LEPTOGENESIS AND LOW ENERGY CP VIOLATION: A NEW PERSPECTIVE

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1 – Outline

- Leptonic Dirac and Majorana CP-violation
- The see-saw mechanism and leptogenesis
- Connection between Low energy and High energy (leptogenesis) CP-violation: flavour effects
- Conclusions

2 – Dirac and Majorana CPV phases

In the case of 3 neutrino mixing, U can be parametrized as

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i(\frac{\alpha_{31}}{2}+\delta)} \end{pmatrix}$$

- one universal CPV phase: $\boxed{\delta}$.

It enters both $\Delta L = 0$ and $\Delta L = 2$ processes.

- two Majorana CPV phases $\boxed{\alpha_{21}}$ and $\boxed{\alpha_{31}}$. They are physical

only if neutrinos are Majorana particles.

From probing

leptonic CP-violation at low energy,

which information

can we obtain

about the physics at high energy

and in particular about leptogenesis?

3 – The see-saw mechanism and Leptogenesis

The see-saw mechanism provides a natural explanation for the smallness of neutrino masses. [Minkovski; Yanagida; Gell-Mann, Ramond, Slansky; Glashow; Mohapatra, Senjanovic]

$$\mathcal{L} = (\nu_L^T N^T) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

At low energy, integrating out the heavy neutrinos, the light neutrino masses are naturally small.

$$m_2 \simeq \frac{m_D^2}{M_R} \sim \frac{1 \text{ GeV}^2}{10^9 \text{ GeV}} \sim 1 \text{ eV}$$

In a 3 neutrino mixing, light masses are given by:

$$m_\nu = U^* d_m U^\dagger \simeq -\lambda^T M_R^{-1} \lambda v^2$$

- Light neutrinos are predicted to be Majorana particles.

- The orthogonal parametrisation:

$\lambda = 1/v \sqrt{M}\, R\, \sqrt{m} U^\dagger$. [Casas, Ibarra]

where R is a complex orthogonal matrix.

Leptogenesis takes place in the context of see-saw models. The decays of N produce a lepton asymmetry, which is then converted into a baryon asymmetry. Leptogenesis can succesfully explain the observed baryon asymmetry of the Universe.

[Fukugita, Yanagida; Covi, Roulet, Vissani; Buchmuller, Plumacher]

It requires:

- out of equilibrium;
- L violation;
- C and CP violation.

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It requires:

- out of equilibrium;
- L violation; $(\beta\beta)_{0\nu}$-decay
- C and CP violation.

The one-flavour approximation

For high $T > 10^{12}$ GeV, charged leptons Yukawa interactions are out-of-equilibrium and **flavours are indistinguishable**.

The baryon asymmetry is given by:

$$\eta_B/s = C\eta_L/s \sim -10^{-4}\,\epsilon_1$$

ϵ_1 is the decay asymmetry which depends on the CPV phases in λ:

$$\epsilon_1 \equiv \frac{\Gamma\big(N\to lH\big) - \Gamma\big(N\to l^c H^c\big)}{\Gamma\big(N\to lH\big) + \Gamma\big(N\to l^c H^c\big)} \propto \sum_j \mathrm{Im}(\lambda\lambda^\dagger)^2_{1j}\frac{M_j}{M_1}$$

Taking flavour into account

At $T < 10^{12}$ GeV, the τ charged lepton is a distinguishable mass eigenstate. The asymmetries in the τ and $\mu + e$ flavours need to be considered separately. [Abada et al.; Nardi et al.; Di Bari et al.; See also Antush, Barbieri et al., Pilaftsis and Underwood; Anisimov et al., Endoh et al., Fujihara et al., Vives]

We take $M_1 \ll M_2 \ll M_3$ with $10^9 < M_1 < 10^{12}$ GeV.

The baryon asymmetry is given by:

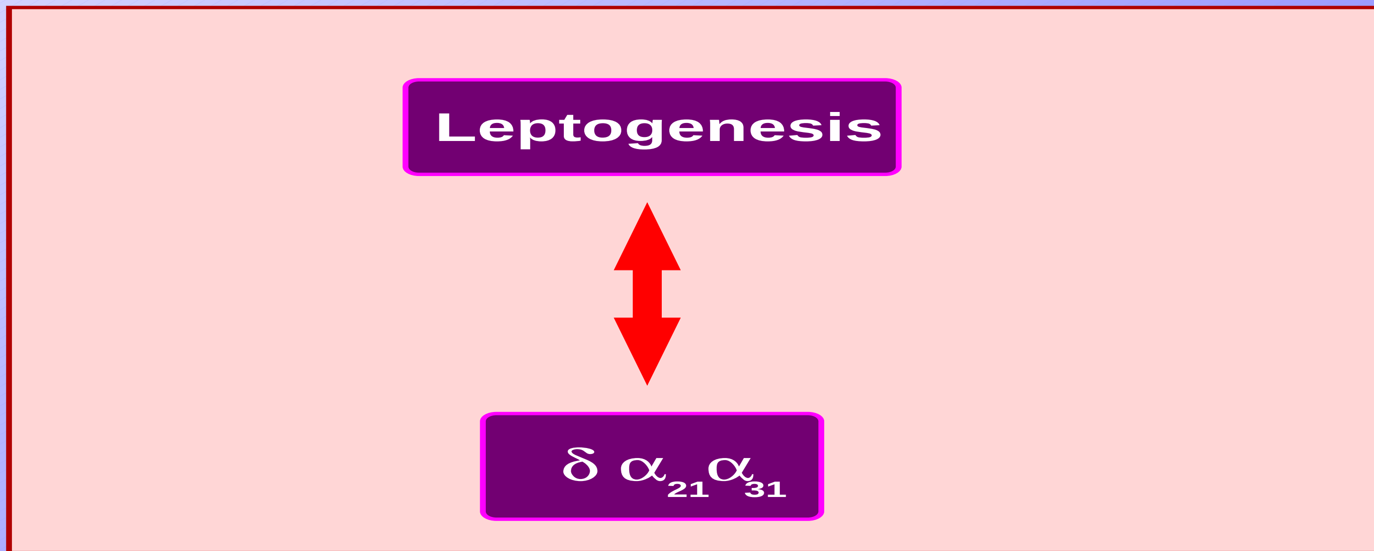
$$Y_B \simeq -\frac{12}{37 g_*} \left(\epsilon_\tau \eta \left(\frac{390}{589} \widetilde{m_\tau} \right) + \epsilon_2 \eta \left(\frac{417}{589} \widetilde{m_2} \right) \right)$$

- The flavour CP-asymmetry:

$$\epsilon_l \propto \frac{1}{(\lambda\lambda^\dagger)_{11}} \sum_j \mathrm{Im} \left(\lambda_{1l} (\lambda\lambda^\dagger)_{1j} \lambda^*_{jl} \right) \frac{M_1}{M_j}$$

- Flavour-dependent washout effects: $\widetilde{m_l} \equiv |\lambda_{1l}|^2 \, v^2 / M_1$

4 – Is there a connection between CP-V at low energy and in leptogenesis?



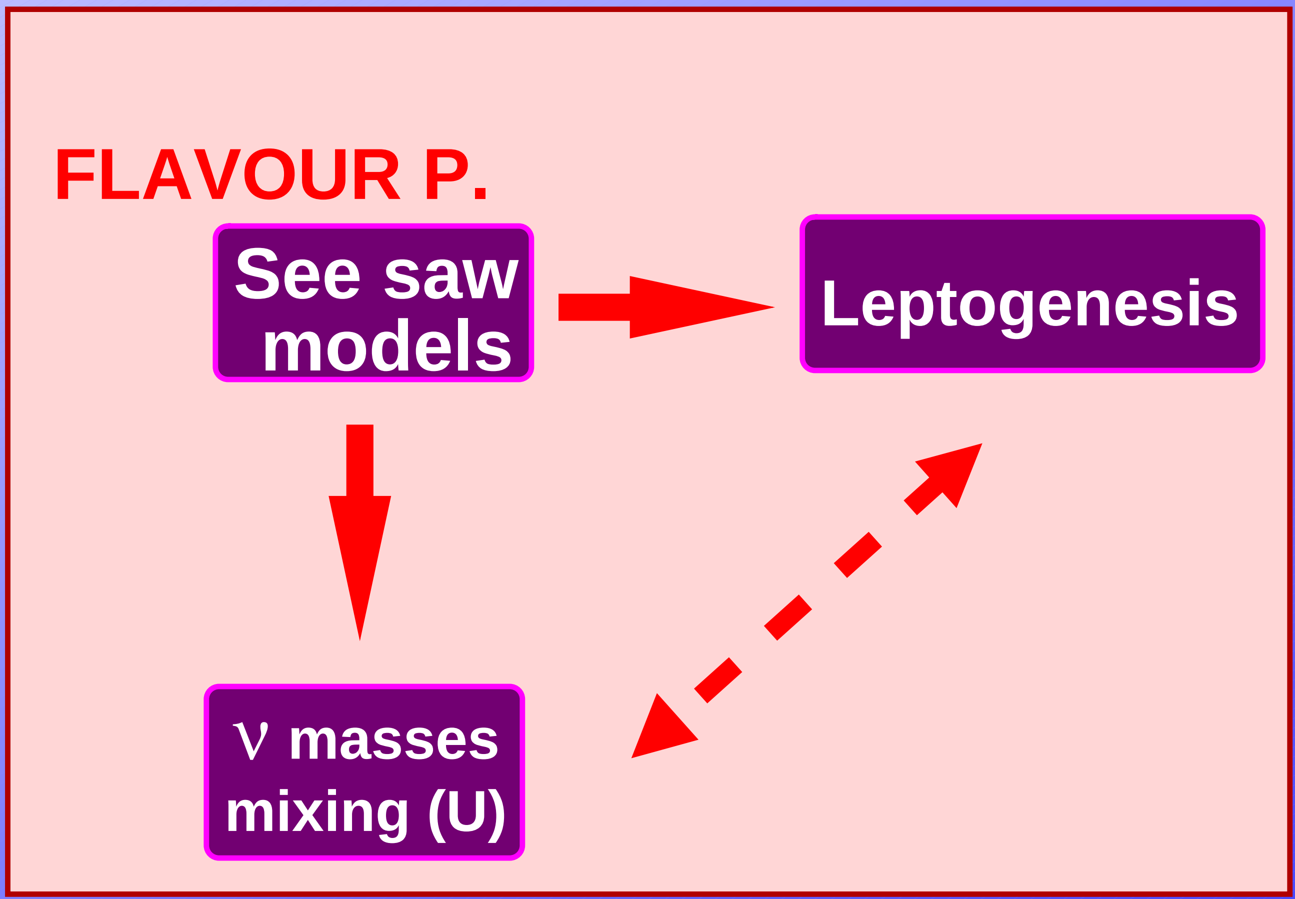
High energy parameters			Low energy parameters		
M_R	3	0	d_m	3	0
λ	9	6	U	3	3

9 parameters are lost, of which 3 phases. In a model-independent way there is **no one-to-one connection** between the low-energy phases and the ones entering leptogenesis. [see, e.g., S.P., MPLA]

In understanding the origin of the flavour structure, the see-saw models have a reduced number of parameters, with no independent R. In some cases,

it is possible to predict

the baryon asymmetry from the Dirac and/or Majorana phases.



5 – Observing low-energy CPV implies leptogenesis?

We use the orthogonal parametrization: $\lambda = 1/v\,\sqrt{M}\,R\,\sqrt{m}U^\dagger$

with $R_{1i}R_{1j}$ real. [Abada et al., Nardi et al., SP, Petcov, Riotto]

one-flavour

$$\epsilon_1 = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2} = 0$$

with flavour

$$\epsilon_l = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{l\beta}^* U_{l\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

ϵ_l depends on the mixing matrix U directly (NEW!).

NH spectrum

Let's consider $m_1 \ll m_2 \simeq \sqrt{\Delta m^2_\odot} \ll m_3 \simeq \sqrt{\Delta m^2_{\rm atm}}$.

[SP, Petcov, Riotto]

1. $\epsilon_\tau \propto$

$$M_1 f(R_{ij}) \left[c_{23} s_{23} c_{12} \sin\left(\frac{\alpha_{32}}{2}\right) - c_{23}^2 s_{12} s_{13} \sin\Big(\delta - \Big(\frac{\alpha_{32}}{2}\Big)\Big)\right]$$

Direct dependence on the Majorana and Dirac phases.

2. Washout factor: $\eta\left(\frac{390}{589}\widetilde{m_\tau}\right) - \eta\left(\frac{417}{589}\widetilde{m_2}\right)$.

$$\widetilde{m_2} \simeq \sqrt{\Delta m^2_{\rm atm}} \Big(\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}} |R_{12}|^2 (1 - c_{12}^2 s_{23}^2) + |R_{13}|^2 s_{23}^2\Big) \,,$$

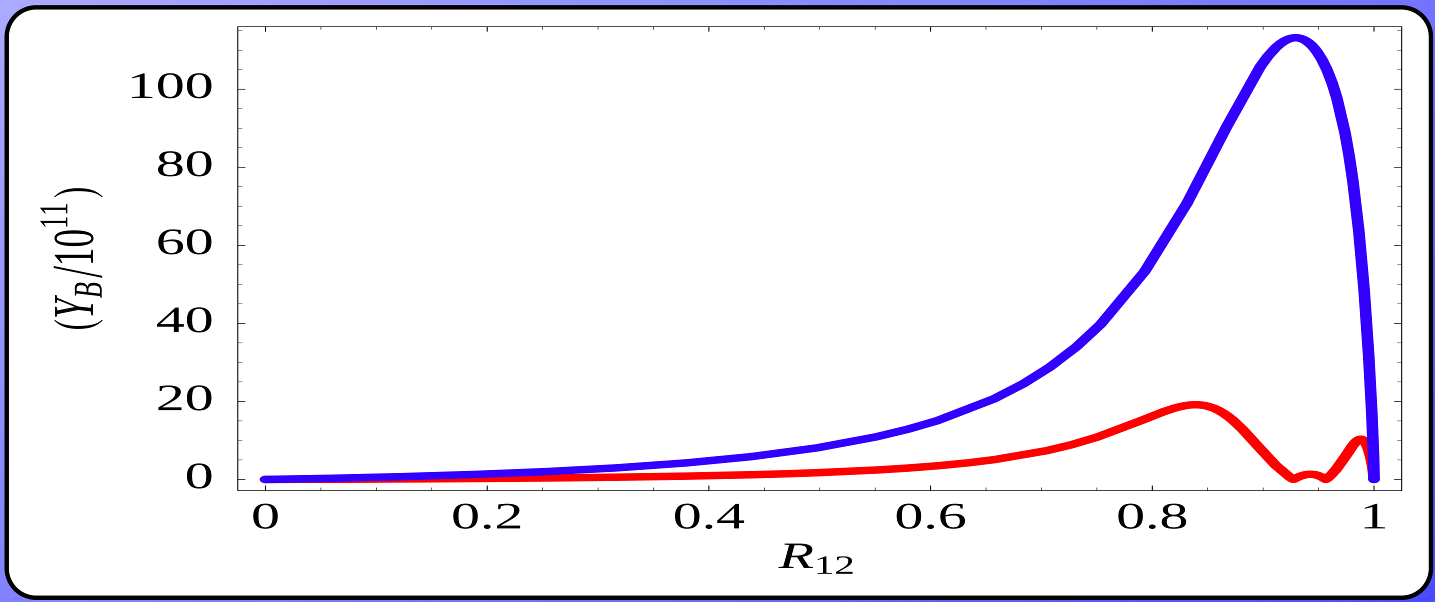
$$\widetilde{m_\tau} \simeq \sqrt{\Delta m^2_{\rm atm}} \Big(\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}} |R_{12}|^2 c_{12}^2 s_{23}^2 + |R_{13}|^2 c_{23}^2\Big) \,.$$

Dependence on R

$$|Y_B| \sim 10^{-8} \frac{M_1}{10^{11}\ \mathrm{GeV}} \frac{|R_{12}||R_{13}|}{\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\mathrm{atm}}}\right)^{\frac{1}{2}} |R_{12}|^2+|R_{13}|^2} \left|\eta\left(\frac{390}{589}\widetilde{m_\tau}\right) - \eta\left(\frac{417}{589}\widetilde{m_2}\right)\right|$$

$$\sim 2.9 \times 10^{-11} \frac{|R_{12}|}{|R_{13}|^{3.32} c_{23}^{2.32}} \left|1 - \left(\frac{390}{417}\ \frac{c_{23}^2}{s_{23}^2}\right)^{1.16}\right|$$ Strong washout

$$\sim 1.5 \times 10^{-9} |R_{12}||R_{13}|$$ Weak washout

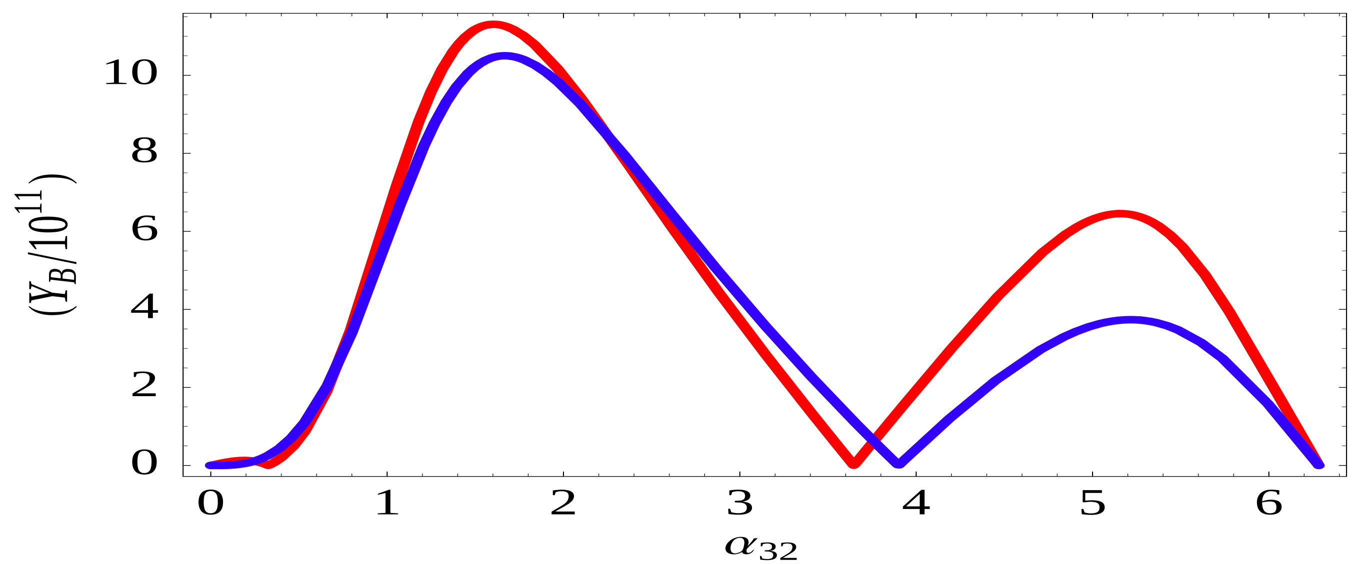


Leptogenesis due to the Majorana phase.

$$|Y_B| \propto c_{23}\, c_{13}\, \left(s_{23}c_{12} + c_{23}s_{12}s_{13}\right) \left|\sin \frac{\alpha_{32}}{2}\right|.$$

Taking $R_{12}^2 = 0.85$, $R_{13}^2 = 0.15$, we get

$$|Y_B| \cong 2.0\,(2.2) \times 10^{-10} \left(\frac{\sqrt{\Delta m^2_{\rm atm}}}{0.05 \text{ eV}}\right) \left(\frac{M_1}{10^{11} \text{ GeV}}\right)$$



Leptogenesis due uniquely to the Dirac phase.

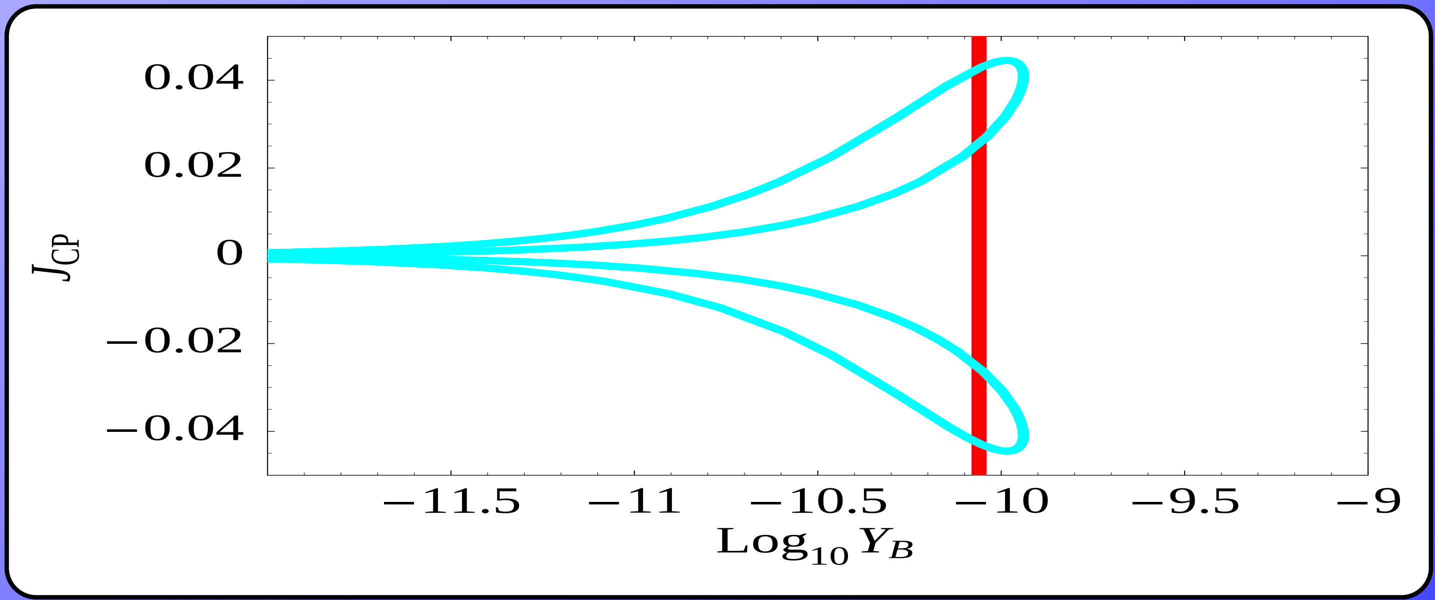
$$|Y_B| \propto c_{23}^2\, s_{12}\, s_{13}\ |\sin\delta|.$$

For $R_{12}^2 = 0.85$, $R_{13}^2 = 0.15$, we get

$$|Y_B| \cong 2.8 \times 10^{-11}\, |\sin\delta|\ \left(\frac{s_{13}}{0.2}\right) \left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right)\ .$$

Imposing $M_1 < 5 \times 10^{11}$ GeV for flavour effects to be important, we find

$$|\sin\theta_{13}\ \sin\delta| \gtrsim 0.11\,, \quad \sin\theta_{13} \gtrsim 0.11\,.$$

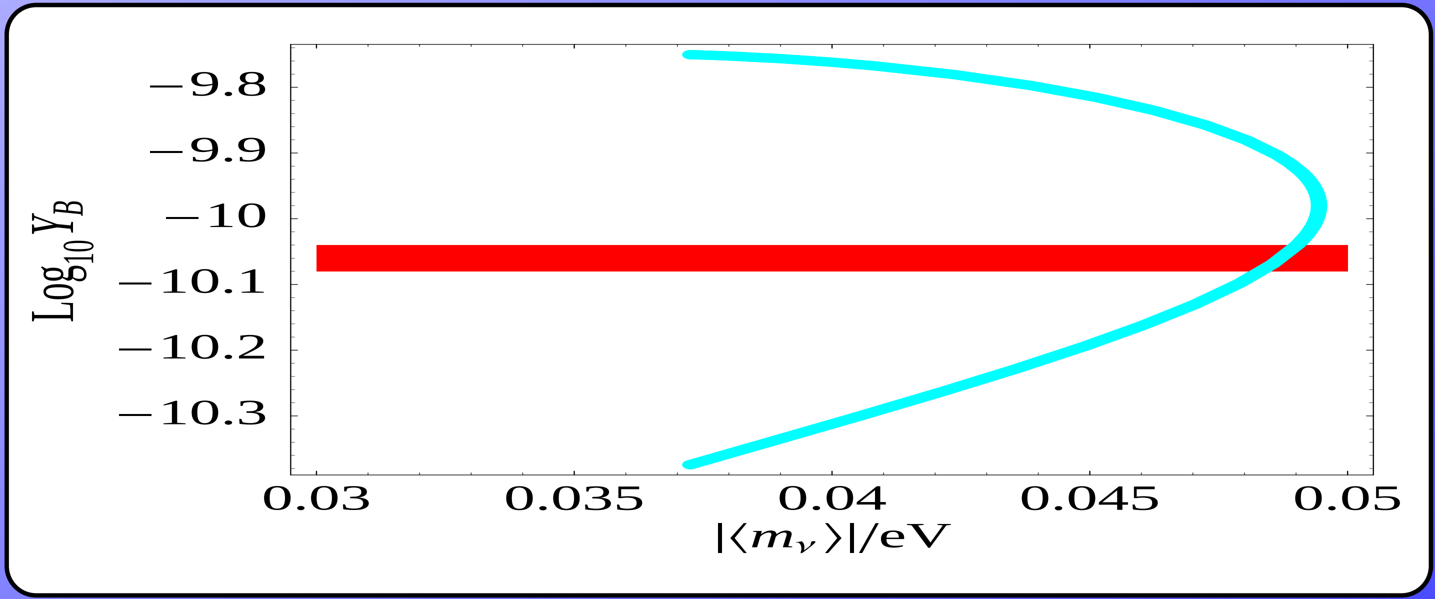


IH spectrum

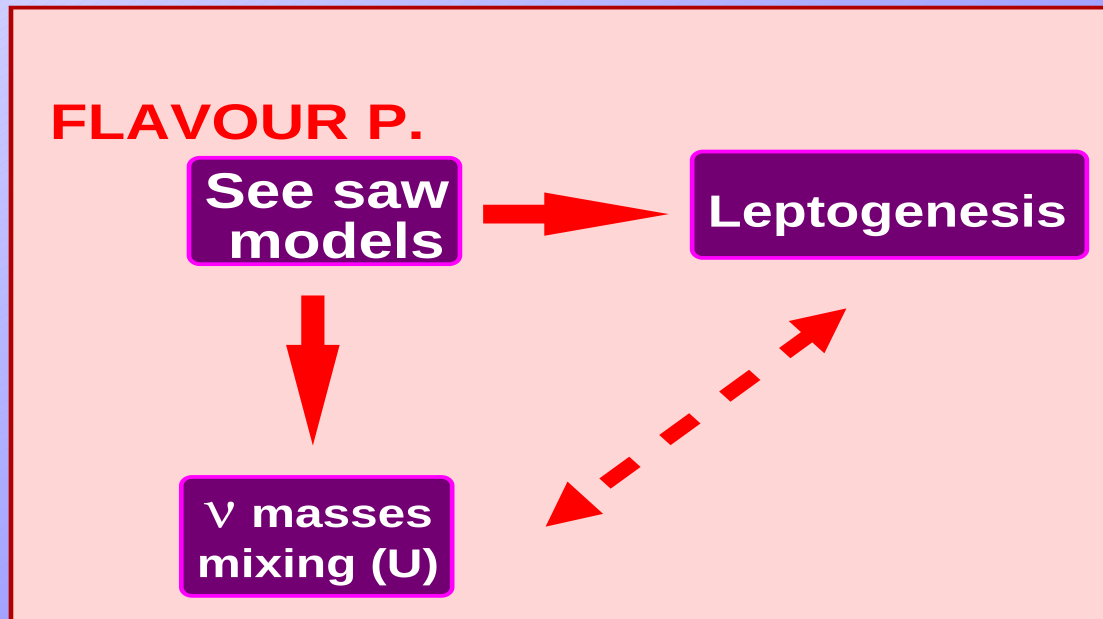
$$\epsilon_l \simeq \frac{3M_1\sqrt{\Delta m^2_{\rm atm}}}{32\pi v^2}\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)^{\frac{1}{4}}\frac{|R_{11}R_{12}|}{|R_{11}|^2+|R_{12}|^2}\,{\rm Im}\,\left(U^*_{l1}U_{l2}\right).$$

$$|Y_B| \cong 2.2\times 10^{-12}\left(\frac{\sqrt{\Delta m^2_{\rm atm}}}{0.05\ {\rm eV}}\right)\left(\frac{M_1}{10^{11}\ {\rm GeV}}\right).$$

In order to have Y_B compatible with observations, $R_{11}R_{12}$ purely imaginary:



6 – Conclusions



In presence of flavour effects, there is

a direct link between low energy phases and leptogenesis.

The observation of L violation ($(\beta\beta)_{0\nu}$-decay)

and of CPV in the lepton sector (neutrino oscillations and/or $(\beta\beta)_{0\nu}$-decay)

would be a strong indication, even if not a proof, of leptogenesis.