

# Phenomenology of Baryogenesis from Mixing of Lepton Doublets

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November 2013



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- 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

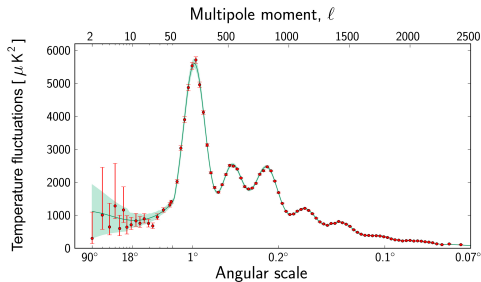


Figure: CMB spectra measured by the Planck mission

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

# Sakharov conditions

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

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- B number violation  $\rightarrow$  Yes, but also erases B-L  $\times$
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- C and CP violation  $\rightarrow$  Yes, but CP violation is small in the early Universe  $\times$
- Out-of-equilibrium

# Sakharov conditions: beyond the $SM$

- 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

	I	II	III	
mass --	2.4 MeV	1.27 GeV	171.2 GeV	
charge --	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
name --	<b>u</b>	<b>c</b>	<b>t</b>	<b>g</b>
	Left up Right	Left charm Right	Left top Right	gluon
				0
				<b><math>\gamma</math></b>
				photon
				0
				<b>Z</b>
				weak force
				91.2 GeV
				<b>H</b>
				Higgs boson
				>114 GeV
				spin 0
				80.4 GeV
				<b>W</b>
				weak force
				$\pm 1$
				<b>W<sub>1</sub></b>
				spin 1
				0 eV
				<b><math>\nu_e</math></b>
				electron neutrino
				0 eV
				<b><math>\nu_\mu</math></b>
				muon neutrino
				0 eV
				<b><math>\nu_\tau</math></b>
				tau neutrino
				0 eV
				<b><math>\nu_{RH}</math></b>
				Right Handed Neutrino
				0.511 MeV
				<b>e</b>
				electron
				105.7 MeV
				<b><math>\mu</math></b>
				muon
				1.777 GeV
				<b><math>\tau</math></b>
				tau



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mass →	2.4 MeV	1.27 GeV	171.2 GeV	
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name →	Left <b>u</b> Right up	Left <b>c</b> Right charm	Left <b>t</b> Right top	
				0 0 <b>g</b> gluon
Quarks	4.8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4.2 GeV $-\frac{1}{3}$	0 0 <b><math>\gamma</math></b> photon
	Left <b>d</b> Right down	Left <b>s</b> Right strange	Left <b>b</b> Right bottom	
				91.2 GeV 0 <b>Z</b> weak force
	0 $\nu_e$ $N_1$ left electron neutrino sterile neutrino	0 $\nu_\mu$ $N_2$ left muon neutrino sterile neutrino	0 $\nu_\tau$ $N_3$ left tau neutrino sterile neutrino	>114 GeV 0 0 <b>H</b> Higgs boson
Leptons	0.511 MeV -1	105.7 MeV -1	1.777 GeV -1	80.4 GeV $\pm 1$ <b>W</b> weak force
	Left <b>e</b> Right electron	Left <b><math>\mu</math></b> Right muon	Left <b><math>\tau</math></b> Right tau	spin 0

Bosons (Forces) spin 1

# Sakharov conditions: beyond the SM

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

	I	II	III		
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0	>114 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
name →	Left <b>u</b> Right up	Left <b>c</b> Right charm	Left <b>t</b> Right top	0 <b>g</b> gluon	0 <b>Z</b> weak force
	Left <b>d</b> Right down	Left <b>s</b> Right strange	Left <b>b</b> Right bottom	0 <b><math>\gamma</math></b> photon	0 <b>H</b> Higgs boson
Quarks	0 <b><math>\nu_e</math></b> <b><math>N_1</math></b> left electron neutrino / sterile neutrino	0 <b><math>\nu_\mu</math></b> <b><math>N_2</math></b> left muon neutrino / sterile neutrino	0 <b><math>\nu_\tau</math></b> <b><math>N_3</math></b> left tau neutrino / sterile neutrino	91.2 GeV <b>0</b> weak force	spin 0
Leptons	0.511 MeV Left <b>e</b> Right electron	105.7 MeV Left <b><math>\mu</math></b> Right muon	1.777 GeV Left <b><math>\tau</math></b> Right tau	80.4 GeV <b><math>W^\pm</math></b> weak force	

Bosons (Forces) spin 1

# Sakharov conditions: Beyond the $SM$

- B number violation  $\rightarrow$  Majorana  $\checkmark$
- C and CP violation  $\rightarrow$  Extra Yukawa couplings  $\checkmark$
- Out-of-equilibrium  $\rightarrow$  Weakly coupled  $\checkmark$

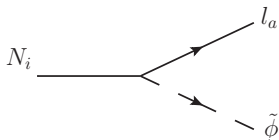
► We add to the SM three Right Handed Neutrinos

► At  $T \simeq M_{N1}$ :

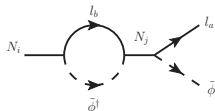
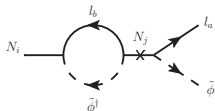
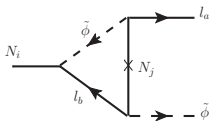
$$\mathcal{L} = \frac{1}{2} \bar{\psi}_{Ni} (i\not{\partial} - M_{Nij}) \psi_{Nj} + \bar{\psi}_{e_a} i\not{\partial} \psi_{e_a} + (\partial^\mu \phi^\dagger) (\partial_\mu \phi) \\ - Y_{ia}^* \bar{\psi}_{e_a} \tilde{\phi} P_R \psi_{Ni} - h_{ab} \phi^\dagger \bar{\psi}_{R_a} P_L \psi_{e_b} + h.c.$$

# 1 Loop Corrections

Tree level

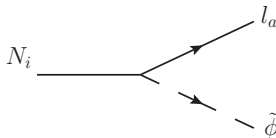


1-Loop terms:

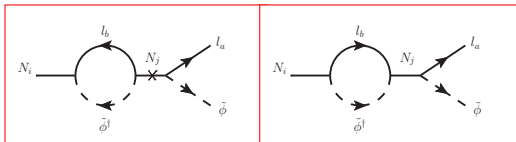
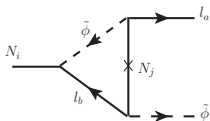


# 1 Loop Corrections

Tree level



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



# Boltzmann Equations

$$\frac{dY_{la}^{Ni}}{dz_i} = \epsilon_{la}^{Ni} (Y_{Ni} - Y_{Ni}^{\text{eq}}) + \bar{W}_{la} Y_{la},$$

$$\frac{dY_{Nk}}{dz_i} = \bar{C}_{Nk} (Y_{Nk} - Y_{Nk}^{\text{eq}}),$$

Where :

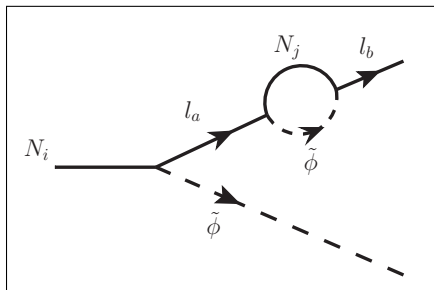
$$z_i = \frac{M_{Ni}}{T} \propto t^{-\frac{1}{2}}$$

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

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

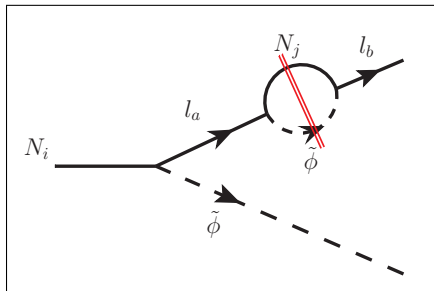
$3 \cdot 10^8 \leq T \leq 10^{12} [\text{GeV}] \rightarrow \text{Flavoured Leptogenesis}$

# New contributions



CP violation diagram from mixing of lepton doublets

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CP violation diagram from mixing of lepton doublets



# Boltzmann Equations

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

# Boltzmann Equations

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

$$\frac{dY_{Nk}}{dz_i} = \bar{C}_{Nk} (Y_{Nk} - Y_{Nk}^{\text{eq}})$$

$$\bar{S}_{la}^{Ni} \propto e^{-\frac{M_{Nj}}{M_{Ni}} z_i} Q_{lab}^i \left( Y_{ai}^\dagger Y_{ic} Y_{cj}^\dagger Y_{ja} - Y_{aj}^\dagger Y_{jc} Y_{ci}^\dagger Y_{ia} \right)$$

$$Q_{lab} = \frac{(h_{aa}^2 - h_{bb}^2)(T^4/8)}{\left[ (h_{aa}^2 - h_{bb}^2)/16 \right]^2 T^4 + (h_{aa}^2 + h_{bb}^2) B^{\#} [2B^g + (h_{aa}^2 + h_{bb}^2) B^{\#}]}$$

# Parametrization

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

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

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

# Parametrization

- 2 RH Neutrino case ( $M_{N1}, M_{N2} \ll M_{N3}$ )
  - $m_1=0$
  - $\omega_{13} = 0, \omega_{23} = \pi/2$
  - $\alpha_2$  independent
- Parameters space reduced to:
  - $M_{N1} \rightarrow$  Lightest right handed neutrino
  - $M_{N2} \rightarrow$  Second lightest right handed neutrino
  - $\delta \rightarrow$  Delta phase from the PMNS matrix
  - $\alpha_1 \rightarrow$  Majorana phase
  - $\omega_{12} \rightarrow$  Complex angle of the  $\mathcal{R}$  matrix

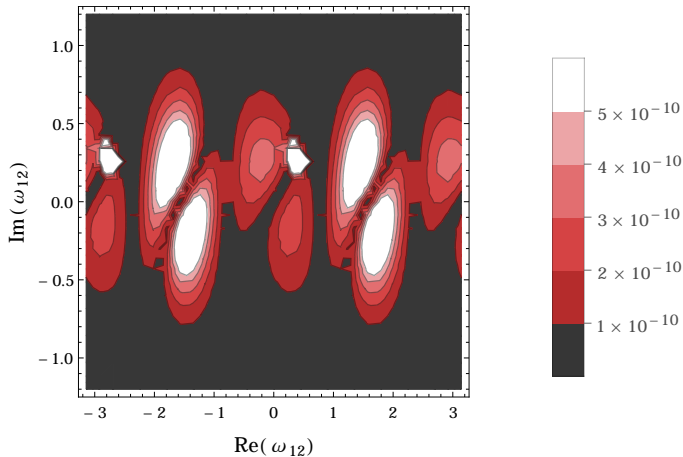
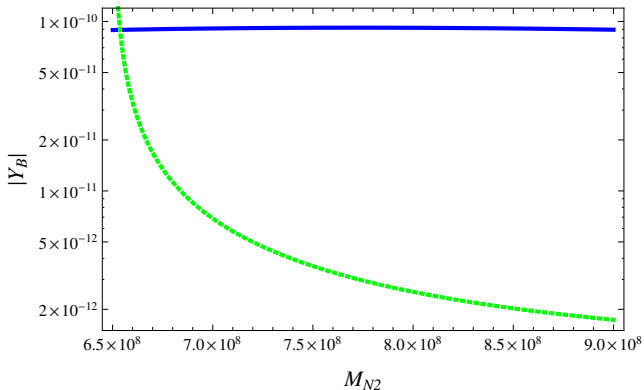
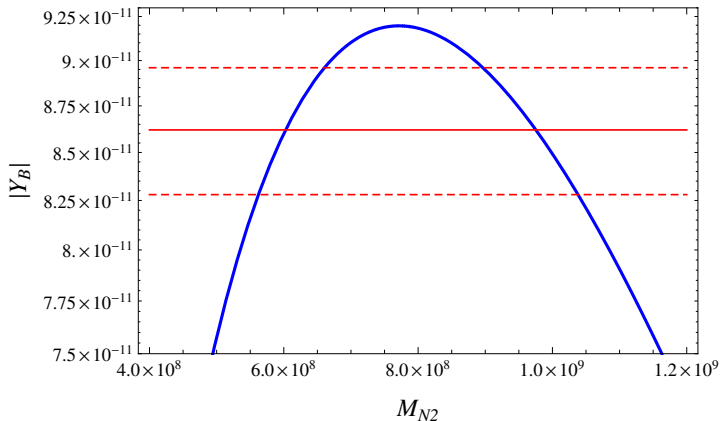


Figure: Final value for  $Y_l$  as a function of the  $\text{Re}(\omega_{12})$  and  $\text{Im}(\omega_{12})$  .



**Figure:**  $|Y_B|$  as a function of  $M_{N2}$  [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  $|Y_I|$  as a function of the  $M_{N2}$  [GeV]. The value of  $M_{N1}$  is set to  $6.5 \cdot 10^8$  [GeV] (the red line represents the observed

- Lower bound for  $M_{N_1}$

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



- Lower bound for  $M_{N1}$

$$M_{N1} \geq 6.5 \cdot 10^8 [\text{GeV}]$$

- Since for the the lower  $z_f \simeq 2.2$

$$T_{R,min} = \frac{M_{N1,min}}{z_f} \gtrsim 3 \cdot 10^8 [\text{GeV}]$$

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- Since for the the lower  $z_f \simeq 2.2$

$$T_{R,min} = \frac{M_{N1,min}}{z_f} \gtrsim 3 \cdot 10^8 [\text{GeV}]$$

- $T_R$  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

- $M_{N1} \geq 6.5 \cdot 10^8 [\text{GeV}]$

- $T_{R,min} = \frac{M_{N1,min}}{z_f} \gtrsim 3 \cdot 10^8 [\text{GeV}]$

► Relevant for the *gravitino problem* in the SUSY scenarios

Thank you for your attention

Back up slides

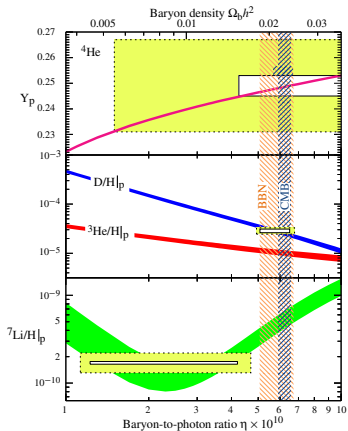
# Seesaw Mechanism

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

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

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

# weak washout



# Tree Level

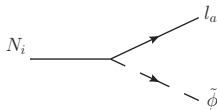


Figure: Tree Level contribution



## Tree Level

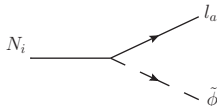


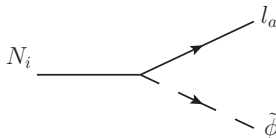
Figure: Tree Level contribution

- Decay rate

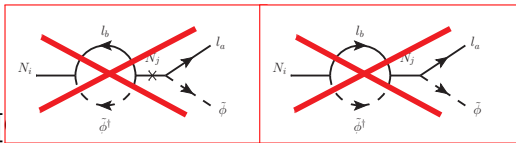
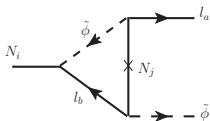
$$\Gamma(N \rightarrow l\phi) = \Gamma(N \rightarrow \bar{l}\bar{\phi})$$

# 1 Loop Corrections

Tree level



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



# CP Violation

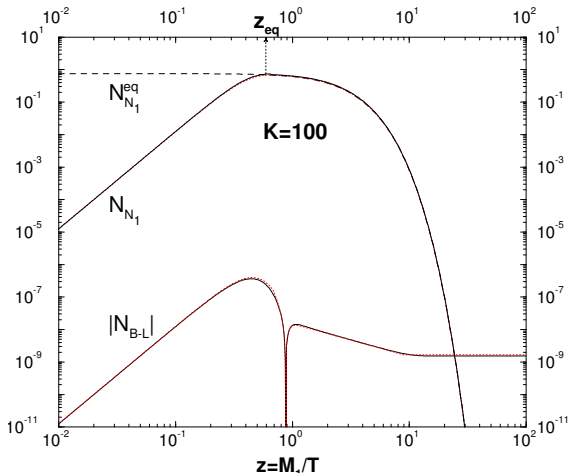
$$\varepsilon_a^{Ni} = \frac{3}{16\pi[\mathbf{Y}\mathbf{Y}^\dagger]_{ii}} \sum_{\substack{j,b \\ j \neq i}} \left\{ \text{Im} \left[ Y_{ai}^\dagger Y_{ib}^* Y_{bj}^t Y_{ja} \right] \frac{\xi(x_j)}{\sqrt{x_j}} \right. \\ \left. + \text{Im} \left[ Y_{ai}^\dagger Y_{ib} Y_{bj}^\dagger Y_{ja} \right] \frac{2}{3(x_j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

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

# Parametrization

- Interaction rate  $h_\alpha$  ( $\mathcal{L} = \dots h_{ab} \phi^\dagger \bar{\psi}_{Ra} P_L \psi_{Lb} \dots$ )  
 $\Gamma_\alpha \simeq 5 \times 10^{-2} h_\alpha^2 T$
- Temperature range of the calculations  
 $3 \cdot 10^8 \leq T \leq 10^{12}$  [GeV]
  - $h_\tau$  in equilibrium
- Two “effective flavours”
  - $Y_{\tau\tau}$
  - $Y_\sigma = Y_{ee} + Y_{\mu\mu}$

# strong washout



# weak washout

