Leptogenesis without violation of $B - L$

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OUTLINE

1. Inverse seesaw or almost conserved lepton number

2. The CP Asymmetries

3. Basic requirements for the generation of B

4. Boltzmann Equations

5. Results

1. Inverse seesaw or almost conserved lepton number

• Neutrino masses naturally explained by the seesaw mechanism → generically no testable

• Inverse seesaw → global lepton number $U(1)_L$ slightly broken by a small parameter μ , protected from radiative corrections.

Mohapatra, Valle (1986)

• Rich phenomenology:

- Flavour and CP violation effects no suppressed by light neutrino masses

Bernabeu et al. (1987); NR, Valle (1990); González-García, Valle (1992)

- $\mathcal{O}(1)$ neutrino Yukawa couplings and heavy neutrino masses at the TeV scale

- Two strongly degenerate RH neutrinos (quasi-Dirac fermion) → resonant leptogenesis at $T \sim \mathcal{O}(1$ TeV$)$

Pilaftsis, Underwood (2005); Asaka, Blanchet (2008); Blanchet et al. (2009)

Example: SM + 2 RH neutral fermions per generation, ν_{Ri}, s_{Li}

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

where $m_D \equiv \lambda_{\alpha i}\, v$

For μ ,$m_D \ll M$,

$$m_\nu = m_D {M^T}^{-1} \mu M^{-1} m_D^T$$

- We assume small lepton number violating affects negligible during leptogenesis, i.e., $\mu \to 0$

- RH neutrinos combine exactly into Dirac fermions

$$N_i = \nu_{Ri} + s_{Li}$$

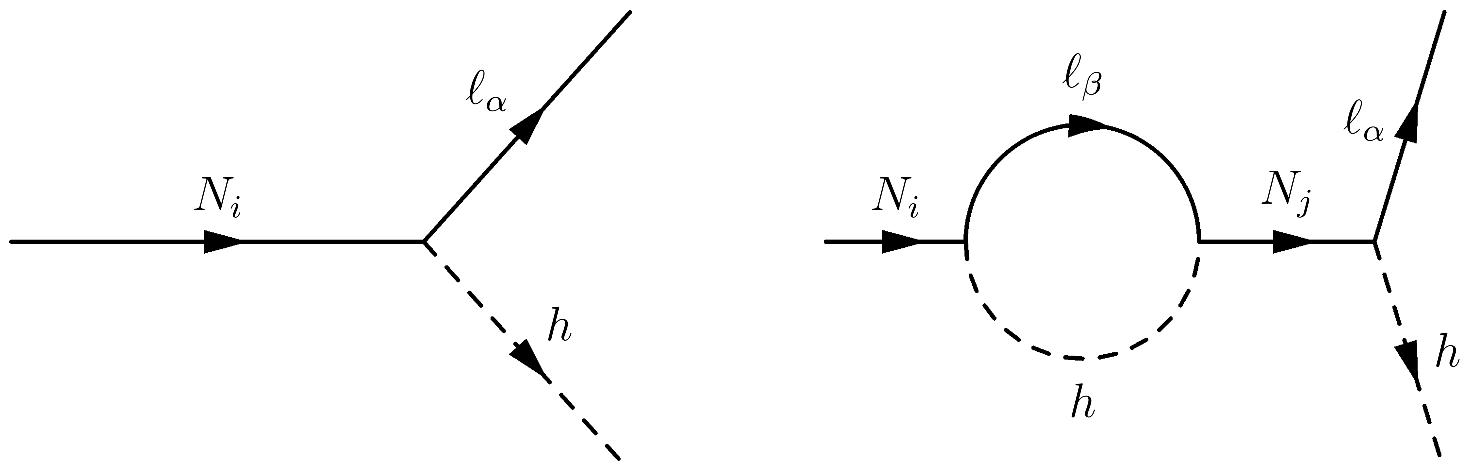
Total lepton number $L = L_{SM} + L_N$ conserved $\rightarrow$ $B - L$ conserved

2. The CP asymmetries

CP asymmetry produced in the decay of the Dirac neutrinos N_i into leptons of flavour α:

$$\epsilon_{\alpha i} \equiv \frac{\Gamma(N_i \to \ell_\alpha h) - \Gamma(\bar{N}_i \to \bar{\ell}_\alpha \bar{h})}{\sum_\alpha \Gamma(N_i \to \ell_\alpha h) + \Gamma(\bar{N}_i \to \bar{\ell}_\alpha \bar{h})} \,.$$

$\longrightarrow$ Only the self-energy diagram contributes at one loop:



(a) Tree (b) Wave function

$$\epsilon_{\alpha i} = \frac{-1}{8\pi(\lambda^\dagger\lambda)_{ii}} \sum_{j\neq i} \frac{a_j - 1}{(a_j-1)^2 + g_j^2} \mathrm{Im}\left[\lambda^*_{\alpha j}\lambda_{\alpha i}(\lambda^\dagger\lambda)_{ij}\right]$$

where $a_j \equiv M_j^2/M_i^2$, $g_j \equiv \Gamma_j/M_i$ and

$$\Gamma_i = \frac{M_i}{8\pi}(\lambda^\dagger\lambda)_{ii} \equiv \frac{1}{8\pi}\frac{\tilde{m}_i}{v^2}M_i^2$$

Covi et al. (1996)

It arises from lepton number conserving dimension 6 effective operator $\rightarrow$ not suppressed by small neutrino masses

Antusch et al. (2010)

- CP asymmetry supressed by $(M_i/M_j)^2$, instead of M_i/M_j for Majorana neutrinos

- Resonantly enhanced if $M_j - M_i \sim \Gamma_j$ by a factor $M_j/2\Gamma_j$

The total CP asymmetry exactly vanishes

$$\epsilon_i \equiv \sum_\alpha \epsilon_{\alpha i} = 0\,,$$

by CPT invariance and unitarity.

In terms of projection coefficients, $\lambda_{\alpha i} = \sqrt{K_{\alpha i}}\sqrt{(\lambda^\dagger\lambda)_{ii}}e^{i\phi_{\alpha i}}$

$$\epsilon_{\alpha i} = \frac{-1}{8\pi}\sum_{j\neq i}\frac{a_j-1}{(a_j-1)^2+g_j^2}(\lambda^\dagger\lambda)_{jj}\sqrt{K_{\alpha i}}\sqrt{K_{\alpha j}}\sum_{\beta\neq\alpha}\sqrt{K_{\beta i}}\sqrt{K_{\beta j}}\,p^{ij}_{\alpha\beta}\,,$$

where

$$p^{ij}_{\alpha\beta} = -p^{ij}_{\beta\alpha} = -p^{ji}_{\alpha\beta} = \sin(\phi_{\alpha i} - \phi_{\alpha j} + \phi_{\beta j} - \phi_{\beta i})$$

$$\epsilon^{res}_{\alpha i} = -\tfrac{1}{2}\sqrt{K_{\alpha i}}\sqrt{K_{\alpha j}}\sum_{\beta\neq\alpha}\sqrt{K_{\beta i}}\sqrt{K_{\beta j}}\,p^{ij}_{\alpha\beta}$$

3. Basic requirements for the generation of B

- Flavour effects

- Sphaleron departure from thermal equilibrium during the leptogenesis epoch

$\longrightarrow$ baryon asymmetry freezes at

$$Y_B \propto Y_{B-L_{SM}}(T = T_f) \neq 0$$

since $B - L_{SM} = 0$ after the heavy RH neutrinos disappear.

- M_1 and M_2 close to $T_f \rightarrow M_i \lesssim \mathcal{O}$(TeV)

4. Boltzmann equations

Evolution of the number densities $Y_X \equiv n_X/s$:

$Y_{\Delta_\alpha} \equiv Y_B/3 - Y_{L_\alpha}$

$Y_{N_i+\bar{N}_i} \equiv Y_{N_i} + Y_{\bar{N}_i}$

$Y_{N_i-\bar{N}_i} \equiv Y_{N_i} - Y_{\bar{N}_i} \to$ 0 for Majorana RH neutrinos.

- $\Delta L_{SM} = 2$ washout processes $\ell_\alpha h \to \bar{\ell}_\beta \bar{h}$, etc. absent, since total lepton number is perturbatively conserved

- Washout of the lepton asymmetries due to $\Delta L_{SM} = 0$ lepton flavour violating scatterings mediated by N_i, $\ell_\alpha h \to \ell_\beta h$, etc.and $\Delta L_{SM} = -\Delta L_N = \pm 1$ reactions with one external N_i.

- Since N_1 and N_2 have similar masses, they coexist during the leptogenesis era $\to$ we include both in the BEs.

- Strong lepton flavour violating washout due to N_2

Aristizabal et al. (2009)

- $B-L$ conservation + initial conditions $\rightarrow \sum_\alpha Y_{\Delta_\alpha} - \sum_i Y_{N_i - \bar{N}_i} = 0$
- For temperatures $M_W(T) \ll T \ll M_W(T)/\alpha_W$,

$$\Gamma_{\Delta(B+L)} \sim M_W((M_W(T)/\alpha_W T)^3 (M_W(T)/T)^3 \exp[-E_{sp}/T]$$

Arnold and McLerran (1987); Pilaftsis and Underwood (2005)

$\alpha_W \rightarrow SU(2)_L$ fine structure constant,

$M_W(T) = gv(T)/\sqrt{2}$

sphaleron energy $\rightarrow$

$E_{sp} \sim M_W(T)/\alpha_W$

$\rightarrow$ the lepton asymmetry is not converted into baryon asymmetry below T_f, for which $\Gamma_{\Delta(B+L)}(T_f)/H(T_f) \leq 1$.

For $T_c > T > T_f$:

$$Y_B(T) = 4\frac{77T^2+54v(T)^2}{869T^2+666v(T)^2}\sum_\alpha Y_{\Delta_\alpha}(T)$$

with $v(T) = v\left(1 - \frac{T^2}{T_c}\right)^{\frac{1}{2}}$

and

$$T_c = v\left(\frac{1}{4} + \frac{{g'}^2}{16\lambda} + \frac{3g^2}{16\lambda} + \frac{\lambda_t}{4\lambda}\right)^{-\frac{1}{2}}$$

Harvey and Turner (1990); Laine and Shaposhnikov (2000)

5. Results

Resonant case → mechanism works in a wide range of the parameter space

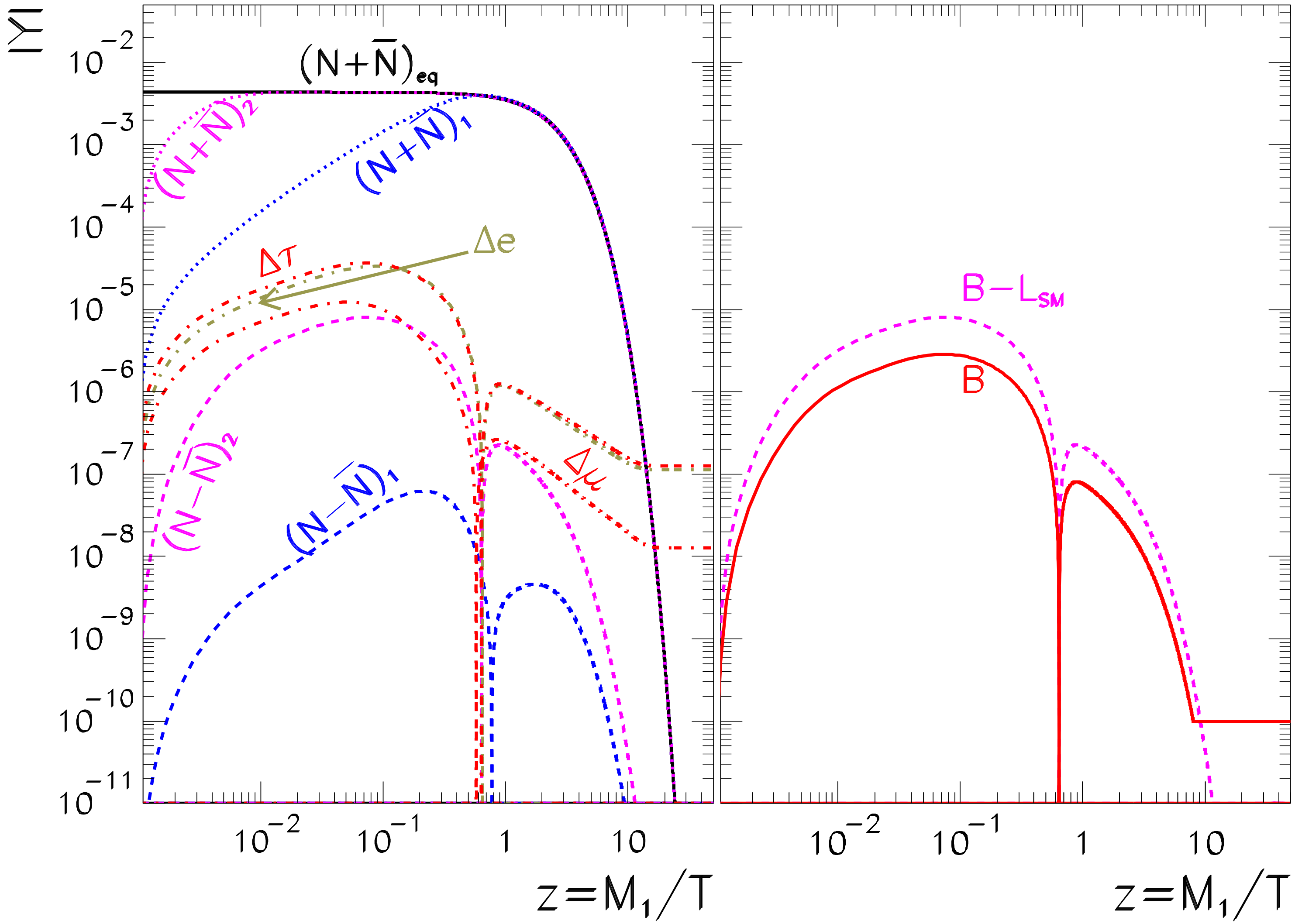
$$M_1 = 800 \text{ GeV} , \quad M_2 = M_1 + \frac{\Gamma_{N_2}}{2}$$

$$(\lambda^\dagger \lambda)_{11} = 10^{-12} , \quad (\lambda^\dagger \lambda)_{22} = 10^{-10}$$

$$K_{e1} = 0.3, \quad K_{\mu 1} = 0.3, \quad K_{\tau 1} = 0.4$$

$$K_{e2} = 0.1, \quad K_{\mu 2} = 0.1, \quad K_{\tau 2} = 0.8$$

$$p^{12}_{e\mu} = p^{12}_{e\tau} = p^{12}_{\mu\tau} = 1$$



|Y|
$(N+\bar{N})_{eq}$
$(N+\bar{N})_2$
$(N+\bar{N})_1$
Δe
$\Delta\tau$
$\Delta\mu$
$(N-\bar{N})_2$
$(N-\bar{N})_1$
B−L_{SM}
B
$z=M_1/T$
$z=M_1/T$

Non resonant case:

$\rightarrow$ at least one large N_2 Yukawa, $\lambda_{\alpha 2} \lesssim \lambda_\tau \sim 10^{-2}$, to have flavour effects

Blanchet et al. (2007)

$\rightarrow$ Experimental bounds from weak universality, lepton flavour violation processes and collider signatures $|(\lambda^\dagger \lambda)_{22}| \lesssim 5 \times 10^{-3} (M_2/v)^2$.

Antusch et al. (2006,2009)

$\rightarrow$ one N_2 Yukawa very small, to avoid washout in that flavour $K_{\alpha 2} \ll 1$

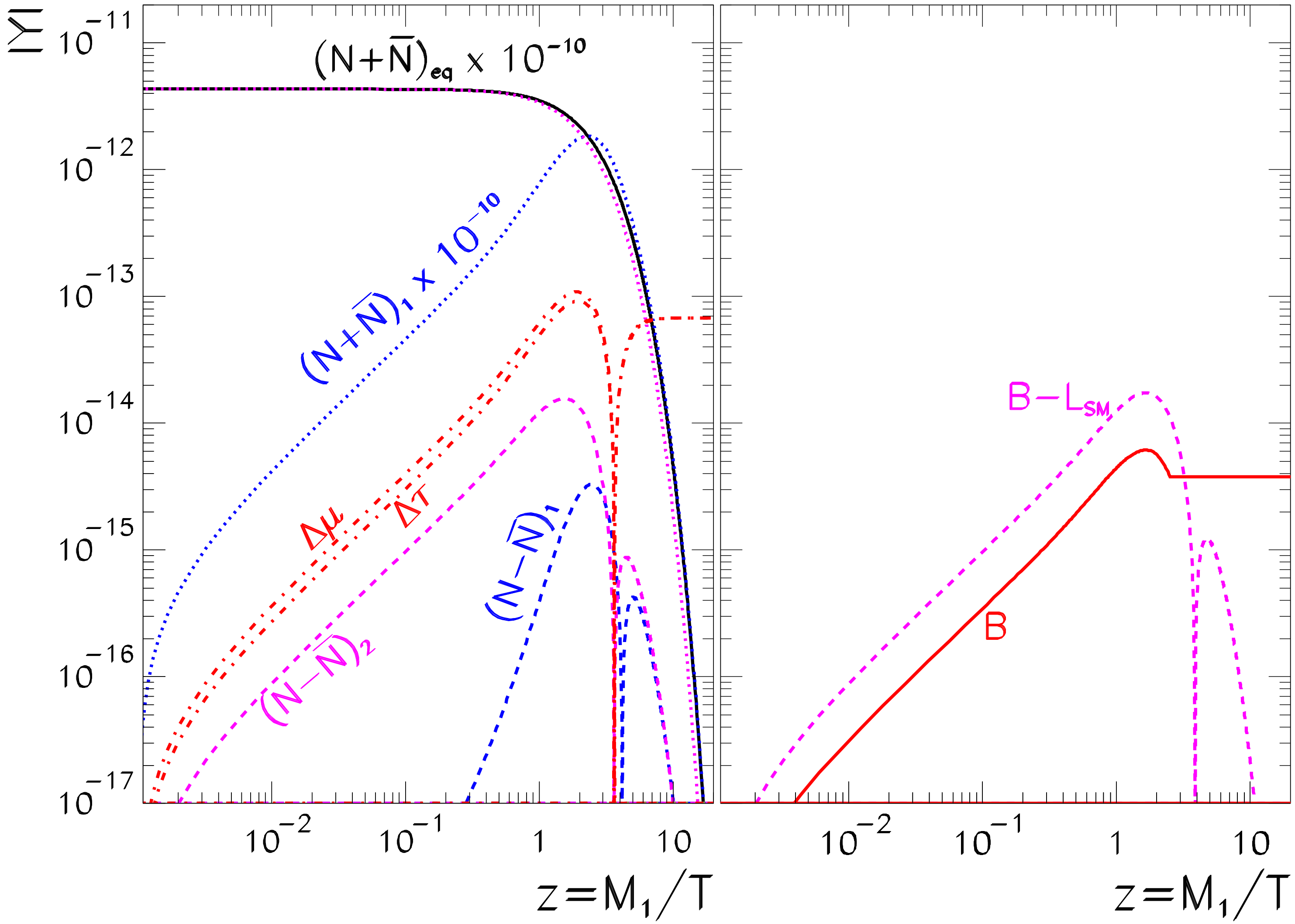
$M_1 = 250$ GeV, $\quad M_2 = 275$ GeV

$(\lambda^\dagger \lambda)_{11} = 8.2 \times 10^{-15}$ $(\tilde{m}_1 = 10^{-3}$ eV$) \quad (\lambda^\dagger \lambda)_{22} = 10^{-4}$

$K_{e1} = 0.\ , \quad K_{\mu 1} = 0.3\ , \quad K_{\tau 1} = 0.7$

$K_{e2} = 0.\ , \quad K_{\mu 2} = 10^{-10}\ , \quad K_{\tau 2} \simeq 1$

$p^{12}_{e\mu} = p^{12}_{e\tau} = p^{12}_{\mu\tau} = 1$



|Y|
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
$(N+\bar{N})_{eq} \times 10^{-10}$
$(N+\bar{N})_1 \times 10^{-10}$
$\Delta\mu$
ΔT
$(N-\bar{N})_1$
$(N-\bar{N})_2$
10^{-2}
10^{-1}
1
10
$z=M_1/T$
$B-L_{SM}$
B
10^{-2}
10^{-1}
1
10
$z=M_1/T$

$\rightarrow$ only works for $(M_2 - M_1)/M_1 \sim 2.4 \times 10^{-5} > \Gamma_2/M_1 = 4 \times 10^{-6}$

Reaction densities normalized to Hn_ℓ^{eq}