Flavours for leptogenesis

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Based on hep-ph/0605281, in collaboration with Asmaa Abada,

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(see also talk by Yossi Nir)

Rencontres du Vietnam

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Introduction

⋆ Neutrino masses can be described by adding a dimension five operator to the Standard Model lagrangian:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{1}{2}\kappa_{\alpha\beta}(\ell_\alpha \cdot H)^T(\ell_\beta \cdot H) + h.c.$$

Weinberg

so that after the electroweak symmetry breaking $\mathcal{M}_\nu = \kappa_{\alpha\beta} \langle H^0 \rangle^2$

What is the origin of the effective operator?

$\downarrow$

The see-saw mechanism

Minkowski
Gell-Mann, Ramond, Slansky
Yanagida
Mohapatra, Senjanovic

⋆ Add to the SM three right-handed neutrino fields

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \nu_R^{c\,T} \lambda\, \ell \cdot H - \frac{1}{2}\nu_R^{c\,T} \mathcal{M}\, \nu_R^c + h.c.$$

If $M_i \gg \langle H^0 \rangle$ the right-handed neutrinos decouple and the theory is well described by $\mathcal{L}_{eff}$ with

$$\boxed{\kappa_{\alpha\beta} = \lambda^T \mathcal{M}^{-1} \lambda}$$

Naturally suppressed!!

$\star$ EXTRA BONUS: natural mechanism to explain the baryon asymmetry of the Universe

$$Y_{\mathcal{B}} = \frac{(n_{\mathcal{B}} - n_{\bar{\mathcal{B}}})}{s} \simeq 9 \times 10^{-11}$$

LEPTOGENESIS

(Fukugita, Yanagida)

① Generation of RH-neutrinos

② Decay of RH-neutrinos at high T. This creates a lepton asymmetry

$$Y_{\mathcal{L}} = \frac{n_\ell - n_{\bar{\ell}}}{s} = \frac{n_{\nu_R} + n_{\tilde{\nu}_R}}{s} \epsilon_1 \, \kappa$$

$$\epsilon_1 = \frac{1}{8\pi} \sum_{j \neq 1} \frac{\mathrm{Im}\left[(\lambda\lambda^\dagger)_{j1}^2\right]}{(\lambda\lambda^\dagger)_{11}} g\left(\frac{M_j^2}{M_1^2}\right)$$

③ Conversion of a L-asymmetry into a B-asymmetry (sphaleron processes)

$$Y_{\mathcal{B}} = -\tfrac{28}{51} Y_{\mathcal{L}} \text{ (in the Standard Model)}$$

Is it justified to talk about <u>a</u> lepton asymmetry, when in fact there are <u>three</u> flavours? Yes, but only when $T \gtrsim 10^{12}$GeV.

Barbieri, Creminelli, Strumia, Tetradis
Fujihara,Kaneko, Kang, Kimura, Morozumi, Tanimoto
Nardi, Nir, Roulet, Racker
Abada, Davidson, Josse-Michaux,Losada, Riotto

When $T \lesssim 10^{12}$GeV (or $M_1 \lesssim 10^{12}$GeV) the one flavour description is **not** correct, and we have to deal with different flavour asymmetries, a set of flavoured Boltzmann equations, etc.

The reason is that when $T \lesssim 10^{12}$GeV charged lepton Yukawa interactions are in thermal equilibrium, and break the coherent evolution of the lepton doublets ℓ_i between $\not{L}$ interactions $\longrightarrow$ below $T \sim 10^{12}$GeV flavours are distinguishable.

Every leptonic flavour asymmetry evolves differently!!

The total lepton asymmetry in the one flavour approximation

$$Y_{\mathcal{L}} = \frac{n_{\nu_R} + n_{\tilde{\nu}_R}}{s}\,\epsilon_1\,\kappa = \frac{n_{\nu_R} + n_{\tilde{\nu}_R}}{s}\left(\epsilon_e + \epsilon_\mu + \epsilon_\tau\right)\left(\kappa_e + \kappa_\mu + \kappa_\tau\right)$$

has to be substituted by

$$Y_{\mathcal{L}} = \frac{n_{\nu_R} + n_{\tilde{\nu}_R}}{s}\left(\epsilon_e\,\kappa_e + \epsilon_\mu\,\kappa_\mu + \epsilon_\tau\,\kappa_\tau\right)$$

Furthermore, the equilibrium conditions for the asymmetries in the number densities are different depending on T. The relation $Y_{\mathcal{B}} = -\frac{28}{51} Y_{\mathcal{L}}$ also has to be modified.

Three regimes:

- $\boxed{T \lesssim 10^9 \mathrm{GeV}}$ Tau and muon Yukawa interactions are in equilibrium $\longrightarrow$ All the three flavours are distinguishable.

- $\boxed{10^9 \mathrm{GeV} \lesssim T \lesssim 10^{12} \mathrm{GeV}}$ Only the tau Yukawa interactions are in equilibrium $\longrightarrow$ tau is distinguishable, but μ and e aren't.

- $\boxed{T \gtrsim 10^{12} \mathrm{GeV}}$ No charged lepton Yukawa interactions are in equilibrium $\longrightarrow$ All the flavours are indistinguishable, and the one flavour approximation is valid.

$\boxed{T \lesssim 10^9 \mathrm{GeV}}$ Tau and muon Yukawa interactions are in equilibrium.

Three distinguishable flavours

★ Three different lepton asymmetries ($\alpha = e,\ \mu,\ \tau$):

$$\epsilon_\alpha \equiv \frac{\Gamma(\nu_{R_1}\to H\ell_\alpha)-\Gamma(\nu_{R_1}\to \bar H\bar\ell_\alpha)}{\sum_\alpha[\Gamma(\nu_{R_1}\to H\ell_\alpha)+\Gamma(\nu_{R_1}\to \bar H\bar\ell_\alpha)]} = \frac{1}{(8\pi)}\frac{1}{(\lambda\lambda^\dagger)_{11}}\sum_j \mathrm{Im}\left\{(\lambda_{1\alpha})(\lambda\lambda^\dagger)_{1j}\lambda^*_{j\alpha}\right\} g\left(\frac{M_j^2}{M_1^2}\right)$$

$$\left(\text{instead of } \epsilon_1 \equiv \frac{\sum_\alpha[\Gamma(\nu_{R_1}\to H\ell_\alpha)-\Gamma(\nu_{R_1}\to \bar H\bar\ell_\alpha)]}{\sum_\alpha[\Gamma(\nu_{R_1}\to H\ell_\alpha)+\Gamma(\nu_{R_1}\to \bar H\bar\ell_\alpha)]}\right)$$

★ Three different Boltzmann equations (instead of one)

$$Y'_\alpha = \epsilon_\alpha K z\,\frac{K_1(z)}{K_2(z)} f_1(z)\Delta_{N_1} - \frac{1}{2} z^3 K_1(z)\, f_2(z)\, K_\alpha Y_\alpha$$

★ Sphaleron processes yield

$$Y_{\mathcal{B}} = -\frac{12}{37}\left(\frac{40}{13}\,Y_e + \frac{51}{13}\,Y_\mu + \frac{51}{13}\,Y_\tau\right)$$

$$\left(\text{instead of } Y_{\mathcal{B}} = -\frac{28}{51} Y_{\mathcal{L}}\right)$$

$\boxed{10^9\mathrm{GeV} \lesssim T \lesssim 10^{12}\mathrm{GeV}}$ Only the τ Yukawa interactions are in equilibrium.

Two distinguishable flavours

(τ, and a combination of μ and e)

★ Two different lepton asymmetries ($\alpha = \tau$ and $\alpha = 2$, the combination of e and μ):

$$\epsilon_\alpha \equiv \frac{\Gamma(\nu_{R_1} \to H\ell_\alpha) - \Gamma(\nu_{R_1} \to \bar{H}\bar{\ell}_\alpha)}{\sum_\alpha [\Gamma(\nu_{R_1} \to H\ell_\alpha) + \Gamma(\nu_{R_1} \to \bar{H}\bar{\ell}_\alpha)]} = \frac{1}{(8\pi)} \frac{1}{(\lambda\lambda^\dagger)_{11}} \sum_j \mathrm{Im}\left\{(\lambda_{1\alpha})(\lambda\lambda^\dagger)_{1j}\lambda^*_{j\alpha}\right\} g\left(\frac{M_j^2}{M_1^2}\right)$$

$$\left(\text{instead of } \epsilon_1 \equiv \frac{\sum_\alpha [\Gamma(\nu_{R_1} \to H\ell_\alpha) - \Gamma(\nu_{R_1} \to \bar{H}\bar{\ell}_\alpha)]}{\sum_\alpha [\Gamma(\nu_{R_1} \to H\ell_\alpha) + \Gamma(\nu_{R_1} \to \bar{H}\bar{\ell}_\alpha)]}\right)$$

★ Three different Boltzmann equations (instead of one)

$$Y'_\alpha = \epsilon_\alpha K z \frac{K_1(z)}{K_2(z)} f_1(z) \Delta_{N_1} - \frac{1}{2} z^3 K_1(z)\, f_2(z)\, K_\alpha Y_\alpha$$

★ Sphaleron processes yield

$$Y_{\mathcal{B}} = -\frac{12}{37}\left(\frac{115}{36} Y_2 + \frac{37}{9} Y_\tau\right)$$

$$\left(\text{instead of } Y_{\mathcal{B}} = -\frac{28}{51} Y_{\mathcal{L}}\right)$$

The case of the see-saw model with two right-handed neutrinos:

an illustration of the impact of flavour on leptogenesis.

⋆ Observations tell us that at least two new mass scales have to be introduced (Δm^2_{sol}, Δm^2_{atm}). Two right-handed neutrinos can do the job.

⋆ At high-energies the model is defined by two right-handed neutrino masses and a 2×3 Yukawa matrix. In total, there are 8 real parameters and 3 phases. On the other hand, at low energies we can measure two masses, three mixing angles, and two phases. There is in the high-energy parameters an ambiguity of 3 real parameters and one phase, that can be expressed as:

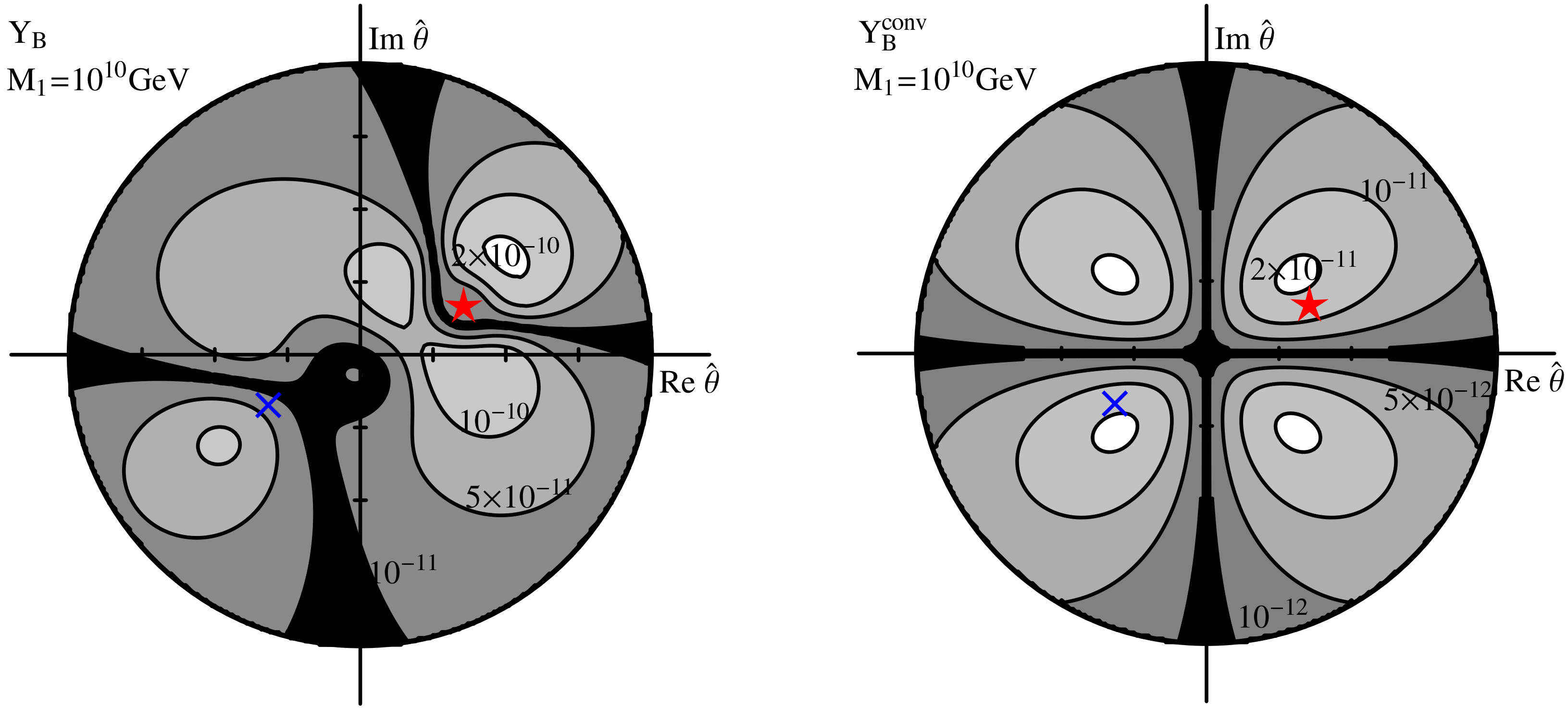
$$\boxed{\lambda = D_{\sqrt{\mathcal{M}}} R D_{\sqrt{m}} U^\dagger / \langle H^0 \rangle}$$

with

$$R = \begin{pmatrix} 0 & \cos\hat\theta & \xi \sin\hat\theta \\ 0 & -\sin\hat\theta & \xi\cos\hat\theta \end{pmatrix} \qquad R = \begin{pmatrix} \cos\hat\theta & \xi \sin\hat\theta & 0 \\ -\sin\hat\theta & \xi\cos\hat\theta & 0 \end{pmatrix}$$

normal hierarchy — inverted hierarchy

The ambiguity of the parameters at high energy is encoded in M_1, M_2, and $\hat\theta$.



normal hierarchy , $\theta_{13} = 0.1$, $\delta = \pi/4$, $\phi = \pi/3$

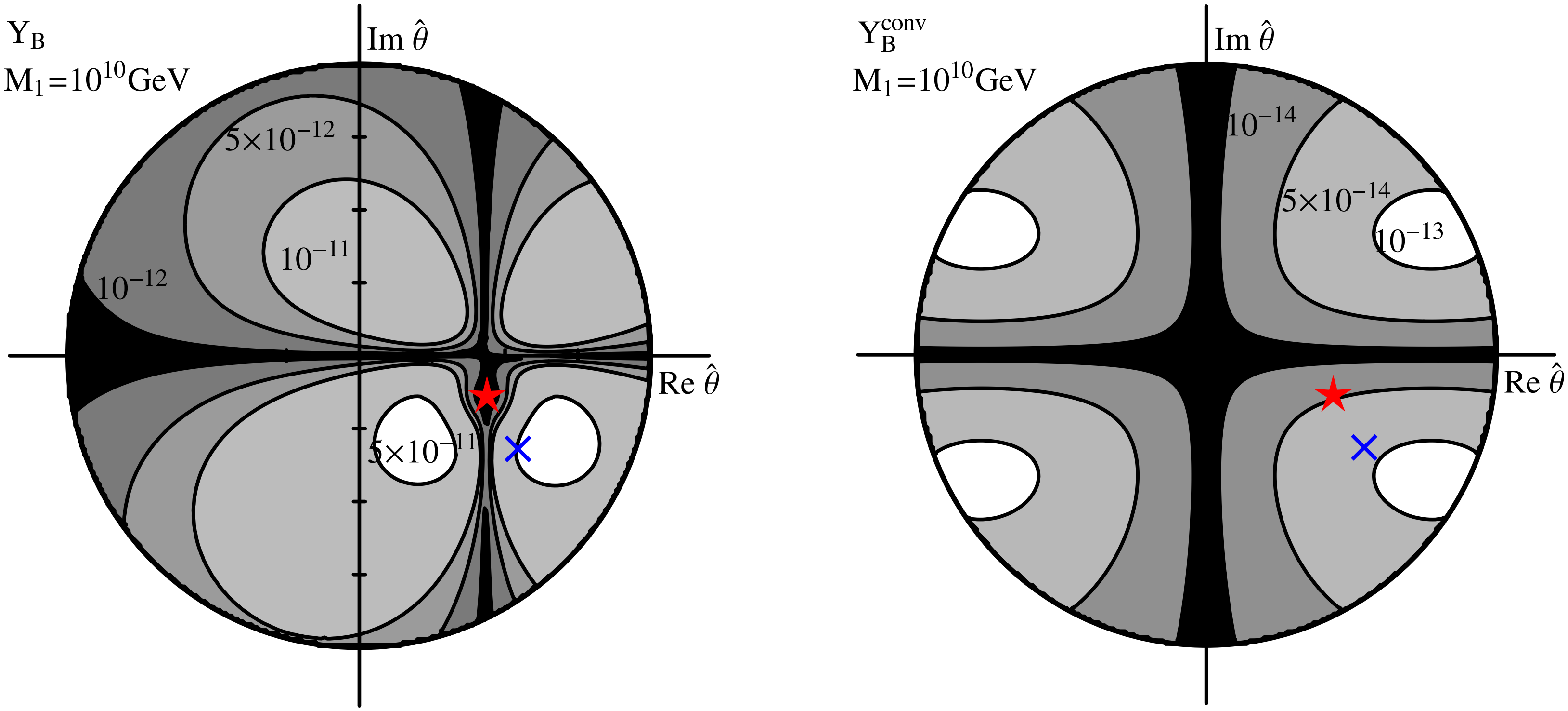
The differences are maximal:

- Along the axes: R is real or pure imaginary.

  In the one flavour approximation, $\epsilon_1 \propto \mathrm{Im} \sin^2 \hat\theta$

- Around texture zeros in the neutrino Yukawa matrix ★ $\lambda_{13} = 0$ × $\lambda_{12} = 0$

  The asymmetry in the corresponding flavour is only weakly washed-out



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Conclusions

⋆ The observation of neutrino masses gives strong support to leptogenesis as the mechanism to generate the baryon asymmetry of the Universe.

⋆ If leptogenesis occurs at $T \lesssim 10^{12}$GeV, a rigurous treatment of leptogenesis requires to include flavour effects.

⋆ The effect of flavour on leptogenesis is not only conceptually important, but also quantitavely important when computing predictions from particular models.