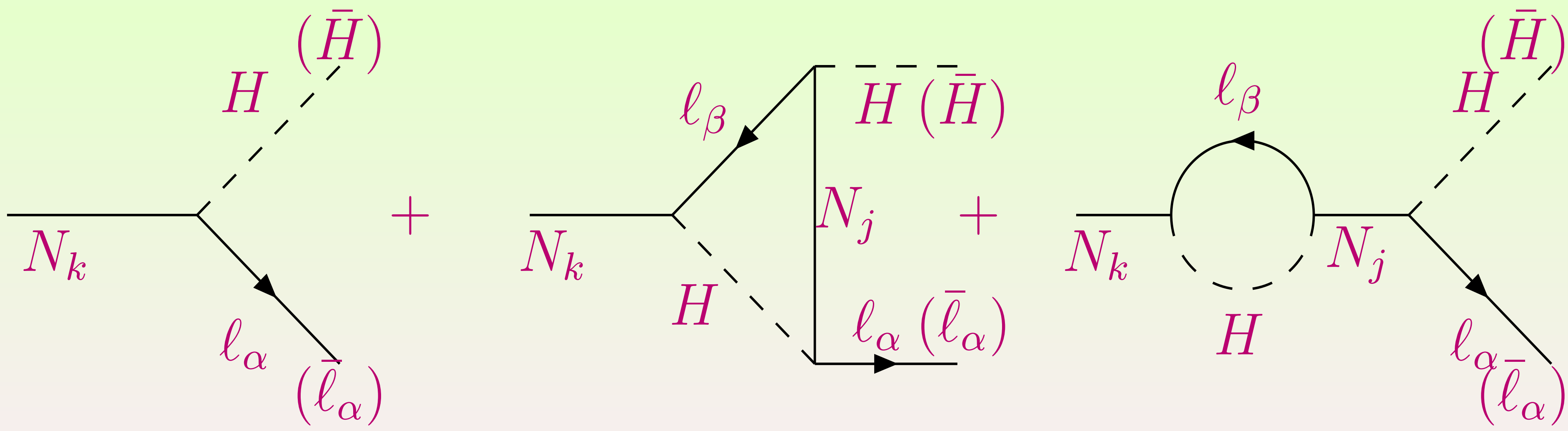
Thus $\widetilde{m}(\geq m_1) \approx \sqrt{\Delta m^2_\odot}, \sqrt{\Delta m^2_\oplus}$ is an optimal size to realize Sakharov III

A new ingredient: CP Violation in heavy Majorana neutrino decays

Sakharov II: The source of ~~CP~~ are the complex Yukawa couplings $\lambda_{i\alpha}$

They induce CP violation in the interference between the

tree level and the loop decay amplitudes.



The DI bound allows for a more quantitative limit on m_ν !

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

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

$D_5 \Rightarrow$ neutrino mass operator; $D_6 \Rightarrow$ non unitarity in lepton mixing; $D_7 \Rightarrow$ spoils the DI bound.

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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 $M_1 \ll M_{2,3}$. (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 $\epsilon_{2,3}$.)

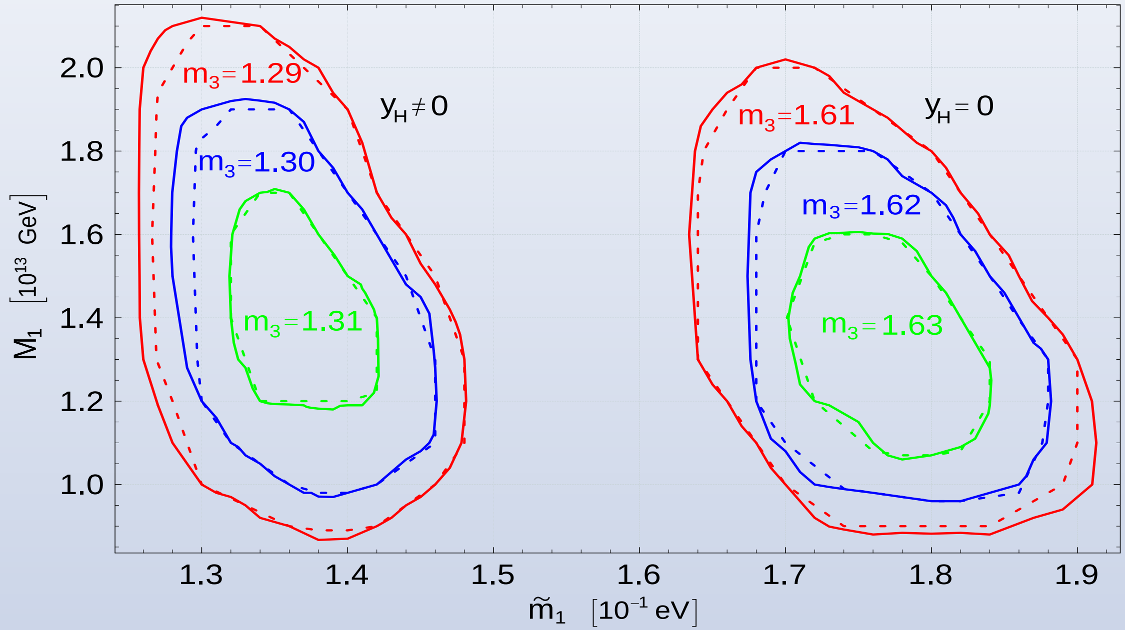
If $m_\nu^{\mathrm{obs}} > m_\nu^{\mathrm{max}}$ (KATRIN?, $0\nu2\beta$?, cosmology?) then one of the above conditions is not realized.

So what is the m_ν limit ? (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 $(c_H = 0)$.
- Left picture: Effects of the Higgs asymmetry included $(c_H = -1/3)$.
- Renormalizing the mass parameters to the light neutrino mass scale:

$$\boxed{m_{\nu_3}^{\max} = 0.10\,\mathrm{eV}} \qquad \boxed{\tilde{m}_1^{\max} = 0.22\,\mathrm{eV}}$$

Recap: Mass limits in (type I seesaw) Leptogenesis :

- The Single 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 $m_\nu^{\max} = 0.10\,\mathrm{eV}$.
  - 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 $\epsilon_1 \approx 0, \quad \tilde{m}_1 \ll m_*$. Then $\epsilon_{2,3}$ 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, beyond standard LG, and beyond type 1 seesaw

- SUSY Leptogenesis
  - The SUSY seesaw model gives a qualitatively different (but quantitatively similar) realization of leptogenesis.
  - Soft Leptogenesis can be successful at much lower scale, because of new flavoured sources of $\cancel{CP}$. **[Fong, Gonzalez-Garcia, EN, JCAP 1102 (2011) 032.]**
  - For $10^7 \lesssim T \lesssim 10^9$ GeV SoftLG reembodies into R-genesis with an $\mathcal{O}(10^2)$ larger efficiency **[Fong, Gonzalez-Garcia, EN, JCAP 1102 (2011) 032.]**
- Resonant Leptogenesis
  - Resonant enhancements of the CP asymmetry when $\Delta M \sim \Gamma_N$ allow for much lower scales **[A. Pilaftsis, T. Underwood, NPB692 (2004); PRD72 (2005)]** **[A. Pilaftsis, PRL95, (2005)]**
- Other types of Seesaw give different realizations viable at lower T:
  - Type II seesaw ($SU(2)_L$ scalar triplet)
  - Type III seesaw ($SU(2)_L$ fermion triplet)

New developments? Yes! "Early Universe Effective Theory"

[C.S. Fong, M.C. Gonzalez-Garcia, EN, J. Racker, JCAP 1012 (2010) 013]
[C.S. Fong, M.C. Gonzalez-Garcia, EN, JCAP 1102 (2011) 032; Int.J.Mod.Phys. A26 (2011)]

At each specific T, particle reactions in the early Universe can be classified according to their thermally averaged rates γ as:

[1.] Much faster than the Universe expansion: $\gamma \gg H(T)$. Can be "resummed" in chem. eq. conditions: $\sum_i \mu_i = \sum_f \mu_f$ (top Yukawa, gauge).

[2.] Much slower than the expansion. $\gamma \ll H(T)$. They enforce conservation laws: $\gamma_{B+L} \ll H(T) \Rightarrow \Delta B = 0$, $\gamma_{\ell e H} \ll H(T) \Rightarrow \Delta n_e = 0$

[3.] Comparable to the expansion: $\gamma_{N \to \ell H} \sim H(T)$. They spoil conservation laws but do not enforce chem.eq. conditions. Their effects must be tracked in detail (e.g. with BE).

The symmetries arising when the parameters controlling reactions [2.] are set to zero can be anomalous. <u>Handle with care!</u>

Supersymmetric Leptogenesis

[C.S. Fong, M.C. Gonzalez-Garcia, EN, J. Racker, JCAP 1012 (2010) 013]

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

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

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

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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 asymmetry $\Delta_{\tilde N} = n_{\tilde N} - n_{\tilde N^*}$ joins the L-asymmetries $\Delta_\alpha = \frac{B}{3} - L_\alpha$ as a new independent quantity

SusyLG: no large effects (no new sources of $\not{CP}$)
SoftLG ($T \gtrsim 10^8$GeV): new CP asymmetries in $\mathcal{R}$ charges ($\mathcal{R}$-genesis) can yield $\sim \mathcal{O}(100)$ quantitative effects!

Leptogenesis: proving vs. disproving.

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

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

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A direct evidence: 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 $\Delta L_e = \Delta L_\mu = \Delta L_\tau$

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Indirect tests: Reconstruct the complete seesaw model

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

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

Can be satisfied for $\widetilde{m}_1 \sim 10^{-3} \div 10^{-1}\,\mathrm{eV}$

Values of $\Delta m^2_{\odot,\oplus}$ are optimal. Possibly a first (marginal) circumstantial evidence...

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THANKS FOR YOUR ATTENTION