Flavoured leptogenesis

a successful thermal leptogenesis with m_{N_1} below 10^8 GeVs

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Leptogenesis

(single flavour approximation)

Baryon asymmetry: $\eta^B_{\rm CMB} = \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$

- Addition of $\nu_{\rm R}$ to the SM explains smallness of neutrino masses through Seesaw mechanism

$$\Rightarrow \qquad m_{\nu_L} = v^2 Y_\nu \cdot \frac{1}{M_{\nu_R}} \cdot Y_\nu^T$$

- L $(B-L)$ violation supplied by Majorana nature of ν_R, CP violation through complex Yukawa matrices, departure from thermal equilibrium at $T < M_{\nu_R}$, ν_R cannot follow eq. distribution.

$$\Gamma_{N_i} = \Gamma\left(N_i \to H l_L\right) + \Gamma\left(N_i \to H^\dagger l_L^\dagger\right) = \frac{1}{8\pi}\left(Y^\dagger Y\right)_{ii} M_i$$

$$\varepsilon_1 = \frac{3}{16\pi} \frac{1}{\left(Y^\dagger Y\right)_{11}} \sum_{i=2,3} \mathrm{Im}\left[\left(Y^\dagger Y\right)_{i1} \frac{M_1}{M_i} \left(Y^\dagger Y\right)_{i1}\right]$$

in basis M_R diagonal and with $M_1 \ll M_2, M_3$.

This CP asymmetry then leads to a $(B-L)$ asymmetry:

$$Y_{B-L} \simeq -Y_L = -\frac{n_L - n_{\overline{L}}}{s} = -\kappa \, \frac{\varepsilon_1}{g_*}$$

$s = 7.04\, n_\gamma$ entropy, $g_* = 106.75^{(SM)}$ number of d.o.f. in the plasma

$\kappa < 1$ washout processes $\longrightarrow$ solving the Boltzmann equations

Neutrinos out of TE when $\Gamma_1(T) < H(T)$:

$$\Longrightarrow \tilde{m}_1 \equiv v^2 \frac{\left(Y^\dagger Y\right)_{11}}{M_1} < m_* \equiv \frac{16\pi^{5/2}}{3\sqrt{5}} g_*^{1/2} \frac{v^2}{M_{\mathrm{Plank}}} \simeq 10^{-3}\mathrm{eV}$$

Baryon (lepton) asymmetry result of competition between production and washout processes.

- Defining the decay parameter $K = \frac{\Gamma_D(z=\infty)}{H(z=1)} = \frac{\tilde{m}_1}{m_*}$

the regimes of weak and strong washout correspond to $K \ll 1$ and $K \gg 1$

- Weak washout regime $(\tilde{m}_1 \ll m_*)$:

i) An initial lepton asymmetry is not washed away by N_1 (inverse) decays

ii) Few N_1 created by inverse decays and thus, if $Y^i_{N_1} = 0$, $\kappa_f(K) \simeq \frac{9\pi^2}{64} K^2$

- Strong washout regime $(\tilde{m}_1 \gg m_*)$:

i) $Y^i_{N_1}$ efficiently erased by N_1, independence of initial conditions

ii) $Y_{N_1}(z)$ follows closely the equilibrium distribution, approximately

the efficiency factor $\kappa_f \simeq (2 \pm 1) 10^{-2} \left(\frac{0.01\text{eV}}{\tilde{m}_1}\right)^{1.1\pm0.1}$

Standard Leptogenesis

- $m_{\rm Atm} \simeq 0.05$ eV and $m_{\rm Sol} \simeq 8\times 10^{-3}$ eV both $\gg m_*$

$\Rightarrow$ $\tilde{m}_1$ typically lies in the strong washout regime.

- $Y_{B-L} \simeq -Y_L = -\frac{\varepsilon_1}{g_*}(2\pm 1)10^{-2}\left(\frac{0.01\text{eV}}{\tilde{m}_1}\right)^{1.1\pm 0.1} \simeq 10^{-4}\ \varepsilon_1 \left(\frac{0.01\text{eV}}{\tilde{m}_1}\right)^{1.1\pm 0.1}$

- Sphalerons from 100 GeV $< T < 10^{12}$ GeV, convert the $(B-L)$ into a baryon asymmetry. $Y_B = \frac{24+4n_H}{66+13n_H}\ Y_{B-L} \simeq \frac{1}{3}\ Y_{B-L}$.

- Therefore, we clearly need a CP asymmetry at least $\varepsilon_1 \geq 10^{-6}$.

$$\varepsilon_1 = \frac{3}{16\pi}\ \frac{M_1}{\left(Y^\dagger Y\right)_{11}} \sum_{i=2,3} \text{Im}\left[\left(Y^\dagger Y\right)^2_{i1}\ \frac{1}{M_i}\right] = \frac{3}{16\pi}\ \frac{M_1}{\left(Y^\dagger Y\right)_{11}} \text{Im}\left[Y^T m_\nu^\dagger Y\right]_{11}$$

$$\Rightarrow \varepsilon_1 \lesssim \frac{3}{16\pi}\ \frac{M_1}{v^2}\left(m_3 - m_1\right) \simeq \frac{3}{16\pi}\ \frac{M_1\ m_{\rm Atm}}{v^2} \simeq 2\times 10^{-6}\left(\frac{M_1}{10^{10}\ \text{GeV}}\right)\left(\frac{m_{\rm Atm}}{0.05\ \text{eV}}\right).$$

ν_R in models of Yukawa unification

"Measured" left-handed neutrino masses and mixings:

$$m_\nu^{-1} = \frac{1}{\tilde{m}_1}\begin{pmatrix} \frac{1}{2} & -\frac{1}{2\sqrt{2}} & \frac{1}{2\sqrt{2}} \\ -\frac{1}{2\sqrt{2}} & \frac{1}{4} & -\frac{1}{4} \\ \frac{1}{2\sqrt{2}} & -\frac{1}{4} & \frac{1}{4} \end{pmatrix} + \frac{1}{\tilde{m}_2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \frac{1}{\tilde{m}_3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

Neglecting left-handed mixings in Yukawa in the basis of diagonal $Y_\nu^\dagger Y_\nu$:

$$M_R = v_2^2 \, Y_\nu^T \cdot m_\nu^{-1} \cdot Y_\nu = \frac{v_2^2}{m_1}\begin{pmatrix} \left(\frac{1}{2}+x\right)\varepsilon^8 & -\frac{1}{2\sqrt{2}}\,\varepsilon^6 & \frac{1}{2\sqrt{2}}\,\varepsilon^4 \\ -\frac{1}{2\sqrt{2}}\,\varepsilon^6 & \left(\frac{y}{2}+\frac{1}{4}\right)\varepsilon^4 & \left(\frac{y}{2}-\frac{1}{4}\right)\varepsilon^2 \\ \frac{1}{2\sqrt{2}}\,\varepsilon^4 & \left(\frac{y}{2}-\frac{1}{4}\right)\varepsilon^2 & \left(\frac{y}{2}+\frac{1}{4}\right) \end{pmatrix}$$

ν_R eigenvalues $\Rightarrow$ $M_3 \simeq \frac{v_2^2}{4\, m_1}$, $M_2 \simeq \frac{v_2^2\,\varepsilon^4}{m_3} \simeq \frac{m_c^2}{m_3}$ and $M_1 \simeq \frac{2\, v_2^2\,\varepsilon^8}{m_2} \simeq \frac{2m_u^2}{m_2}$.

$$M_2 \simeq \frac{(1.4)^2}{5 \times 10^{-11}} = 3.9 \times 10^{10} \text{ GeV} \quad \text{and} \quad M_1 \simeq \frac{2\,(.004)^2}{8 \times 10^{-12}} = 4 \times 10^6 \text{ GeV}.$$

$\Rightarrow$

M_1 too light to generate enough baryon asymmetry !!!

What about ν_{R_2}??, Can this asymmetry survive ν_{R_1} whashout??

In this case, we have $\tilde{m}_1 = m_{\text{Sol}}$, $\Rightarrow K_1 = \frac{m_{\text{Sol}}}{m_*} \simeq 8$

$$\frac{d\,Y_{B-L}}{dz} = -\frac{1}{4} z^2 e^{-z} \sqrt{1 + \frac{\pi}{2} z}\; K_1\, Y_{B-L}$$

$$\Rightarrow Y_{B-L}^{\text{fin}} = Y_{B-L}^{\text{ini}}\; e^{-0.75 K_1} \simeq 0.0025\; Y_{B-L}^{\text{ini}}$$

But this is wrong!, because we are not taking into account **flavour**!!!

Flavoured Leptogenesis

Barbieri et al., NPB **575**, 61 (2000), Pilaftsis Underwood, PRD **72**, 113001 (2005)

Vives PRD **73**, 073006 (2006), Abada et al., JCAP 0604:004 (2006) , Nardi et al., JHEP 0601:164 (2006)

- Below 10^{12} (10^9) GeV, ν_{R_2} generates two (three) different asymmetries in the τ, and l (μ and e channels).

$$\varepsilon_2^a = \frac{1}{8\pi \ \left(Y^\dagger Y\right)_{22}} \left(\frac{3}{2}\frac{M_2}{M_3}\mathrm{Im}\left[Y_{a2}^* Y_{a3} Y_{k2}^* Y_{k3}\right] + \frac{M_1}{M_2}\mathrm{Im}\left[Y_{a2}^* Y_{a1} Y_{k2}^* Y_{k1}\right]\right)$$

$$\varepsilon_2^a \simeq \frac{3}{8\pi}\ \frac{M_2\ m_3}{v^2}\ \frac{|Y_{a2}|}{|Y_{32}|}\delta_\nu \Rightarrow \varepsilon_2^\tau \simeq 3\times 10^{-6}\left(\frac{M_2}{10^{10}\ \mathrm{GeV}}\right)$$

- Below M_2 the lepton asymmetries are $Y_i = Y_{\nu_2}\varepsilon_2^i \kappa(K_2^a)$

with $K_2^a = \dfrac{\tilde{m}_2^a}{m_*}$ $\qquad \tilde{m}_2^i = v^2 \dfrac{Y_{i2}Y_{i2}^*}{M_2}$

- After ν_{R_2} decay, Y_τ, Y_μ and Y_e are unchanged from $T \simeq M_2$ to $T \simeq M_1$.
- At $T \simeq M_1$ only interactions: $\nu_{R_1} \to H L_i$ can erase the Y_i lepton asymmetry.

Generically ν_{R_1} decays differently to different flavours.

- At M_1 we must calculate the washout independently for each channel:

$$\tilde{m}_1^e \simeq \frac{m_{\rm Sol}}{2} \qquad \tilde{m}_1^\mu \simeq \frac{m_{\rm Sol}}{4} \qquad \tilde{m}_1^\tau \simeq \frac{m_{\rm Sol}}{4}$$

$$\Rightarrow K_1^e = \frac{m_{\rm Sol}}{2 m_*} \simeq 4 \qquad K_1^\mu \simeq K_1^\tau = \frac{m_{\rm Sol}}{4 m_*} \simeq 2$$

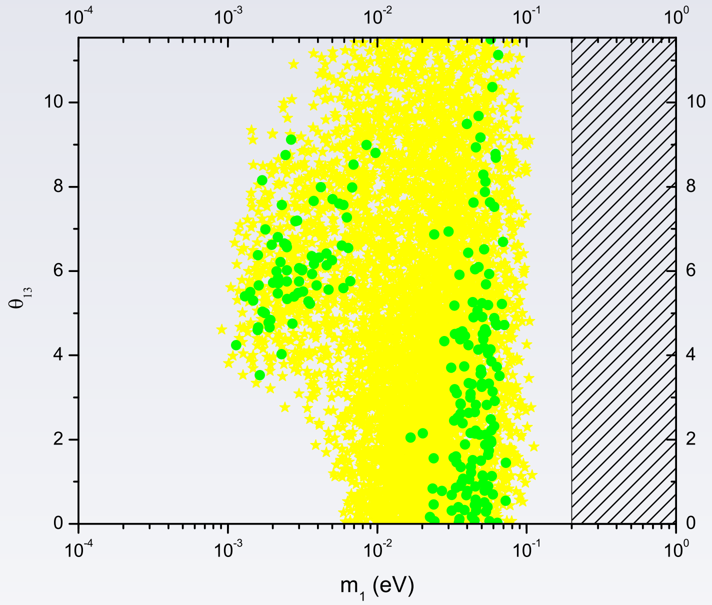
- In this case the washout from the lightest neutrino is exponential!

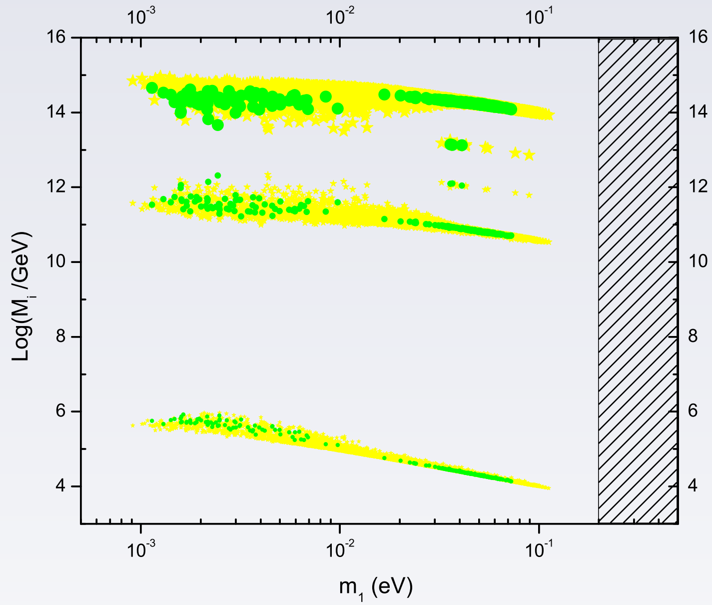
and the final asymmetry in the τ channel only washed out a factor of 0.22 !!!!!

$\Rightarrow$ Flavour effects change the result by orders of magnitude!!

Full computation under these conditions

Pascuale Di Bari and Antonio Riotto, arXiv:0809.2285





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Successful leptogenesis possible for $M_2 \gtrsim 10^{10.5}$ GeV

and $m_1 \gtrsim 10^{-3}$ eV $(M_3/M_2 > 10$, hierarchical ν_R spectrum)