Resonant Leptogenesis

(and large flavour effects)

Tom Underwood

with Apostolos Pilaftsis

PRD**72** 113001 (2005); NPB**692** 303-345 (2004).

Durham University

Outline

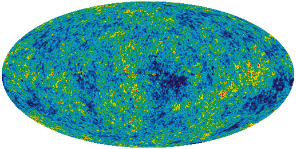
- Resonant Leptogenesis
  - Enhancement of the CP-asymmetry in the decays of heavy Majorana neutrinos
- Large Flavour Effects
  - Significant effects of relaxing the one flavour approximation – especially in resonant leptogenesis
- An example with interesting phenomenology
  - Resonant-τ-leptogenesis

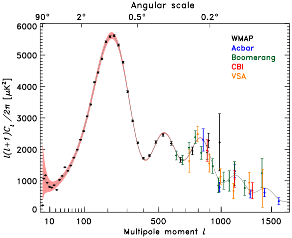
Outline

- Resonant Leptogenesis
- Large Flavour Effects
- Phenomenologically interesting example

We know the Universe possesses a baryon - antibaryon asymmetry and the baryon abundance has now been "measured" reasonably well:

- using cosmic microwave background (+ large scale structure) measurements

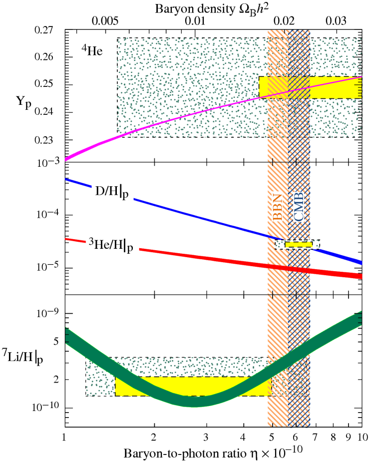




D. N. Spergel *et al.* [WMAP Collaboration], ApJS**148**(2003)175

$$\frac{n_B}{n_\gamma} \equiv \eta = (6.14 \pm 0.25) \times 10^{-10}$$

- using measurements of the primordial abundances of the light elements and calculations of their synthesis

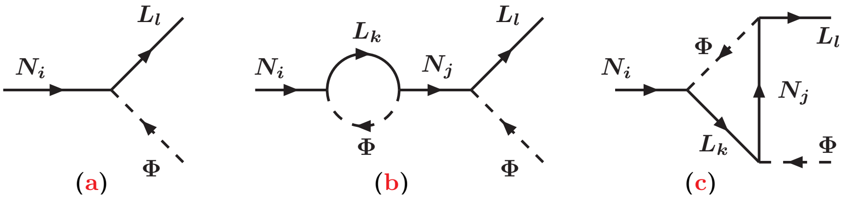


$$4.7 \leq (\eta \times 10^{10}) \leq 6.5 \quad (95\,\%\,\text{C.L.})$$

In remarkable agreement with the CMB determination

B. Fields and S. Sarkar, astro-ph/0601514

Resonant Leptogenesis



- If $M_i - M_j \ll M_i$ then the self-energy (a)(b) contribution to the CP-asymmetry becomes dominant.
- If $M_i - M_j \sim \Gamma_i$ then the CP-asymmetry can become very large, even $\mathcal{O}(1)$.

For 2 nearly degenerate heavy neutrinos, in the limit $m_{N_i} - m_{N_j} \ll m_{N_i}$, the ε-type contribution dominates and is given by

$$\varepsilon_{N_i} = \frac{\mathrm{Im}(h^{\nu\dagger}\, h^{\nu})^2_{ij}}{(h^{\nu\dagger}\, h^{\nu})_{ii}(h^{\nu\dagger}\, h^{\nu})_{jj}} \, \frac{(m^2_{N_i} - m^2_{N_j}) m_{N_i} \Gamma^{(0)}_{N_j}}{(m^2_{N_i} - m^2_{N_j})^2 + m^2_{N_i} \Gamma^{(0)\,2}_{N_j}}$$

CP asymmetries of order 1 are possible when

$$m_{N_2} - m_{N_1} \sim \frac{1}{2}\, \Gamma^{(0)}_{N_{1,2}} \,, \qquad \frac{\mathrm{Im}(h^{\nu\dagger}\, h^{\nu})^2_{ij}}{(h^{\nu\dagger}\, h^{\nu})_{ii}(h^{\nu\dagger}\, h^{\nu})_{jj}} \sim 1$$

[A. Pilaftsis PRD**56**(1997)5431]

For 3 nearly degenerate heavy neutrinos, see [A. Pilaftsis, T.U., NPB**692** 303-345 (2004)]

Outline

- Resonant Leptogenesis
- Large Flavour Effects
- Phenomenologically interesting example

Large Flavour Effects

- $\frac{1}{3}B - L_l$ is exactly conserved in the SM
- In the early Universe lepton number is distributed amongst distinguishable lepton flavours and is created and destroyed by flavour dependent processes
- The dynamics of leptogenesis are sensitive to the neutrino Yukawa flavour structure
- The charged lepton Yukawa couplings distinguish between lepton flavours in the plasma
  - $T \gtrsim 10^{12}$ GeV no charged lepton Yukawas in equilibrium
  - $10^9 \lesssim T \lesssim 10^{12}$ GeV τ Yukawa in equilibrium
  - $10^5 \lesssim T \lesssim 10^9$ GeV τ and μ Yukawas in equilibrium
  - $T \lesssim 10^5$ GeV τ, μ and e Yukawas in equilibrium

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Other work on flavour and the dynamics of leptogenesis;

R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, hep-ph/9911315,

O. Vives, hep-ph/0512160,

A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0601083,

E. Nardi, Y. Nir, E. Roulet and J. Racker, hep-ph/0601084

A. Abada, S. Davidson, A. Ibarra, F. X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0605281,

S. Blanchet and P. Di Bari, hep-ph/0607330,

S. Blanchet, P. Di Bari and G. G. Raffelt, hep-ph/0611337,

T. Shindou and T. Yamashita, hep-ph/0703183.

- Why can flavour effects be much larger in resonant leptogenesis scenarios?

- $T \lesssim 10^5$ GeV the charged lepton Yukawa interections are all in equilibrium.
  - We should solve Boltzmann equations taking three distinguishable flavours into account.

$$\frac{dn_{L_l}}{dt} + 3H\, n_{L_l} = (n_N - n_N^{\rm eq})\delta_N^l \gamma^D + \ldots$$

- Consider the dynamics of one heavy neutrino
- $n_N - n_N^{\rm eq}$ controls the dynamics of leptogenesis
- if you increase the N_1 Yukawa coupling to some flavours n_N comes closer to equilibrium and the leptogenesis efficiency drops

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- $n_N - n_N^{\rm eq}$ controls the dynamics of leptogenesis
- if you increase the N_1 Yukawa coupling to some flavours n_N comes closer to equilibrium and the leptogenesis efficiency drops – it is difficult to generate and protect a single flavour asymmetry this way

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- Resonant Leptogenesis
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An example

Resonant τ-leptogenesis

$$-\mathcal{L}_{\rm mass} = \frac{1}{2}\sum_{i,j=1}^{3}\Big((\bar{\nu}_{iR})^C\,(M_S)_{ij}\,\nu_{jR} \,+\, \text{h.c.}\Big) + \sum_{i=e,\mu,\tau}\Big[\hat{h}^l_{ii}\,\bar{L}_i\,\Phi\,l_{iR} \,+\, \Big(\sum_{j=1}^{3} h^{\nu_R}_{ij}\,\bar{L}_i\,\tilde{\Phi}\,\nu_{jR} \,+\, \text{h.c.}\Big)\Big]$$

- Impose an SO(3) flavour symmetry on the ν_{Ri}

$$M_S = m_N\,\mathbf{1}_3 \,+\, \Delta M_S$$

  - leads to 3 nearly degenerate heavy neutrinos

[A. Pilaftsis, hep-ph/0408103, A.P., T.U., hep-ph/0506107]

An example

Resonant τ-leptogenesis

$$-\mathcal{L}_{\rm mass} = \frac{1}{2}\sum_{i,j=1}^{3}\Big((\bar{\nu}_{iR})^C\,(M_S)_{ij}\,\nu_{jR} + {\rm h.c.}\Big) + \sum_{i=e,\mu,\tau}\Big[\hat{h}^l_{ii}\,\bar{L}_i\,\Phi\,l_{iR} + \Big(\sum_{j=1}^{3} h^{\nu_R}_{ij}\,\bar{L}_i\,\tilde{\Phi}\,\nu_{jR} + {\rm h.c.}\Big)\Big]$$

- The remaining SO(3)$\times$U(1)$_{L_e}\times$U(1)$_{L_\mu}\times$U(1)$_{L_\tau}$ is explicitly broken by the neutrino Yukawas but we can leave a subgroup SO(2)$\simeq$U(1)$_l$ unbroken

$$Q(L_i) = Q(l_{iR}) = 1\,,\, Q(\nu_{1R}) = 0\,,\, Q\Big(\tfrac{\nu_{2R}+i\nu_{3R}}{\sqrt{2}}\Big) = -Q\Big(\tfrac{\nu_{2R}-i\nu_{3R}}{\sqrt{2}}\Big) = 1$$

- In the exact flavour symmetric limit, the light neutrinos are prevented from acquiring a mass

$$h^{\nu_R} = \begin{pmatrix} 0 & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ 0 & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ 0 & c\,e^{-i\pi/4} & c\,e^{i\pi/4} \end{pmatrix} + \delta h^{\nu_R}$$

- Small symmetry breaking terms ΔM_S and δh^{ν_R} will lead to small Majorana masses – these could be generated via the Froggatt-Nielsen mechanism for example.
  - They could also be generated through RG evolution.
- For this example, we restrict δh^{ν_R} to the form

$$\delta h^{\nu_R} = \begin{pmatrix} \varepsilon_e & 0 & 0 \\ \varepsilon_\mu & 0 & 0 \\ \varepsilon_\tau & 0 & 0 \end{pmatrix}$$

A numerical example consistent with light neutrino data

$$h^{\nu_R} = \begin{pmatrix} \varepsilon_e & a\, e^{-i\pi/4} & a\, e^{i\pi/4} \\ \varepsilon_\mu & b\, e^{-i\pi/4} & b\, e^{i\pi/4} \\ \varepsilon_\tau & c\, e^{-i\pi/4} & c\, e^{i\pi/4} \end{pmatrix}$$

- $m_N \sim 250\,\mathrm{GeV}$
- $|a| \sim |b| \sim 10^{-2}$ and $|c| \sim 10^{-6}$ to get accessible phenomenology whilst still protecting the τ-lepton flavour from washout.
- $|\varepsilon_e|$, $|\varepsilon_\mu|$, $|\varepsilon_\tau| \sim 10^{-6}$ and $\Delta M_S/m_N \sim 10^{-5}$ — 10^{-9}
- We place a “naturalness criterion” on the heavy and light neutrino spectra. No cancellations between 1-loop and tree induced contributions smaller than 1 part in 20.

We can solve "flavoured" Boltzmann equations

$$\frac{d\eta_{\Delta L_j}}{dz} =$$

$$\frac{z}{H(z=1)} \Bigg\{ \sum_{\alpha=1}^{3} \delta^{j}_{N_\alpha} \left(\frac{\eta_{N_\alpha}}{\eta^{\rm eq}_{N_\alpha}} - 1 \right) \sum_{k\,=\,e,\mu,\tau} \left(\Gamma^{D\ (\alpha k)} + \Gamma^{S\ (\alpha k)}_{\rm Yukawa} + \Gamma^{S\ (\alpha k)}_{\rm Gauge} \right)$$

$$- \frac{2}{3}\,\eta_{\Delta L_j} \Bigg[\sum_{\alpha=1}^{3} B^{j}_{N_\alpha} \left(\widetilde{\Gamma}^{D\ (\alpha j)} + \widetilde{\Gamma}^{S\ (\alpha j)}_{\rm Yukawa} + \widetilde{\Gamma}^{S\ (\alpha j)}_{\rm Gauge} + \Gamma^{W\ (\alpha j)}_{\rm Yukawa} + \Gamma^{W\ (\alpha j)}_{\rm Gauge} \right)$$

$$+ \sum_{k\,=\,e,\mu,\tau} \left(\Gamma^{\Delta L=2\ (jk)}_{\rm Yukawa} + \Gamma^{\Delta L=0\ (jk)}_{\rm Yukawa} \right) \Bigg]$$

$$- \frac{2}{3} \sum_{k\,=\,e,\mu,\tau} \eta_{\Delta L_k} \Bigg[\sum_{\alpha=1}^{3} \delta^{j}_{N_\alpha}\, \delta^{k}_{N_\alpha} \left(\Gamma^{W\ (\alpha k)}_{\rm Yukawa} + \Gamma^{W\ (\alpha k)}_{\rm Gauge} \right)$$

$$+ \Gamma^{\Delta L=2\ (kj)}_{\rm Yukawa} - \Gamma^{\Delta L=0\ (kj)}_{\rm Yukawa} \Bigg] \Bigg\}$$

$$\eta_X = n_X / n_\gamma\,, \quad z = m_{N_1}/T$$

Define a (flavoured) out-of-equilibrium parameter, $K^l_{N_\alpha}$

$$K^l_{N_\alpha} = \frac{\Gamma(N_\alpha \to L_l \Phi) + \Gamma(N_\alpha \to L_l^C \Phi^\dagger)}{H(T = m_{N_\alpha})}$$

An order of magnitude estimate of the baryon asymmetry, including flavour effects

$$\eta_B \sim -\, 10^{-2} \, \sum_{\alpha=1}^{3} \sum_{l} \delta^l_{N_\alpha} \, \frac{K^l_{N_\alpha}}{K_l \, K_{N_\alpha}}$$

valid for nearly degenerate heavy neutrinos & $K^l_{N_\alpha} \gtrsim 1$.

$$K_{N_\alpha} = \sum_{l=e,\mu,\tau} K^l_{N_\alpha} \,, \qquad K_l = \sum_{\alpha=1}^{3} K^l_{N_\alpha}$$

The flavoured K-factors illustrate why this scenario works:

$K^l_{N_\alpha}$		α 1	2	3
	e	1.0×10^{10}	1.0×10^{10}	25
l	μ	1.4×10^{9}	1.4×10^{9}	20
	τ	2.5	2.5	5.0

One heavy neutrino decays sufficiently out of equilibrium, one flavour is protected from wash-out.

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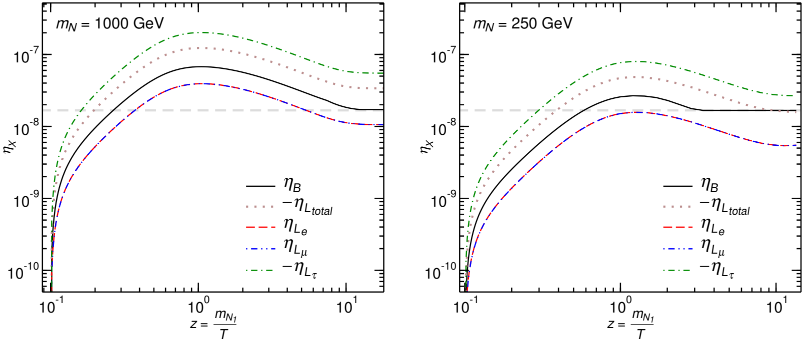
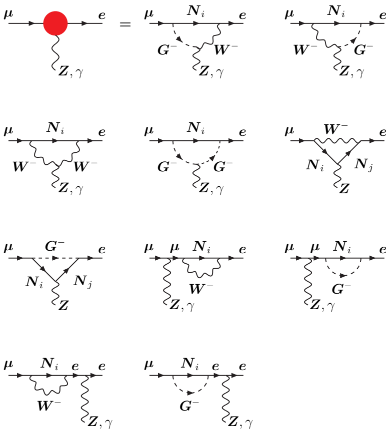


The predicted evolution of η_{L_l} and η_B for models based on $m_N = 1 \text{ TeV}$ and $m_N = 250 \text{ GeV}$.
The scenarios are scaled such that $a/m_N^{\frac{1}{2}} = 6 \times 10^{-4} \text{ GeV}^{-\frac{1}{2}}$.

Lepton Flavour Violation



Heavy Majorana neutrinos can induce lepton flavour violating couplings involving the γ and Z.

In the τ-leptogenesis scenario, these couplings give rise to the decays $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$.
They can also induce coherent $\mu \rightarrow e$ conversion in nuclei.

$\mu \longrightarrow e\gamma$

For two nearly degenerate heavy neutrinos where $m_N^2 \gg M_W^2$, using the $m_N = 250\ \mathrm{GeV}$ example:

$\mu \longrightarrow e\gamma$

$$B(\mu \to e\gamma) \;=\; \frac{\alpha_w^3 s_w^2}{256\pi^2} \frac{m_\mu^4}{M_W^4} \frac{m_\mu}{\Gamma_\mu} |G_\gamma^{\mu e}|^2 \;\approx\; 7 \cdot 10^{-4} \times \frac{|a|^2\,|b|^2\,v^4}{m_N^4}$$

$$\approx\; 1 \times 10^{-12}$$

This is well within reach of the experiment proposed by the MEG collaboration, which will be sensitive to $B(\mu \to e\gamma) \sim 10^{-14}$

$\mu \longrightarrow e$ conversion

For ${}^{48}_{22}\mathrm{Ti}$, and the $m_N = 250\ \mathrm{GeV}$ example:

$\mu \longrightarrow e$ conversion

$$\begin{aligned} B_{\mu e}(26,22) &\simeq 0.5 \times B(\mu \to e\gamma) \\ &\simeq 4.5 \times 10^{-13} \end{aligned}$$

This is just below the present experimental bound, and well within the reach of the experiment proposed by the MECO and PRIME collaborations (sensitive to $B_{\mu e}(26,22) \sim 10^{-16}$).

Summary

- Nearly degenerate heavy neutrinos lead to large CP-asymmetries in the decays of heavy neutrinos – Resonant Leptogenesis
    - Resonant leptogenesis possible with electroweak-scale heavy neutrinos
- Lepton flavour effects can greatly affect the dynamics of resonant leptogenesis scenarios
- These effects can be exploited to build models with a considerable amount of heavy neutrino related phenomenology e.g. lepton flavour violating decays