

Resonant Leptogenesis

(and large flavour effects)

Tom Underwood

with Apostolos Pilaftsis

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



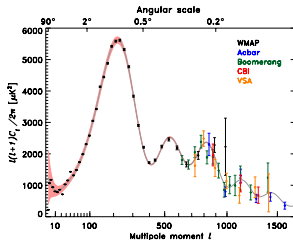
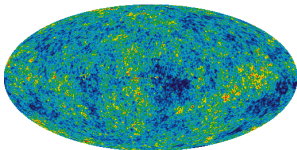
- **Resonant Leptogenesis**
 - Enhancement of the CP-asymmetry in the decays of heavy Majorana neutrinos
- **Large Flavour Effects**
 - Significant effects of relaxing the one flavour approximation – especially in resonant leptogenesis
- **An example with interesting phenomenology**
 - Resonant- τ -leptogenesis

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:

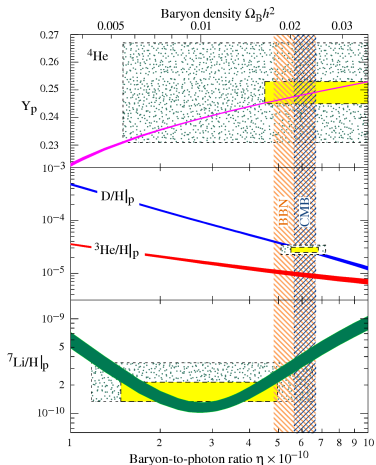
- using cosmic microwave background (+ large scale structure) measurements



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

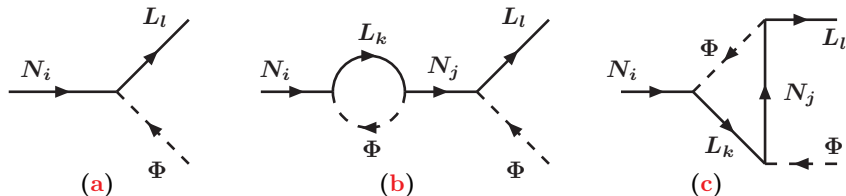


$$4.7 \leq (\eta \times 10^{10}) \leq 6.5 \quad (95\% \text{ C.L.})$$

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

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

CP asymmetries of order 1 are possible when

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

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

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

- Consider the dynamics of **one** heavy neutrino
- $n_N - n_N^{\text{eq}}$ 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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- 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
- Large Flavour Effects
- **Phenomenologically interesting example**

An example

Resonant τ -leptogenesis

$$\begin{aligned}
 -\mathcal{L}_{\text{mass}} = & \frac{1}{2} \sum_{i,j=1}^3 \left((\bar{\nu}_{iR})^C (M_S)_{ij} \nu_{jR} + \text{h.c.} \right) \\
 & + \sum_{i=e,\mu,\tau} \left[\hat{h}_{ii}^l \bar{L}_i \Phi l_{iR} + \left(\sum_{j=1}^3 h_{ij}^{\nu R} \bar{L}_i \tilde{\Phi} \nu_{jR} + \text{h.c.} \right) \right]
 \end{aligned}$$

- 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]

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 \end{aligned}$$

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

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

- 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

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

- $m_N \sim 250 \text{ GeV}$
- $|a| \sim |b| \sim 10^{-2}$ 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

$$\begin{aligned}
 \frac{d\eta_{\Delta L_j}}{dz} = & \\
 \frac{z}{H(z=1)} & \left\{ \sum_{\alpha=1}^3 \delta_{N_\alpha}^j \left(\frac{\eta_{N_\alpha}}{\eta_{N_\alpha}^{\text{eq}}} - 1 \right) \sum_{k=e,\mu,\tau} \left(\Gamma^{D(\alpha k)} + \Gamma_{\text{Yukawa}}^{S(\alpha k)} + \Gamma_{\text{Gauge}}^{S(\alpha k)} \right) \right. \\
 - \frac{2}{3} \eta_{\Delta L_j} & \left[\sum_{\alpha=1}^3 B_{N_\alpha}^j \left(\tilde{\Gamma}^{D(\alpha j)} + \tilde{\Gamma}_{\text{Yukawa}}^{S(\alpha j)} + \tilde{\Gamma}_{\text{Gauge}}^{S(\alpha j)} + \Gamma_{\text{Yukawa}}^W(\alpha j) + \Gamma_{\text{Gauge}}^W(\alpha j) \right) \right. \\
 & \left. \left. + \sum_{k=e,\mu,\tau} \left(\Gamma_{\text{Yukawa}}^{\Delta L=2(jk)} + \Gamma_{\text{Yukawa}}^{\Delta L=0(jk)} \right) \right] \right. \\
 - \frac{2}{3} \sum_{k=e,\mu,\tau} \eta_{\Delta L_k} & \left[\sum_{\alpha=1}^3 \delta_{N_\alpha}^j \delta_{N_\alpha}^k \left(\Gamma_{\text{Yukawa}}^W(\alpha k) + \Gamma_{\text{Gauge}}^W(\alpha k) \right) \right. \\
 & \left. \left. + \Gamma_{\text{Yukawa}}^{\Delta L=2(kj)} - \Gamma_{\text{Yukawa}}^{\Delta L=0(kj)} \right] \right\}
 \end{aligned}$$

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

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

$$K_{N_\alpha}^l = \frac{\Gamma(N_\alpha \rightarrow L_l \Phi) + \Gamma(N_\alpha \rightarrow L_l^C \Phi^\dagger)}{H(T = m_{N_\alpha})}$$

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

$$\eta_B \sim -10^{-2} \sum_{\alpha=1}^3 \sum_l \delta_{N_\alpha}^l \frac{K_{N_\alpha}^l}{K_l K_{N_\alpha}}$$

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

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

The flavoured K -factors illustrate why this scenario works:

$K_{N_\alpha}^l$	1	α 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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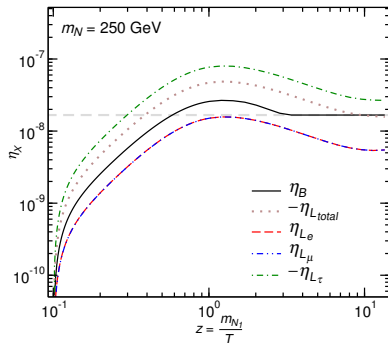
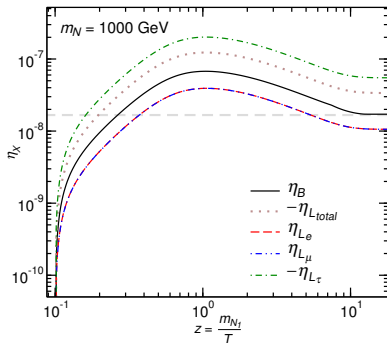
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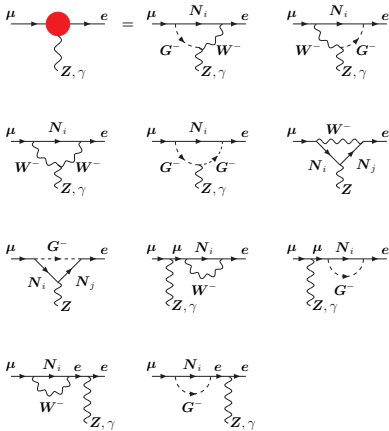
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The predicted evolution of η_{L_l} and η_B for models based on $m_N = 1 \text{ TeV}$ and $m_N = 250 \text{ GeV}$.

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.

$$\mu \rightarrow e\gamma$$

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

$$\mu \rightarrow e\gamma$$

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

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

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

$\mu \rightarrow e$ conversion

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

$\mu \rightarrow e$ conversion

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

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 $B_{\mu e}(26, 22) \sim 10^{-16}$).

- 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