Phenomenology of Baryogenesis from Mixing of Lepton Doublets

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1. Introduction
   - Standard Scenario for Leptogenesis
2. Leptogenesis from Mixing of Lepton Doublets
   - Thermal corrections
3. Parametric Scan
   - Parametrization of the Yukawa Couplings
   - Optimal point
   - Consequences: lower bound for M_{N1} and T_R
4. Conclusions

Planck Results

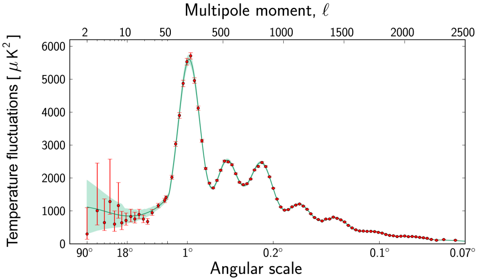

Figure: CMB spectra measured by the Planck mission

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} = 8.62 \cdot 10^{-11}$$

Sakharov conditions

- B number violation
- C and CP violation
- Out-of-equilibrium

Sakharov conditions: beyond the *SM*

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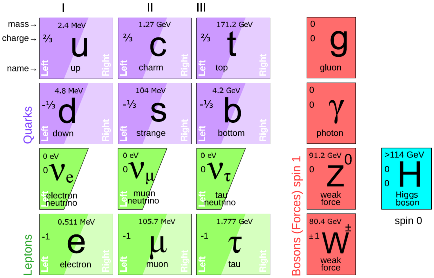
- B number violation $\rightarrow$ Yes, but also erases B-L $\times$
- C and CP violation $\rightarrow$ Yes, but CP violation is small in the early Universe $\times$
- Out-of-equilibrium $\rightarrow$ Yes, but too small because the SM particles are coupled too tightly. $\times$

Sakharov conditions: beyond the *SM*

- B number violation
- C and CP violation
- Out-of-equilibrium
  - We add to the SM three Right Handed Neutrinos



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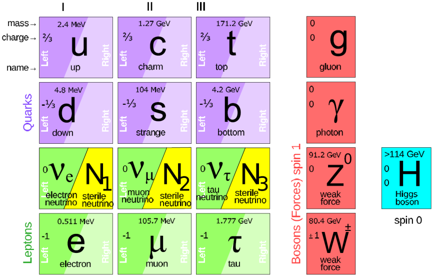
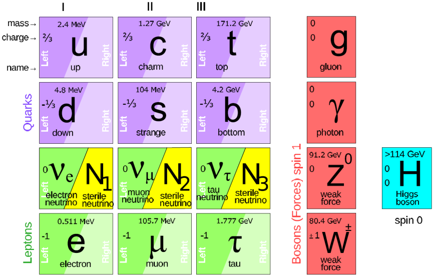


Sakharov conditions: beyond the *SM*

- B number violation → Majorama ✓
- C and CP violation → Extra Yukawa couplings and masses ✓
- Out-of-equilibrium → Weakly coupled ✓
  - ▶ We add to the SM three Right Handed Neutrinos



Sakharov conditions: Beyond the *SM*

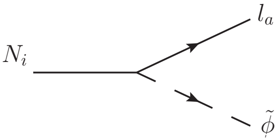
- B number violation → Majorama ✓
- C and CP violation → Extra Yukawa couplings ✓
- Out-of-equilibrium → Weakly coupled ✓

  - We add to the SM three Right Handed Neutrinos
  - At $T \backsimeq M_{N1}$:

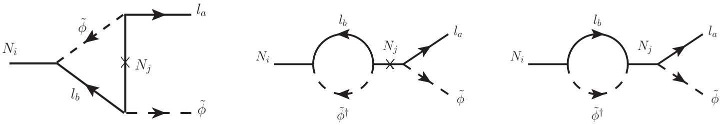
$$\mathcal{L} = \frac{1}{2}\bar{\psi}_{Ni}(\mathrm{i}\partial\!\!\!/ - M_{Nij})\psi_{Nj} + \bar{\psi}_{\ell a}\mathrm{i}\partial\!\!\!/\psi_{\ell a} + (\partial^{\mu}\phi^{\dagger})(\partial_{\mu}\phi)$$
$$-Y^{*}_{ia}\bar{\psi}_{\ell a}\tilde{\phi}P_{\mathrm{R}}\psi_{Ni} - h_{ab}\phi^{\dagger}\bar{\psi}_{\mathrm{R}a}P_{\mathrm{L}}\psi_{\ell b} + h.c.$$

1 Loop Corrections

Tree level



1-Loop terms:



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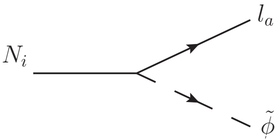
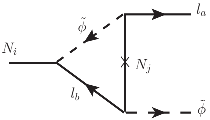
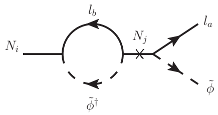
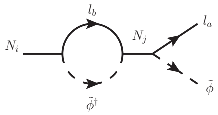


1-Loop terms : $(M_{N1} \simeq M_{N2})$







Boltzmann Equations

$$\frac{dY_{\ell a}^{Ni}}{dz_i} = \epsilon_{\ell a}^{Ni}(Y_{Ni} - Y_{Ni}^{\mathrm{eq}}) + \bar{W}_{\ell a} Y_{\ell a} \,,$$
$$\frac{dY_{Nk}}{dz_i} = \bar{\mathcal{C}}_{Nk}(Y_{Nk} - Y_{Nk}^{\mathrm{eq}}) \,,$$

Where :

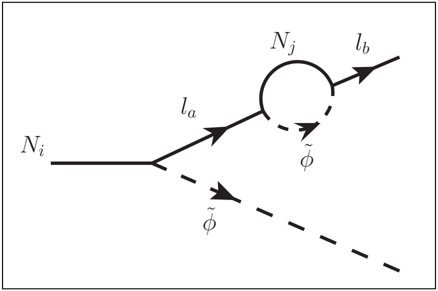
$$z_i = \frac{M_{Ni}}{T} \propto t^{-\frac{1}{2}}$$

$$Y_{Nk} = \frac{n_{Ni}}{s} \quad , \qquad \bar{\mathcal{C}}_{Nk} = \text{Decay term}$$

$$Y_{\ell a}^{Ni} = \frac{n_{\ell a}^{Ni} - \bar{n}_{\ell a}^{Ni}}{s}, \qquad \bar{W}_{\ell a} = \text{Washout term}$$

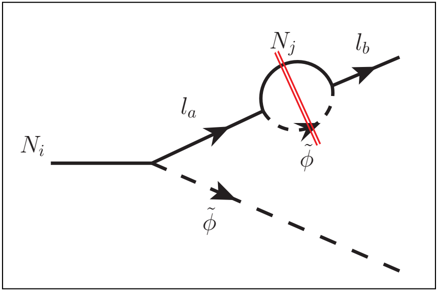
$3 \cdot 10^8 \leq T \leq 10^{12}[GeV] \rightarrow$ Flavoured Leptogenesis

New contributions



CP violation diagram from mixing of lepton doublets

New contributions



CP violation diagram from mixing of lepton doublets

Boltzmann Equations

$$\frac{dY_{\ell a}^{Ni}}{dz_i} = \bar{S}_{\ell a}^{Ni}(Y_{Ni} - Y_{Ni}^{\mathrm{eq}}) + \bar{W}_{\ell a} Y_{\ell a} \,,$$

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$$\bar{S}_{\ell a}^{Ni} \propto \mathrm{e}^{-\frac{M_{Nj}}{M_{Ni}} z_i} \mathcal{Q}_{\ell ac} \mathrm{i} \left(Y_{ai}^{\dagger} Y_{ic} Y_{cj}^{\dagger} Y_{ja} - Y_{aj}^{\dagger} Y_{jc} Y_{ci}^{\dagger} Y_{ia} \right)$$

$$\mathcal{Q}_{\ell ab} = \frac{(h_{aa}^2 - h_{bb}^2)(T^4/8)}{\left[(h_{aa}^2 - h_{bb}^2)/16\right]^2 T^4 + (h_{aa}^2 + h_{bb}^2) B^{\not{f}} [2B^{g} + (h_{aa}^2 + h_{bb}^2) B^{\not{f}}]}$$

Parametrization

$$Y^\dagger = U_\nu \sqrt{m_\nu^{\rm diag}} \mathcal{R} \sqrt{M_N} \frac{\sqrt{2}}{v} \qquad \text{[Casas-Ibarra]}$$

- $U_\nu = U_{PMNS} \cdot \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$
- $m_\nu^{\rm diag} = Diag(0, \ \ 8 \cdot 10^{-3}, \ \ 49 \cdot 10^{-3})$ [eV]
- $M_N = Diag(M_{N1}, M_{N2}, M_{N3})$

$$\mathcal{R} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{12}s_{13}s_{23} + s_{12} - c_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} + s_{12}s_{13} - s_{23} & c_{13}c_{23} \end{pmatrix}$$

Parametrization

- 2 RH Neutrino case ($M_{N1}, M_{N2} \ll M_{N3}$)
  - m_1=0
  - $\omega_{13} = 0$, $\omega_{23} = \pi/2$
  - α_2 independent
- Parameters space reduced to:
  - M_{N1} $\rightarrow$ Lightest right handed neutrino
  - M_{N2} $\rightarrow$ Second lightest right handed neutrino
  - δ $\rightarrow$ Delta phase from the PMNS matrix
  - α_1 $\rightarrow$ Majorama phase
  - ω_{12} $\rightarrow$ Complex angle of the $\mathcal{R}$ matrix

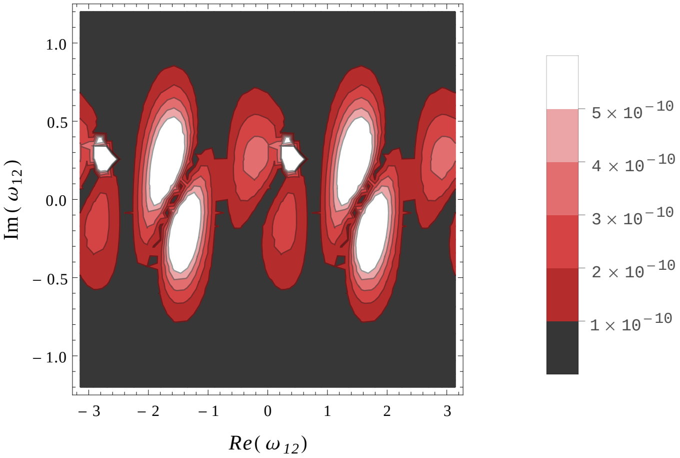

Figure: Final value for Y_l as a function of the $Re(\omega_{12})$ and $Im(\omega_{12})$.

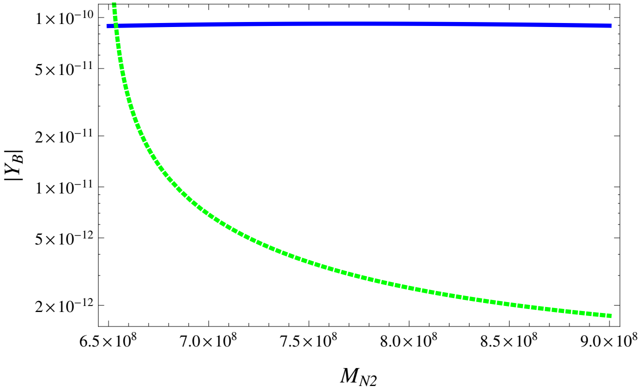

Figure: $|Y_B|$ as a function of M_{N_2} [GeV].($M_{N1} = 6.5 \cdot 10^8$). The green curve is the value obtained in the standard scenario, and the blue curve represents the value from mixing of lepton doublets.

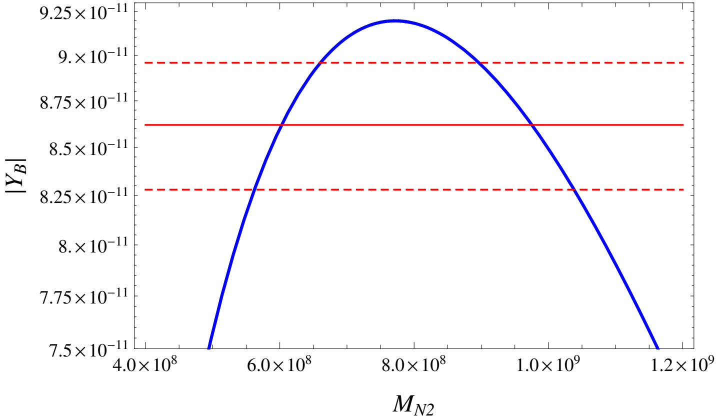

Figure: The figure displays the $|Y_l|$ as a function of the M_{N_2}[GeV]. The value of Mn_1 is set to $6.5 \cdot 10^8 [GeV]$(the red line represents the observed

- Lower bound for M_{N1}

$$\boxed{M_{N_1} \geq 6.5 \cdot 10^8 [GeV]}$$

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- T_R gravitino bounds
  - In a SUSY scenario, the upper limit of th T_R is directly related to the production rate of *gravitinos*
  - Big Bang Nucleosynthesis (BBN) predicts abundance of lights elements (D, He^3,He^4,Li^7)
    - Sets an upper limit for the T_R $(3 \cdot 10^5 - 9 \cdot 10^9)$[GeV]

Conclusions

- Lepton mixing is a viable source of lepton asymmetry when considering thermal effects.
- M_{N1} and M_{N2} are of the same order, but no degeneracy needed $\rightarrow$ it can dominate over the standard source in a wide region of the parameter space
- Lower limits in the "desirable" strong washout regime$\rightarrow$ independent of initial conditions
  - $M_{N_1} \geq 6.5 \cdot 10^8 [GeV]$
  - $T_{R,min} = \frac{M_{N1,min}}{z_f} \gtrsim 3 \cdot 10^8 [GeV]$
    - Relevant for the *gravitino problem* in the SUSY scenarios

Thank you for your attention

Back up slides

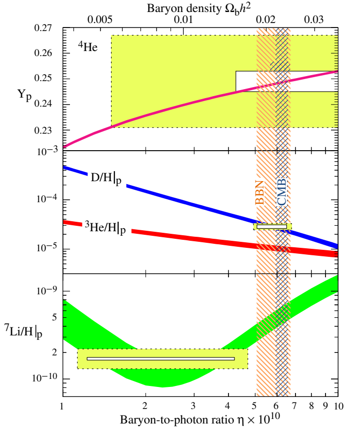
Seesaw Mechanism

$$\mathcal{L} = \quad +[\mathbf{h}]^*_\beta (\bar{\ell}_\beta \phi^{c*})\, e_{R\beta} - [\lambda]^*_{\alpha k} (\bar{\ell}_\alpha \phi^*)\, N_k - \frac{1}{2}\overline{N_j} M_j N_j^c + \mathrm{h.c.}$$

$$[m]_{\alpha\beta} = [\lambda]_{\alpha k} M_k^{-1} [\lambda]_{\beta k} v_u^2$$

$$[m] = U^* D_m U^\dagger$$

weak washout



Tree Level

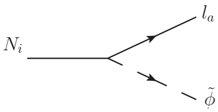


Figure: Tree Level contribution

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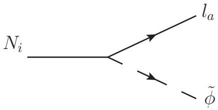


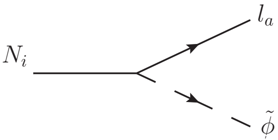
Figure: Tree Level contribution

- Decay rate

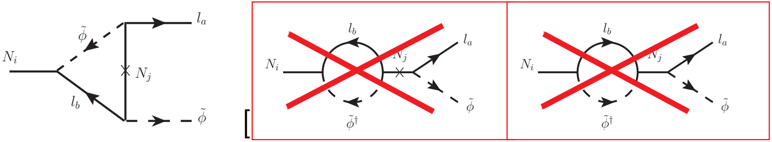
$$\Gamma(N \to l\phi) = \Gamma(N \to \bar{l}\bar{\phi})$$

1 Loop Corrections

Tree level



1-Loop terms :Hierchical limit ($M_{N1} \ll M_{N2}, M_{N3}$)



CP Violation

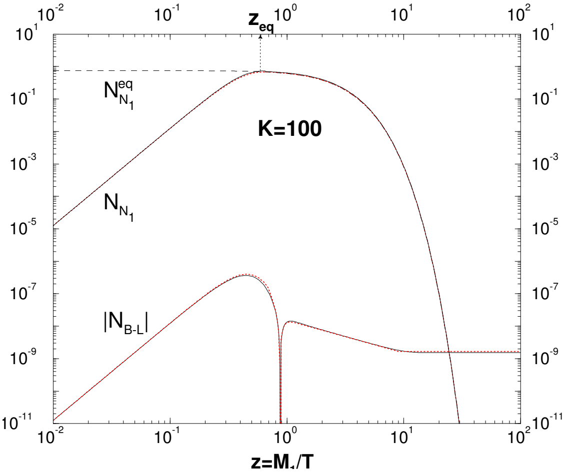
$$\varepsilon_a^{Ni} = \frac{3}{16\pi[YY^\dagger]_{ii}} \sum_{\substack{j,b \\ j\neq i}} \left\{ \mathrm{Im}\left[Y^\dagger_{ai} Y^*_{ib} Y^t_{bj} Y_{ja} \right] \frac{\xi(x_j)}{\sqrt{x_j}} + \mathrm{Im}\left[Y^\dagger_{ai} Y_{ib} Y^\dagger_{bj} Y_{ja} \right] \frac{2}{3(x_j - 1)} \right\}$$

$$x_j = (M_{Nj}/M_{Ni})^2$$

Parametrization

- Interaction rate h_α $\left(\mathcal{L} = ...h_{ab}\phi^\dagger \bar{\psi}_{\mathrm{R}a} P_{\mathrm{L}} \psi_{\ell b}...\right)$
  $\Gamma_\alpha \simeq 5 \times 10^{-2} h_\alpha^2 T$
- Temperature range of the calculations
  $3 \cdot 10^8 \leq T \leq 10^{12}$ [GeV]
  - $\boxed{h_\tau \text{ in equilibrium}}$
- Two "effective flavours"
  - $Y_{\tau\tau}$
  - $Y_\sigma = Y_{ee} + Y_{\mu\mu}$

strong washout



weak washout