Successful Leptogenesis in the Left-Right Symmetric Seesaw Mechanism

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P.H., S. Lavignac and C. Savoy, Nucl. Phys. B755, `arXiv:hep-ph/0606078`
A. Abada, P.H., F-X. Josse-Michaux and S. Lavignac, `arXiv:0711.xxxx`

Type I+II Seesaw Mechanism

The seesaw mechanism is usually realised through couplings of LH leptons to singlet RH neutrinos N_{Ri} (type I) or to an $SU(2)_L$ triplet Δ_L (type II). When both types are present, interactions are encoded into the following Yukawa potential:

$$Y_\nu \overline{N}_R l_L H + \frac{1}{2} M_R \overline{N}_R N_R^c + \frac{1}{2} f_L \bar{l}_L^c \Delta_L l_L - M_\Delta^2 \mathrm{Tr}(\Delta_L^\dagger \Delta_L) + \text{h.c.}$$

which provides a mass matrix for the light neutrinos :

$$\mathbf{m}_\nu = \mathbf{v_L f_L} - \mathbf{v^2 Y_\nu^T M_R^{-1} Y_\nu} \ll v$$

with $v_L = \langle \Delta_L^0 \rangle \sim v^2 / M_\Delta$.

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To reduce the number of parameters, let us consider theories with an extended gauge sector $SU(2)_L \times U(1)_Y \to SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and Left-Right Parity $SU(2)_L \leftrightarrow SU(2)_R$. M_R then comes from the vev of an $SU(2)_R$ triplet Δ_R: $\mathbf{M_R} = \mathbf{v_R f_R}$ and we can have the relations:

$$\mathbf{f_L} = \mathbf{f_R} = \mathbf{f}, \qquad Y_\nu = Y_\nu^T, \qquad v_L \sim \frac{v^2}{v_R}$$

Method of Reconstruction

The seesaw formula we are going to study is thus:

$$\mathbf{m}_\nu = \mathbf{v_L f} - \frac{\mathbf{v}^2}{\mathbf{v_R}}\mathbf{Y}_\nu \mathbf{f}^{-1}\mathbf{Y}_\nu \qquad \text{with } f \text{ and } Y_\nu \text{ symmetric}$$

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Using the symmetry of Y_ν, it can be put in the following simple form:

$$Z = \alpha X - \beta X^{-1}, \qquad \alpha = v_L, \quad \beta = \frac{v^2}{v_R}$$

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Since Z and X are symmetric, we can diagonalise them with the same complex orthogonal matrix: $Z = O_Z^T \hat{Z} O_Z$ and $O_X = O_Z$, translating the equation to the eigenvalues:

$$x_i^\pm = \frac{z_i \pm \sqrt{z_i^2 + 4\alpha\beta}}{2}$$

Thus, knowledge of $Y_\nu \Rightarrow$ **8 solutions for f** (Akhmedov-Frigerio) labeled by "$(+++)$","$(++-)$", etc...

SO(10) embedding

We apply this method to SUSY $SO(10)$ GUTs, which are a natural embedding of L-R symmetric theories: realisation of LR symmetric seesaw is made with a Higgs sector $\supset \mathbf{10_u} + \mathbf{10_d} + \mathbf{126} + \overline{\mathbf{126}} + \mathbf{54}$.

The relevant part of the superpotential is :

$$W \supset (Y_u)_{ij} 16_i 16_j 10_u + (Y_d)_{ij} 16_i 16_j 10_d + f_{ij} 16_i 16_j \overline{126}$$

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$$W \supset Y_u l_L N_R^c H_u + Y_d l_L e_R^c H_d + \frac{1}{2} f \, l_L \Delta_L l_L + \frac{1}{2} f \, l_R^c \Delta_R l_R^c$$

Moreover, $SO(10)$ gives the very useful relations : $\mathbf{Y}_\nu = \mathbf{Y_u}$ and $\mathbf{Y_e} = \mathbf{Y_d}$, fixing Y_ν from low energy parameters up to some complex phases.

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We consider a normal hierarchy ($m_1 = 10^{-3}$ eV), and our free parameters are :

- $\mathbf{v_R} \in [\mathbf{10^{12}}, \mathbf{10^{17}}]$ **GeV**
- $\mathbf{h} = \beta/\alpha = v_u^2/v_L v_R$ that we take $h = 0.1 - 1$
- **a dozen of phases**, remnants of the fact that we cannot rephase leptons and quarks independently in SO(10)

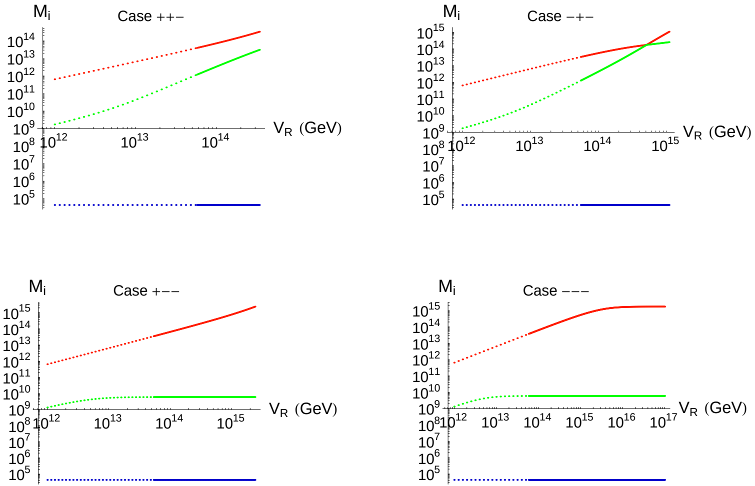
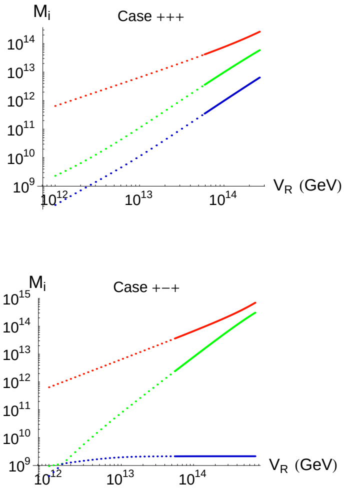


Figure: 4 different mass spectra of heavy neutrinos as function of v_R (dotted region contains fine-tuning in m_ν)



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Leptogenesis

When the RH neutrino spectrum is hierarchical the CP asymmetry from N_1 decays in the early Universe is, **in the one flavour approximation**:

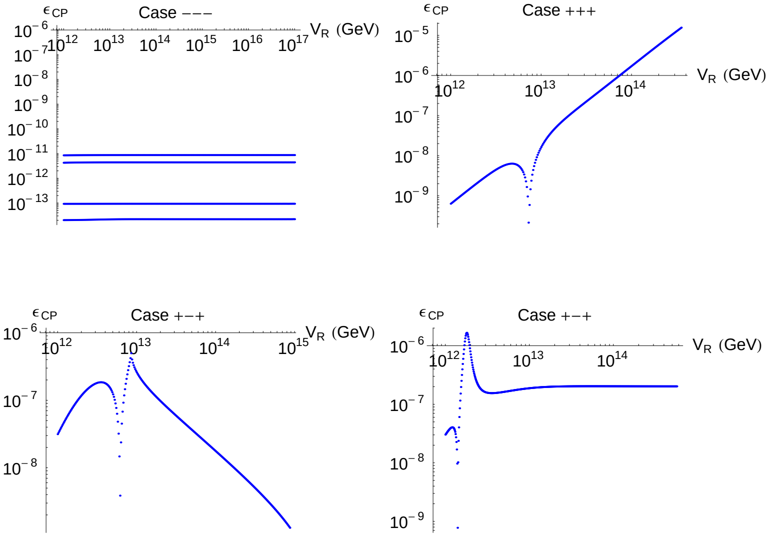
$$\varepsilon_1 \simeq \frac{3}{8\pi} \frac{\mathrm{Im}[Y m_\nu^* Y^T]_{11}}{(YY^\dagger)_{11}} \frac{M_1}{v_u^2}$$

The baryon asymmetry is then given by :

$$y_B = -1.48 \times 10^{-3} \eta_1 \, \varepsilon_1 \simeq 8.7 \times 10^{-11} \quad \Longrightarrow \quad \varepsilon_1 \gtrsim 10^{-6}$$

where $\eta_1 \leq 1$ is the wash-out factor due to lepton number violating scatterings.

In type I theories where $Y_\nu \simeq Y_u$ is very hierarchical, $M_1 \sim 10^5$ GeV, burying the hopes for a succesful leptogenesis from N_1 decays $\Longrightarrow$ **interest of type I+II seesaw**.



$(\pm, -, +)$ are promising, but washout is often strong, we need to solve the Boltzmann equations.

Importance of Flavour Effects

Traditional leptogenesis considers that N_i decay into 1 flavour mainly. However it has been shown (Abada et al, Nir et al) that the washout can be quite different between the different flavours, for $T_{RH} \lesssim 10^{12} \tan^2 \beta$ (when y_τ is in equilibrium) :

$\varepsilon_1 = \sum_\alpha \varepsilon_{1\alpha}$ and $\kappa_1 = \sum_\alpha \kappa_{1\alpha}$ where $\alpha = e, \mu, \tau$ and :

$$y_B \sim 10^{-3} \sum_\alpha \eta_{1\alpha} \varepsilon_{1\alpha} \neq 10^{-3} \sum_\alpha \eta_{1\alpha} \sum_\beta \varepsilon_{1\beta}$$

$\Longrightarrow$ we can have $\kappa = \sum \kappa_{1\alpha}$ large, thus η_1 small, but one $\kappa_{1\alpha}$ small so that one flavour is weakly washed out $\eta_{1\alpha} \sim 1$.

Moreover, preexisting asymmetry from N_2 in flavour α can be preserved while N_1 is in the strong washout regime and all the asymmetry is exponentially washed out in the one flavour approximation (Vives, Shindou et al).

Importance of Flavour Effects

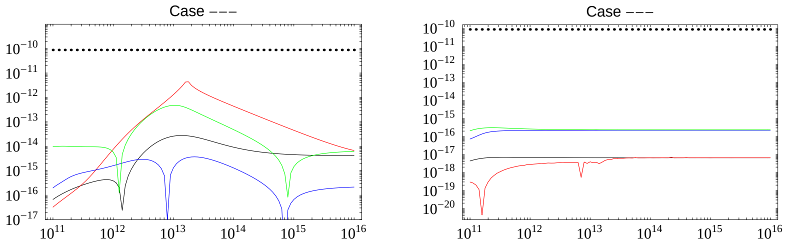


Figure: y_B for different choices of phases in the flavour framework (left) and the one flavour approximation (right)

In the one flavour approximation, when production of CP asymmetry from N_1 can be neglected :

$$Y'_{B-L}(z) = -\kappa_1 f(z) Y_{B-L}(z) \qquad \Rightarrow \qquad Y^{fin}_{B-L} \simeq Y^{ini}_{B-L} \exp\left(-3\pi/8 \times \kappa_1\right)$$

Here $\kappa_1 \gtrsim 10$ so that preexisting asymmetry can be suppressed by a factor up to $\sim 10^{-9}$

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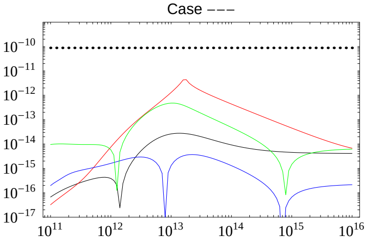

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In the flavour regime, the equation is split by flavour :

$$Y'_{\Delta_\alpha}(z) = -\kappa_\alpha f(z) \sum_\beta A_{\alpha\beta} Y_{\Delta_\beta} \qquad \Rightarrow \qquad Y_{B-L} \gtrsim Y^{ini}_{\Delta_\alpha} \exp\left(-3\pi/8 \times \kappa_\alpha\right)$$

and we have a mild but sufficient hierarchy in the washout parameters.

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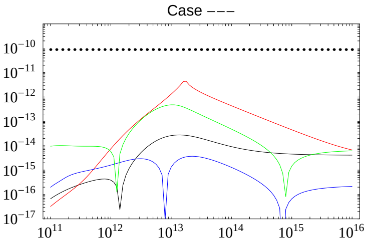

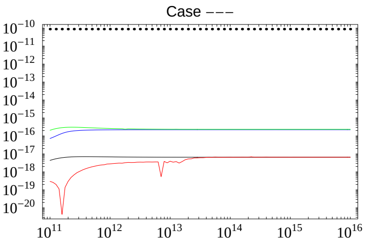

Figure: y_B for different choices of phases in the flavour framework (left) and the one flavour approximation (right)

$\Longrightarrow$ **N_2 decays have to be taken into account in the flavour case**, where some flavours are weakly washed out by N_1 decays.

Correction to $M_e = M_d$

For the moment we worked with the relations : $Y_e = Y_d$ and $Y_\nu = Y_u$. For a more realistic model we must add corrections.

This can be implemented in our SO(10) model by antisymmetric contributions from non-renormalisable operators $\frac{\mathbf{Y^{NR}_{ij}}}{\mathbf{\Lambda}} \mathbf{10_d.45.16_i.16_j}$:

$$M_e = v_d^{10} Y_{10} - 3 v_d^{10} Y_{120} \qquad M_d = v_d^{10} Y_{10} + v_d^{10} Y_{120}$$

and the second contribution is $Y_{120} = \frac{\langle 45 \rangle}{\Lambda} Y^{NR}$ with $\langle 45 \rangle \sim M_{GUT}$.

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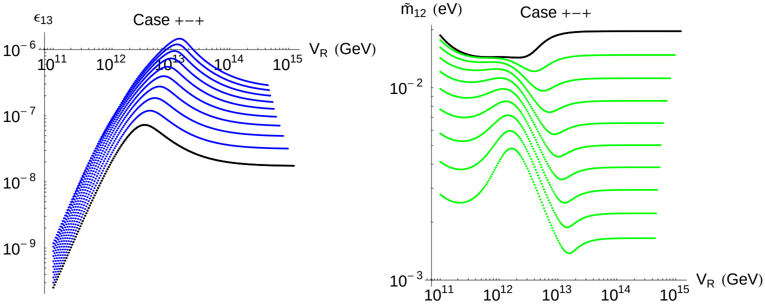
$\Longrightarrow$ consequence : Y_e and Y_d not diagonal in the same basis but still $Y_\nu = Y_u$:

$$Y_\nu = Y_u = U_m^T V_{CKM}^T \hat{Y}_u V_{CKM} U_m$$

U_m is a unitary matrix : 3 angles θ^m_{ij} and 6 phases.

Correction to $M_e = M_d$

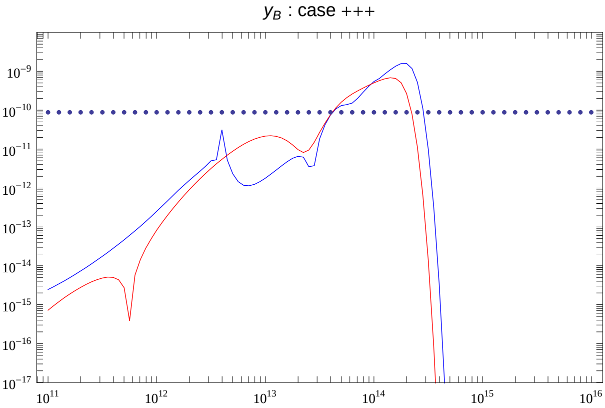
If we take a general U_m we can have non-negligible modifications. Here we take $\theta_{12}^m \in [0; \frac{\pi}{4}]$ and display the deformation of the curves $\varepsilon_{1,\tau}$ and $\tilde{m}_{1,\mu}$ as a function of v_R.



When fitting fermion masses we have some freedom on θ_{12}^m. We take as limiting cases two kinds of sets, with $\theta_{12}^m \simeq 0.2$ and $\theta_{12}^m \simeq 1$, and take **dynamical initial conditions** for the Boltzmann Equations.

Numerical results for y_B ($T_{in} = 10^{11}$ GeV)

Type II-like solutions $(\pm, +, +)$ can yield good values of y_B without any problem thanks to large values of M_1 at large v_R:



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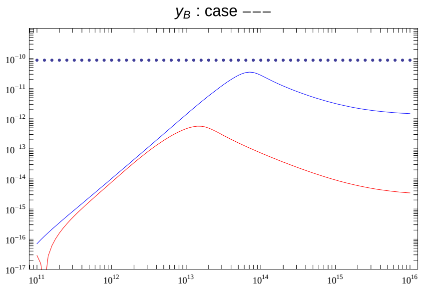
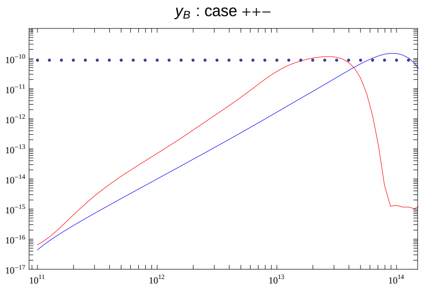
For cases $(\pm, \pm, -)$ with small M_1, experimental constraints are only reachable for the solutions with M_2 increasing with v_R. N_2 decays could be sufficient for $(-, -, -)$ but N_1 reduces by a factor $\gtrsim 10$.





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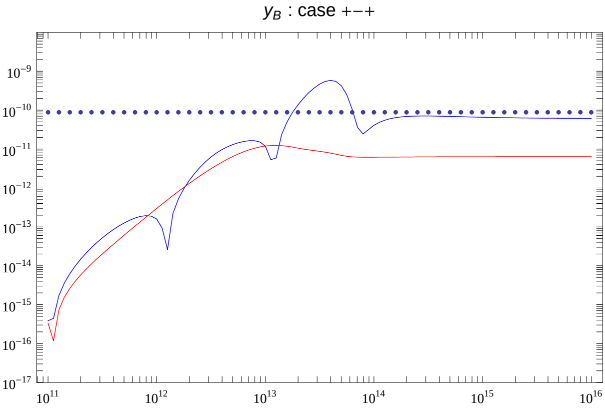
The interesting cases $(\pm, -, +)$ can yield sufficient baryon asymmetry thanks to $M_e = M_d$ corrections with the large θ_{12}^m fits.



Influence of other parameters

- **$\mathbf{T_{in}}$**: lowering T_{in} to **$\mathbf{10^{10}}$ GeV** to reduce tension with gravitino constraint in generic SUSY models eliminates any $(\pm, \pm, -)$ with $M_1 \sim 10^{10}$ GeV but preserves the others. $(\pm, +, +)$ with large M_1 become marginally allowed.

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- **θ_{13}**: large θ_{13} tends to lower y_B in some solutions, $\theta_{13} = 0$ is preferred.
- **$\mathbf{Y}_\nu = \mathbf{Y_u}$**: relaxing equality of the eigenvalues of Y_ν and Y_u can have important consequences since for $(\pm, -, +)$ for example, $M_1 \propto y_2^2 \Rightarrow$ allows fits with small θ_{12}^m to work, which is desirable since **large θ_{12}^m creates tensions with $\mu \to e\gamma$ experimental constraints**.

Conclusion

- We introduced a method for extracting the RH neutrinos mass matrix in the LR symmetric seesaw.
- We found several new solutions for the RH neutrino spectrum, in accordance with previous work $\Rightarrow$ new possibilities for successful leptogenesis in $SO(10)$ models.
- Flavour effects are crucial in some cases for N_2 leptogenesis to be efficient.
- Some solutions yield successful leptogenesis with a large $B - L$ breaking scale $\Rightarrow$ corrections for realistic fermion masses are preponderant.
- Order one deviations from $Y_\nu = Y_u$ can provide large enhancements and allow to avoid tensions with Lepton Flavour Violating constraints.