Behind Neutrino Mass – BeNe 2012

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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)

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

[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: $$Y_{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{s}$$

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

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

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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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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 $H > m_{\rm susy}$ ($T \sim 10^{10}$ GeV).

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

(Spontaneous Baryogenesis, etc.. . .)

With respect to the three Sakharov conditions ('67)

1. $\not{B}$ & $\not{B}\text{-}\not{L}$ | 2. $\not{C}$ & $\not{CP}$ | 3. Deviations from thermal equilibrium

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

$^{(*)}$B. Gavela, P. Hernandez, J. Orloff, O. Pene & C. Quimbay, NPB**430**, 382, (1994)

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

The SM plus the SEESAW ⇒ 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: $m_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$:

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

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

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

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

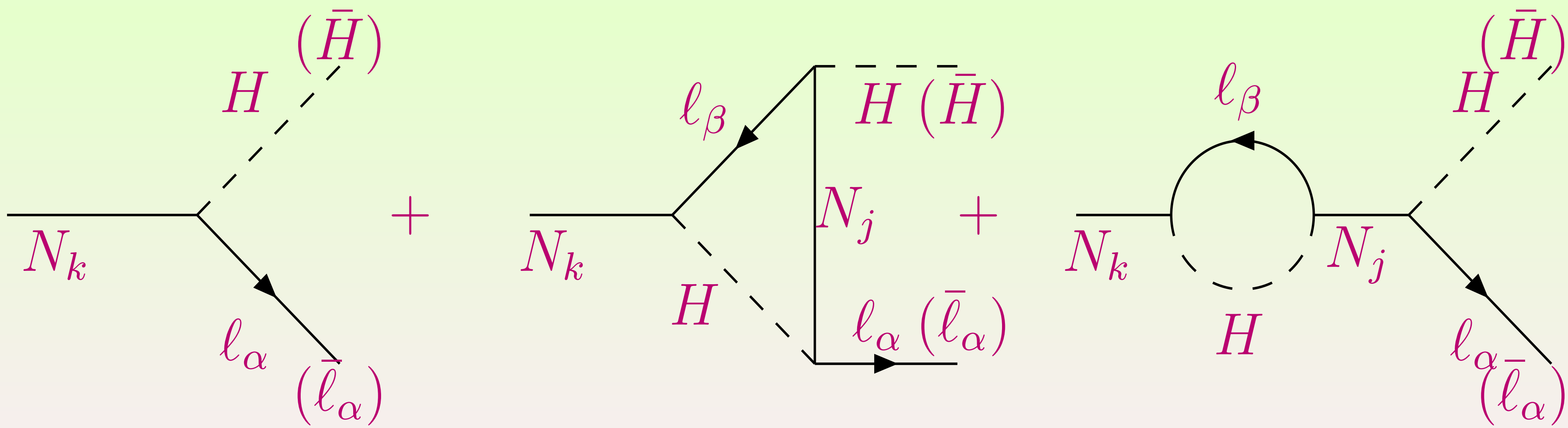
Thus $\widetilde{m}(\geq m_1) \approx \sqrt{\Delta m^2_\odot}, \sqrt{\Delta m^2_\oplus}$ is an optimal size to realize Sakharov III

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)]

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

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

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

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

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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 $\epsilon_{2,3}$.)

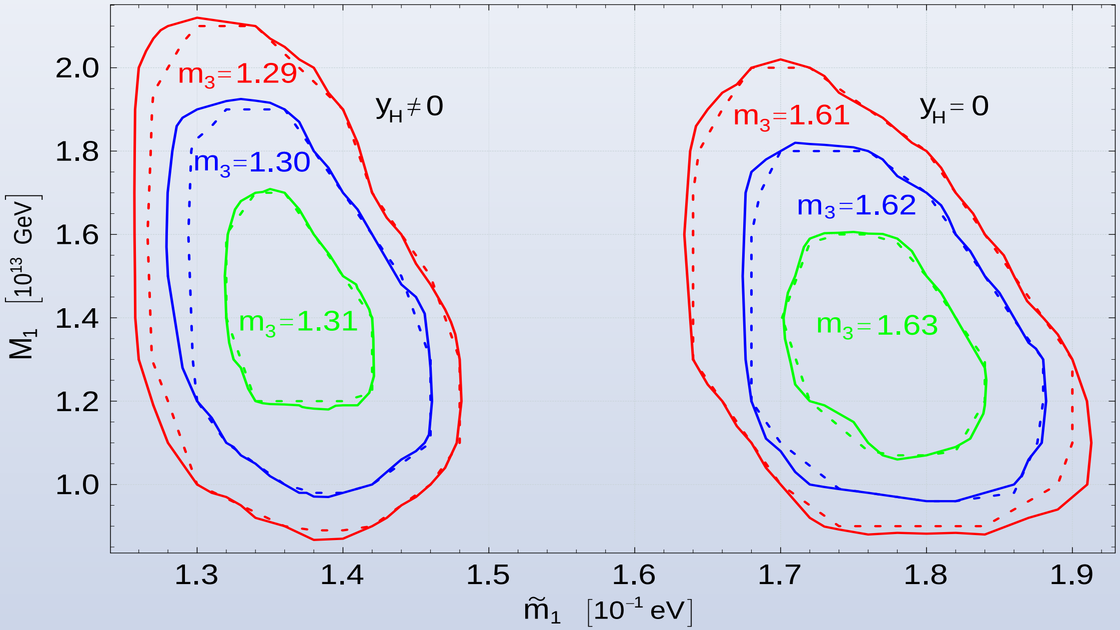
If $m_\nu^{\mathrm{obs}} > m_\nu^{\mathrm{max}}$ (KATRIN?, $0\nu2\beta$?, cosmology?) then one of the above conditions is not realized.

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:

$$m_{\nu_3}^{\max} = 0.10\,\mathrm{eV}$$

$$\tilde{m}_1^{\max} = 0.22\,\mathrm{eV}$$

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 $\epsilon_1 \approx 0, \;\; \tilde{m}_1 \ll m_*$. 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.

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. Handle with care!

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 $\not{C}\not{P}$)
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

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

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 $\Delta L_e = \Delta L_\mu = \Delta L_\tau$

Leptogenesis. $\Delta L \Rightarrow \Delta B$: almost unavoidably $\Delta L_e \neq \Delta L_\mu \neq \Delta L_\tau$ ($T \gg 10\,$MeV)

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$T \gg M_N$: L is conserved ($M_N \to 0$). $T \sim M_N$: L is violated.

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$T \lesssim m_\nu$: L-"evaporation" (neutrinos come at rest - handedness is lost).

$T_\nu^0 \sim 10^{-4}\,\mathrm{eV} \ll \Delta m^2_{atm,sol}$ Impossible to reconstruct the original "LAU"!

Leptogenesis: proving vs. disproving.

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

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

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 $\Delta L_e = \Delta L_\mu = \Delta L_\tau$

Leptogenesis. $\Delta L \Rightarrow \Delta B$: almost unavoidably $\Delta L_e \neq \Delta L_\mu \neq \Delta L_\tau$ ($T \gg 10\,\text{MeV}$)

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Indirect tests: Reconstruct the complete seesaw model

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

What about experiments? *We can only hope for circumstantial evidences. . .*

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

1. $\not{L}$ 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)

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However, phases of U and $Y_{\Delta B}$ are unrelated [G.Branco & al. NPB617,(2001) -unflavored]
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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...

My conclusions about Leptogenesis perspectives

- 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, the heavier Majorana neutrinos, and many other effects.
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THANKS FOR YOUR ATTENTION

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 $\not{CP}$. **[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)

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)
- Two mixing angles are large and one maybe maximal.
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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

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.

Electroweak Baryogenesis within the MSSM

It would be in better shape if m_H and/or $d_{e,n}$ had already been measured

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- Sufficiently strong 1st order PT requires light $\tilde{t}_R$ (ρ constrains $m^2_{\tilde{t}_L} - m^2_{\tilde{b}_L}$)
  - Loop corrections required by $m_H > 114\,\mathrm{GeV}$ imply that at least one scalar that is strongly coupled to the Higgs sector must be very heavy: $\tilde{t}_L$

$$m_{\tilde{t}_R} \lesssim 125\,\mathrm{GeV}; \quad m_{\tilde{t}_L} \gtrsim 6.5\,\mathrm{TeV}$$

[**M. Carena, G. Nardini, M. Quiros & C. E. M.Wagner, NPB 812, 243 (2009)**]

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- Other tensions with the pseudoscalar mass m_A and with $\tan\beta$
- Strongly 1st order PT + constraints from $b \to s\gamma$ prefer heavy m_A
- Charge asymmetry production during EWBG more efficient for light m_A
- Tensions in $\tan\beta$: [large m_H with 1st order PT] vs. [$b \to s\gamma$ with small m_A].

Beyond MSSM and beyond SUSY

- Enlarge the parameter space by adding new parameters
  - MSSM as an effective low energy theory with a few TeV cutoff.

    [**K. Blum, Y. Nir PRD78 (2008); N. Bernal** *et al.* **JHEP 0908 (2009); K. Blum** *et al.* **[arXiv:1003.2447]**]

$$W_{\rm eff} = \frac{\lambda}{\Lambda}\left(\hat{H}_u \hat{H}_d\right)^2$$

(+ corresponding susy-breaking term)

  - Next to minimal SSM (add one Higgs singlet)

    [**M. Pietroni, NPB402, 27, (1993)**]

- Enlarge parameter space by breaking some parameter relations
  - A non-supersymmetric MSSM

    [**M. Carena, A. Megevand, M. Quiros & C.E.M. Wagner, NPB716 319 (2005)**]

$$H^\dagger\left(\lambda_2 \tilde{W} + \lambda_2' \tilde{B}\right)\tilde{H}_2 + \ldots$$

assume $\lambda_2,\, \lambda_2'$ are (non SUSY) large couplings:

$$g \sin\beta,\; g' \sin\beta \;\to\; \lambda,\; \lambda' \gtrsim \mathcal{O}(1)$$

- For sure you can point out many other different possibilities . . .

My opinion about EW Baryogenesis perspectives

- SM EW Baryogenesis died long ago, and MSSM EW Baryogenesis seems to be now agonizing . . .

  Higgs searches at LHC and/or improved limits on electron and neutron EDMs might kill it soon.

- Beyond the MSSM scenarios, are in much better shape, and are able to explain the BAU with EW scale physics.

  However, is there any such scenario that can explain two things with only one new input ? (As is the case for MSSM EWBG and LeptoG.)

- In my opinion disproving MSSM EW Baryogenesis would strengthen the case for Leptogenesis (lack of competitors)

  In the next years, the LHC will play a crucial role in singling out the viable baryogenesis models.

Soft LeptoG: more $\not{C}\not{P}$ from SUSY soft breaking terms

[**Y. Grossman, T.Kashti,Y. Nir, E. Roulet**]
[**G. D'Ambrosio, G.F. Giudice, M. Raidal**]

Because CP asymmetries are temperature dependent flavor effects can enhance the efficiency by $\mathcal{O}(100)$ [**C. S. Fong and M. C. Gonzalez-Garcia, JHEP 0806, 076 (2008)**]
[**C. S. Fong, M. C. Gonzalez-Garcia, EN, J. Racker, JHEP 1007, 001 (2010)**]

$$\epsilon = \epsilon_s(T) + \epsilon_f(T) = \epsilon_0 \cdot \Delta_{BF}(T) \xrightarrow{T=0} 0 \; ; \qquad \Delta_{BF}(z) \sim \frac{2e^{z/2}(e^z - 2)}{e^{2z} - 3e^z + 4} \qquad (z{=}T/M) :$$

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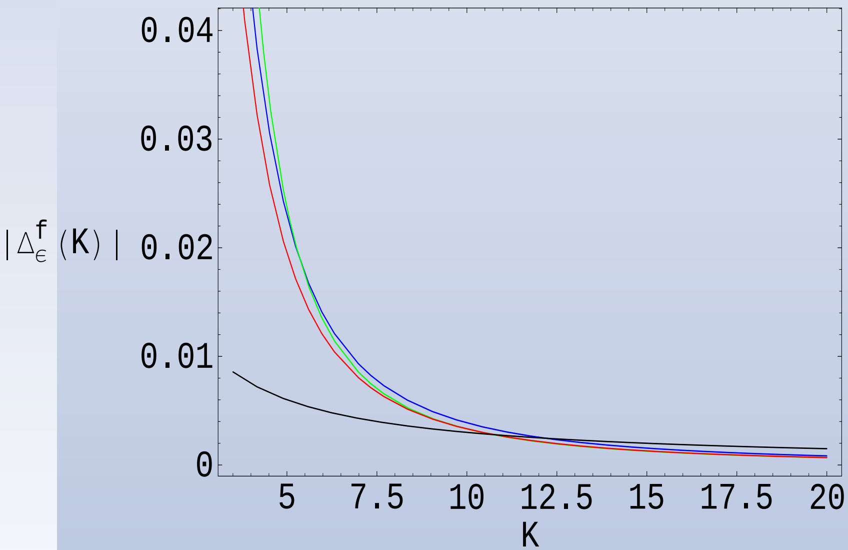
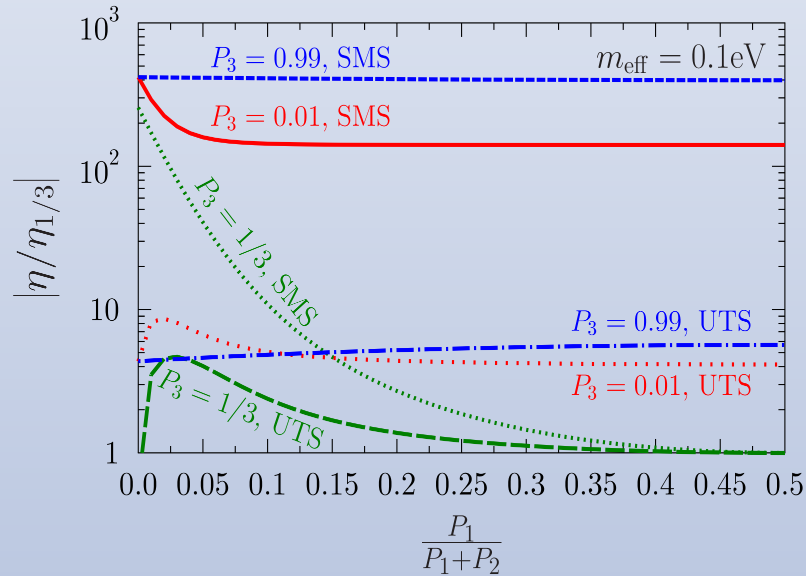
Soft-leptogenesis effective efficiency $\Delta_\epsilon^f(K)$ compared with the constant ϵ case $\eta \sim 1/K$



Global efficiency as a function of $P_1/(P_1+P_2)$ normalized to flavor equipartition $P_\alpha = 1/3$



At $T \gtrsim 10^7$ GeV $\eta_s\epsilon_s + \eta_f\epsilon_f \xrightarrow{T=0} \neq 0$ and even larger enhancements can occur

[C. S. Fong, M. C. Gonzalez-Garcia, EN; arXiv:1012.1597]

LeptoG through D_6: A purely flavored leptogenesis case

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

PFL: Leptogenesis with $\epsilon = \sum_\alpha \epsilon_\alpha = 0$

this does not prevent successful leptogenesis since in the flavor regime

$$Y_{B-L} = \sum_\alpha Y_{\Delta_\alpha} \quad \propto \quad \sum_\alpha \eta_\alpha \epsilon_\alpha \neq 0$$

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- 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 $\sum \epsilon_\alpha \simeq 0$.
- $\epsilon_\alpha^{D_6}$ CP asymmetries not bounded by DI, and can be large at small M_N.

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 lepton flavor equilibration effects suppress too much the final baryon asymmetry: **LFE still enforces a lower limit on M_1.**