

# LEPTOGENESIS AND LOW ENERGY NEUTRINO PHYSICS

UKForum - NuHorizons in the 21th century

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1 – Outline

- A. **Leptogenesis: the basics**
- B. The see-saw mechanism and **leptogenesis**
- C. Leptogenesis in the one-flavour approximation
- D. Flavour effects in leptogenesis
- C. **Connection** between Low energy and High energy  
(leptogenesis) CP-violation
- Conclusions

### 2 – The baryon asymmetry

There is evidence of the **baryon asymmetry**:

$$Y_B = n_B/n_\gamma = (6.1_{-0.2}^{+0.3}) \times 10^{-10}$$

Sakharov conditions necessary for the dynamical creation of a B-asymmetry in the expanding Early Universe:

- **deviation from thermal equilibrium**
- **baryon (lepton) number violation**
- **C and CP violation**

**Leptogenesis** takes place in the context of see-saw models in which **lepton number** is violated.

As the Universe expands, N's go **out of equilibrium** ( $T < M / \text{few}$ ).

Their **CP-violating** decays produce a lepton asymmetry, which is then converted into a **baryon asymmetry** by sphaleron processes. Leptogenesis can successfully explain the observed baryon asymmetry of the Universe.

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

## 3 – Leptogenesis in detail: the see-saw mechanism

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

At high energy ( $10^9 - 10^{15}$  GeV), **RH neutrinos** are introduced. They are singlets with respect to the gauge group of the SM and possess very heavy Majorana masses:

$$\mathcal{L} = -\lambda \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

- **Lepton number is violated.**

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

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

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

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

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

- Light neutrinos are predicted to be Majorana particles (testable in neutrinoless double beta decay exp).

It is useful to use various parametrizations of  $m_D$ :

- Bi-unitary parametrization:

$$m_D = U_R^\dagger m_D^{diag} U_L ,$$

- Orthogonal parametrization.

$$m_D \simeq i \sqrt{M_R} R D_m^{1/2} U_{PMNS}^\dagger .$$

### 4 – Leptogenesis in detail: the baryon asymmetry

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry:

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \rightarrow l\Phi) - \Gamma(N_1 \rightarrow \bar{l}\bar{\Phi})}{\Gamma(N_1 \rightarrow l\Phi) + \Gamma(N_1 \rightarrow \bar{l}\bar{\Phi})}$$

2. solve the Boltzmann equation to take into account the wash-out of the asymmetry:

$$Y_L = k\epsilon_1$$

with k a washout factor.

3. convert the lepton asymmetry into baryon asymmetry

$$\eta_B/s = \frac{k}{g^*} c_s \eta_L/s = -10^{-4} \epsilon_1$$

## The one-flavour approximation: 1. CP-asymmetry

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

$\epsilon_1$  is the total-decay asymmetry which depends on the CPV phases in  $m_D$ :

$$\epsilon_1 \equiv \frac{\Gamma(N \rightarrow lH) - \Gamma(N \rightarrow l^c H^c)}{\Gamma(N \rightarrow lH) + \Gamma(N \rightarrow l^c H^c)}$$

- For hierarchical RH neutrino,  $M_1 \ll M_2 \ll M_3$ ,

$$\epsilon_1 = -\frac{3}{8\pi v^2} \frac{1}{|m_D m_D^\dagger|_{11}} \sum_{i=2,3} \text{Im}((m_D m_D^\dagger)_{1i}^2) \frac{M_1}{M_i}$$

## 2. Departure from equilibrium

In equilibrium, no net lepton asymmetry can be generated.

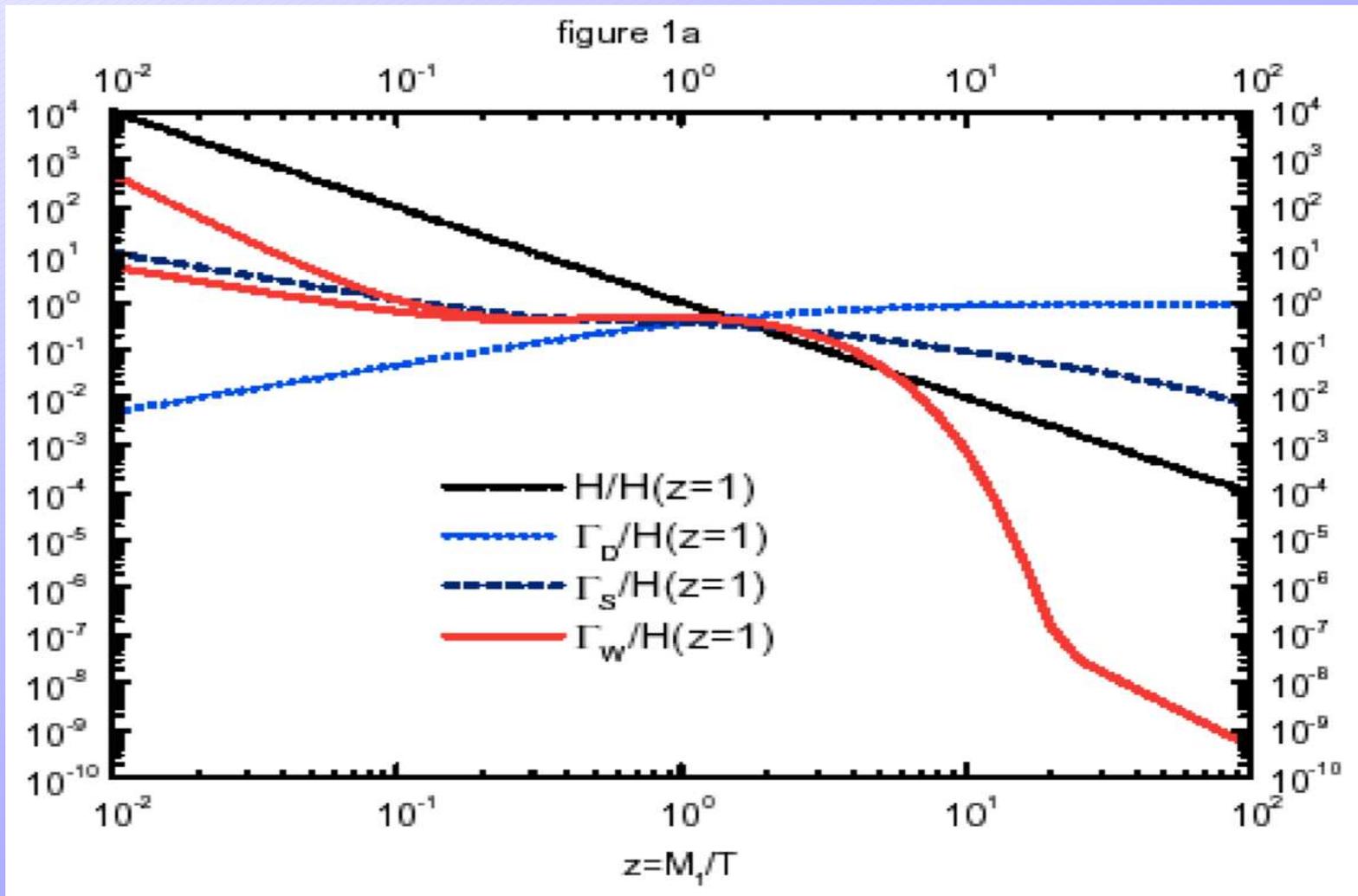
The equilibrium distribution of  $N$  is maintained as far as the processes which create and destroy  $N$  ( $N \leftrightarrow Hl, Nl \leftrightarrow qt$ ) are efficient.

$N$  go out of equilibrium when:

$$\Gamma \sim H$$

$\Gamma$  is the production rate and  $H$  is the expansion rate of the Universe.

## 4 – Leptogenesis in detail: the baryon asymmetry



[Buchmuller, Di Bari, Plumacher]

It is useful to define:

$$\widetilde{m}_1 \equiv \frac{m_D^\dagger m_D}{M_1}$$

$$m_* = \frac{16\pi^{5/2}}{3\sqrt{5}} \sqrt{g^*} \frac{v^2}{M_{\text{Pl}}} \simeq 10^{-3} \text{ eV}$$

The amount of washout can be estimated with:

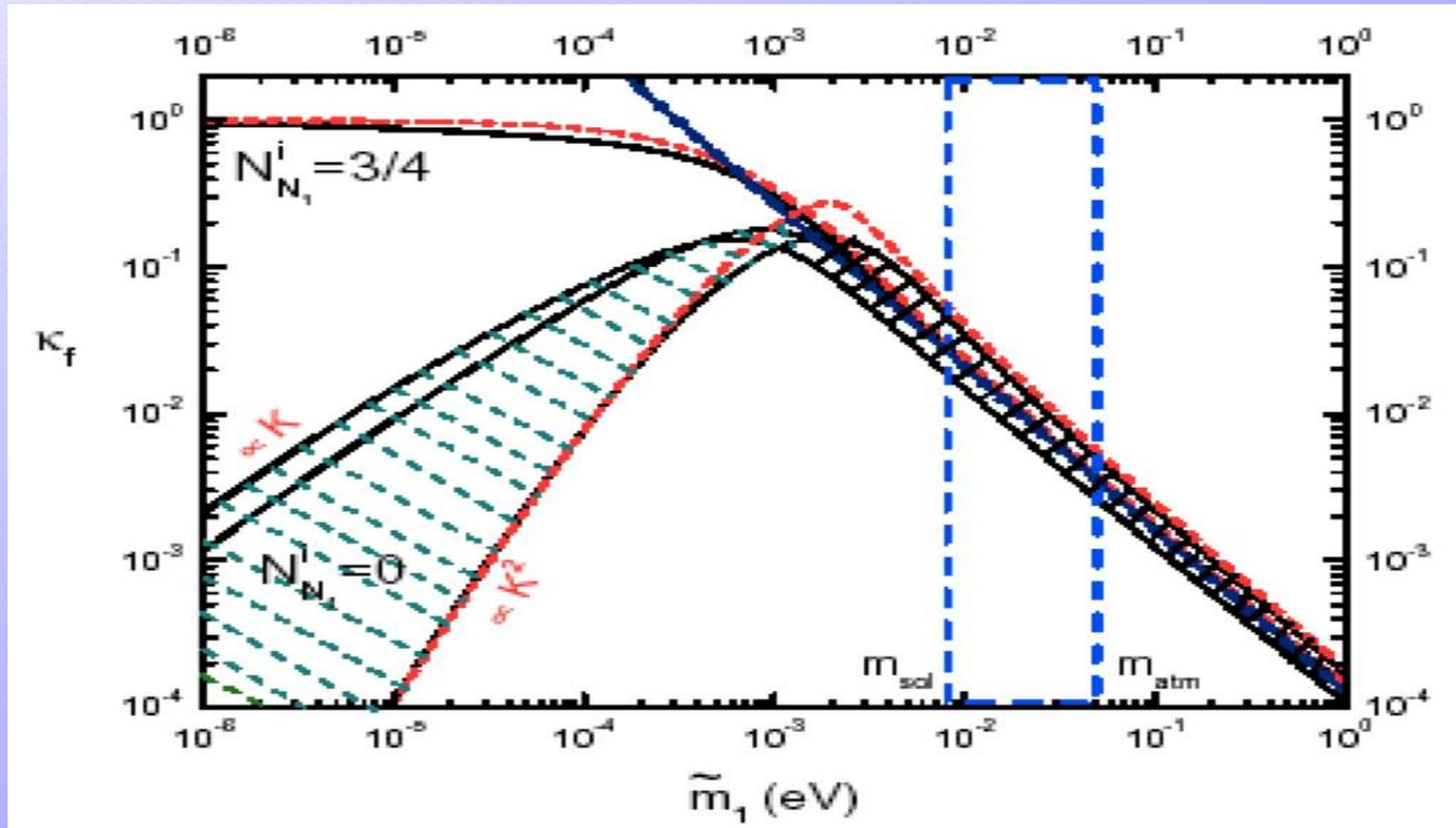
$$K \equiv \frac{\Gamma_D(z \rightarrow \text{inf})}{H(z = 1)} = \frac{\widetilde{m}_1}{m_*}$$

- $K \gg 1$ : strong washout.

The  $N$  abundance tracks the equilibrium one. Any asymmetry produced early on is washed out  $\Rightarrow$  no dependence on the initial conditions.

- $K \ll 1$ : weak washout.

## 4 – Leptogenesis in detail: the baryon asymmetry



[Buchmuller et al.]

### 5 – Flavour effects in leptogenesis

At high  $T$ , the Yukawa interactions for  $l$  are out of equilibrium and effectively  $e$ ,  $\mu$  and  $\tau$  are indistinguishable. They enter in equilibrium when  $\Gamma \sim H$ .

$$\tau : \quad y_{\tau}^2 T / (4\pi) \sim g_*^{1/2} T^2 / M_{\text{Pl}} \quad T \sim 10^{12} \text{ GeV}$$

$$\mu : \quad y_{\mu}^2 T / (4\pi) \sim g_*^{1/2} T^2 / M_{\text{Pl}} \quad T \sim 10^9 \text{ GeV}$$

At  $T < 10^{12}$  GeV, flavour effects need to be taken into account.

- The CP-asymmetry in one flavour is washed out only by the same-flavour washout effects.

[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]

- The flavour CP-asymmetry:

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

- Washout effects are flavour dependent and controlled by:

$$\widetilde{m}_l \equiv \frac{|(m_D)_{1l}|^2}{M_1}$$

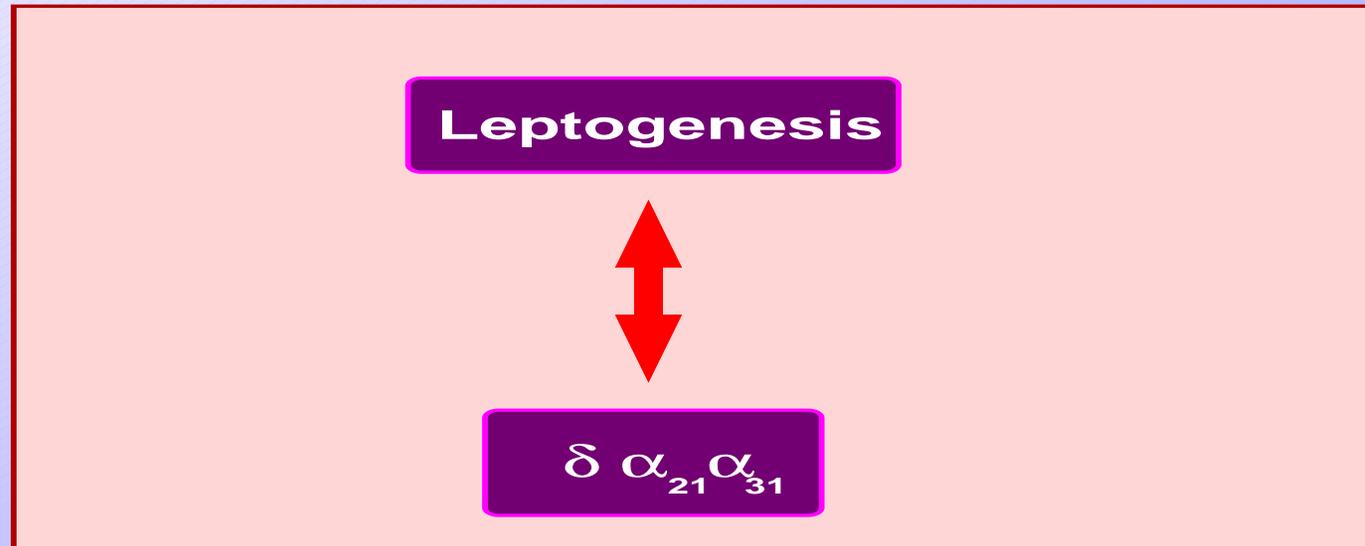
where  $\epsilon_2 = \epsilon_e + \epsilon_\mu$ ,  $\widetilde{m}_2 = \widetilde{m}_e + \widetilde{m}_\mu$  and

- The baryon asymmetry is finally given by:

$$Y_B \simeq -\frac{12}{37g_*} \left( \epsilon_\tau \eta \left( \frac{390}{589} \widetilde{m}_\tau \right) - \epsilon_2 \eta \left( \frac{417}{589} \widetilde{m}_2 \right) \right)$$

**6 – Testing leptogenesis**

**From measuring the CPV phases  
at low energy  
can one compute the amount  
of baryon asymmetry?**



High energy parameters

Low energy parameters

$$M_R \quad 3 \quad 0$$

$$d_m \quad 3 \quad 0$$

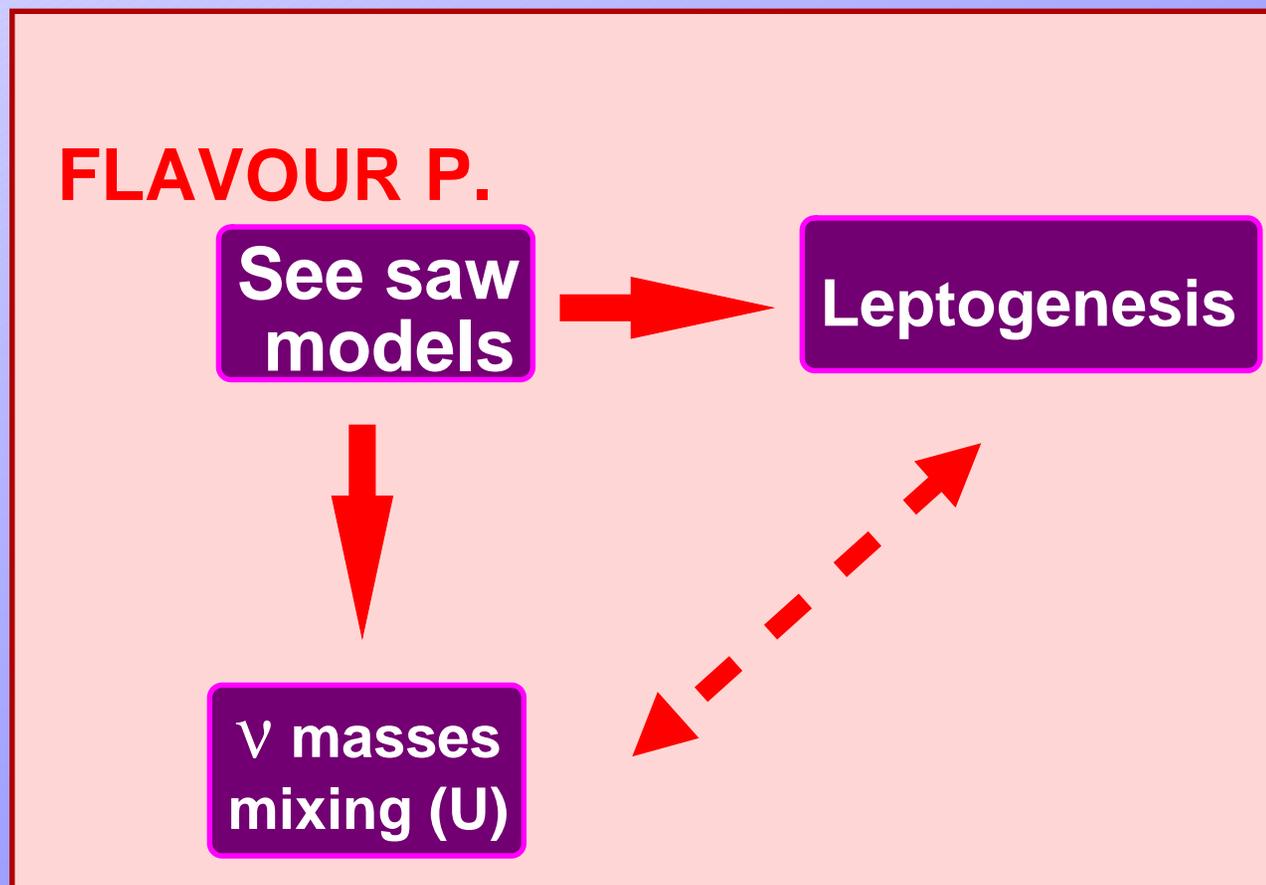
$$\lambda \quad 9 \quad 6$$

$$U \quad 3 \quad 3$$

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.**



An example: 2 RH neutrinos [Frampton, Glashow, Yanagida].

$$\mathcal{L} = \frac{1}{2}(N_1 N_2) \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} + (N_1 N_2) \begin{pmatrix} a & a' & 0 \\ 0 & b & b' \end{pmatrix} \begin{pmatrix} L_1 \\ L_2 \\ L_3 \end{pmatrix} \cdot H + \text{h.c.}$$

In order to reproduce  $\nu$  data, we can take:  $a' = \sqrt{2}a$ ,  $b = b'$ ,  
 $a^2/M_1 \ll b^2/M_2$ .

We get:  $m_1 = 0$ ,  $m_2 = 2a^2/M_1$ ,  $m_3 = 2b^2/M_2$ .

- The baryon asymmetry and the low-energy CP-violation are related:

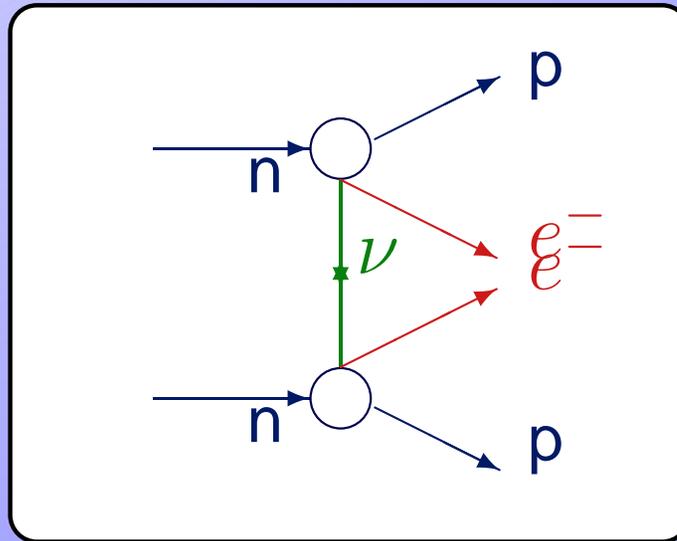
$$\sin \delta \propto -\frac{a^4 b^4}{M_1^3 M_2^3} \epsilon_1$$

**7 – Observing low-energy CPV implies leptogenesis?**

**From observing  
leptonic CP-violation and  
lepton number violation at low energy,  
can we infer that  
a lepton asymmetry is generated?**

- What is the **nature** of neutrinos (Majorana ( $\nu = \bar{\nu}$ ) vs Dirac ( $\nu \neq \bar{\nu}$ ))? Majorana neutrinos violate the lepton number.

Majorana nature can be measured only in **neutrinoless double beta decay**:  $(A, Z) \rightarrow (A, Z + 2) + 2e^-$ .



The **half-life time**,  $T_{0\nu}^{1/2}$ , of  $(\beta\beta)_{0\nu}$ -decay can be factorized as:

$$[T_{0\nu}^{1/2}(0^+ \rightarrow 0^+)]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 |\langle m \rangle|^2$$

- CP-violation?

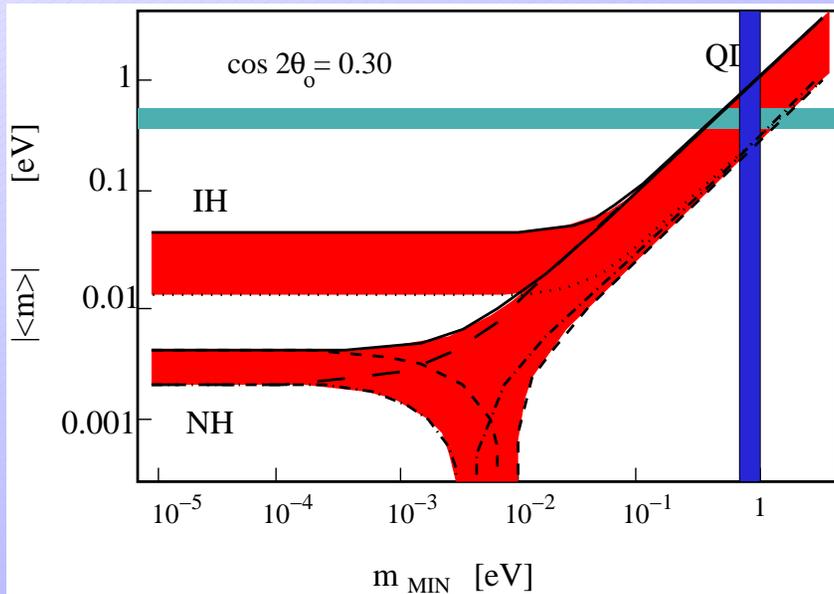
$\delta \neq 0, \pi$  and/or  $\alpha_{ij} \neq 0, \pi$ .

$\delta$  can be measured in LBL appearance  $\nu$ -oscillation experiments. It is necessary to disentangle true CP-V effects due to the  $\delta$  phase from the ones induced by matter:

**problem of DEGENERACIES.**

Future superbeams, betabeams and neutrino factories will have sensitivity to CP-violation.

$\alpha_{12}$  can be measured in principle in  $(\beta\beta)_{0\nu}$ -decay.



A measurement of  $|\langle m \rangle|$  combined with a measurement of  $m_1$  (in tritium  $\beta$ -decay exp. and/or cosmology) might allow to establish if CP is violated.

A very challenging measurement which requires good knowledge of the nuclear matrix elements. [Barger et al.; S.P., Petcov,

Rodejohann; S.P., Petcov, Schwetz]

## 7 – Observing low-energy CPV implies leptogenesis?

Is there a relation between low energy CP-violation and leptogenesis?

We use the orthogonal parametrization:  $m_D = \sqrt{M} R \sqrt{m} U^\dagger$  [Casas, Ibarra]

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

Branco et al.]

one-flavour

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

with flavour

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

**$\epsilon_l$  depends on the mixing matrix  $U$  directly.**

## NH spectrum

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

[SP, Petcov, Riotto, PRD and NPB 2007]

1.  $\epsilon_{\tau} \propto$

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

Direct dependence on the Majorana and Dirac phases.

2. Washout factor:  $\eta\left(\frac{390}{589} \widetilde{m}_{\tau}\right) - \eta\left(\frac{417}{589} \widetilde{m}_2\right)$ .

$$\widetilde{m}_2 \simeq \sqrt{\Delta m_{\text{atm}}^2} \left( \sqrt{\frac{\Delta m_{\odot}^2}{\Delta m_{\text{atm}}^2}} |R_{12}|^2 (1 - c_{12}^2 s_{23}^2) + |R_{13}|^2 s_{23}^2 \right),$$

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

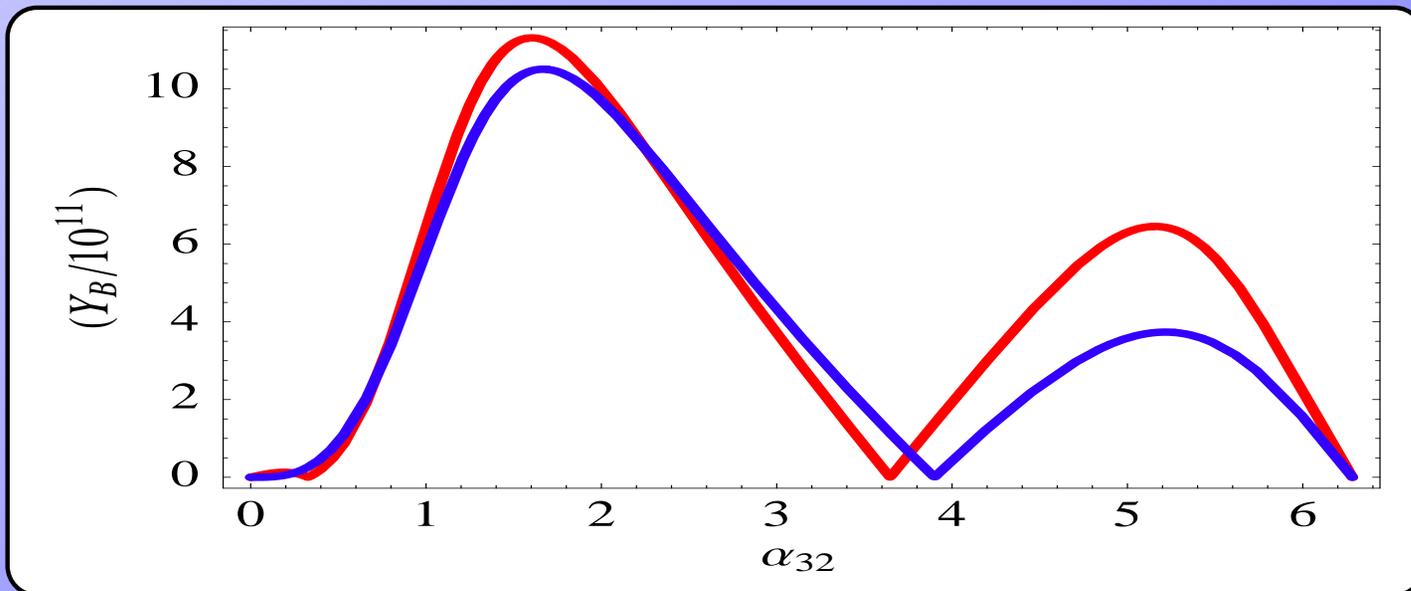
- Maximal asymmetry is obtained in the intermediate regime.

Leptogenesis due to the **Majorana phase**.

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

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

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



## 7 – Observing low-energy CPV implies leptogenesis?

Leptogenesis due uniquely to the **Dirac phase**.

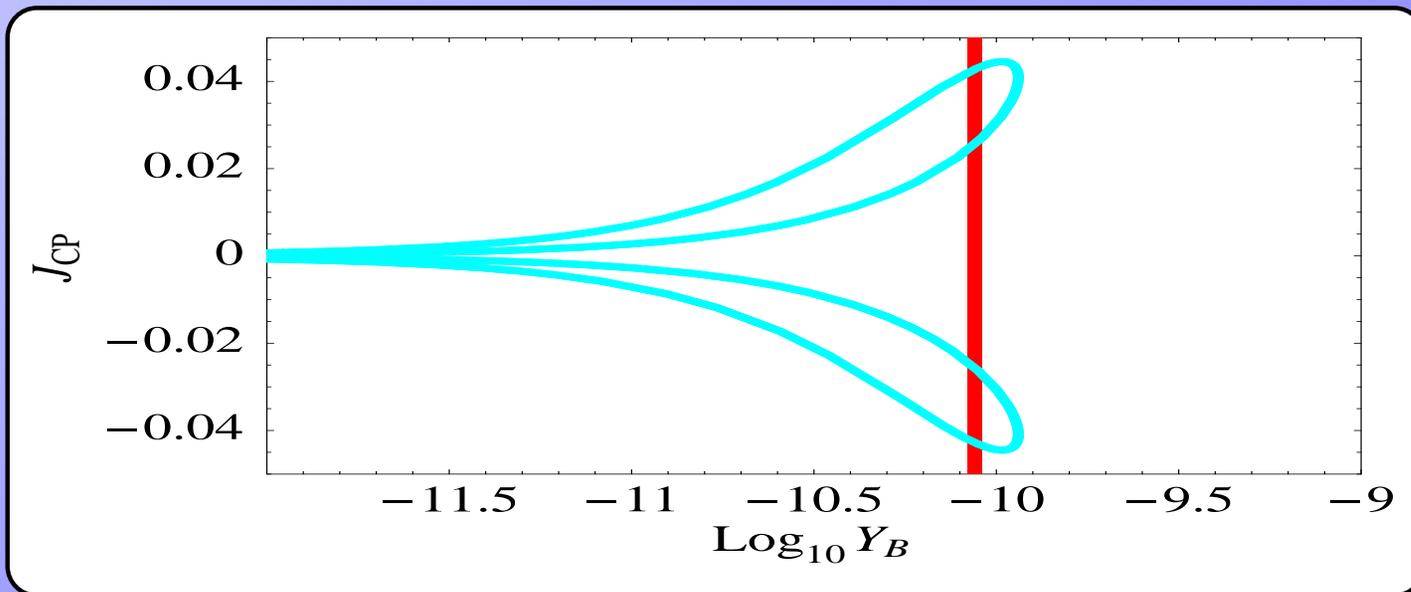
$$|Y_B| \propto c_{23}^2 s_{12} s_{13} |\sin \delta|.$$

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

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

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

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.11, \quad \sin^2 \theta_{13} \gtrsim 0.01.$$

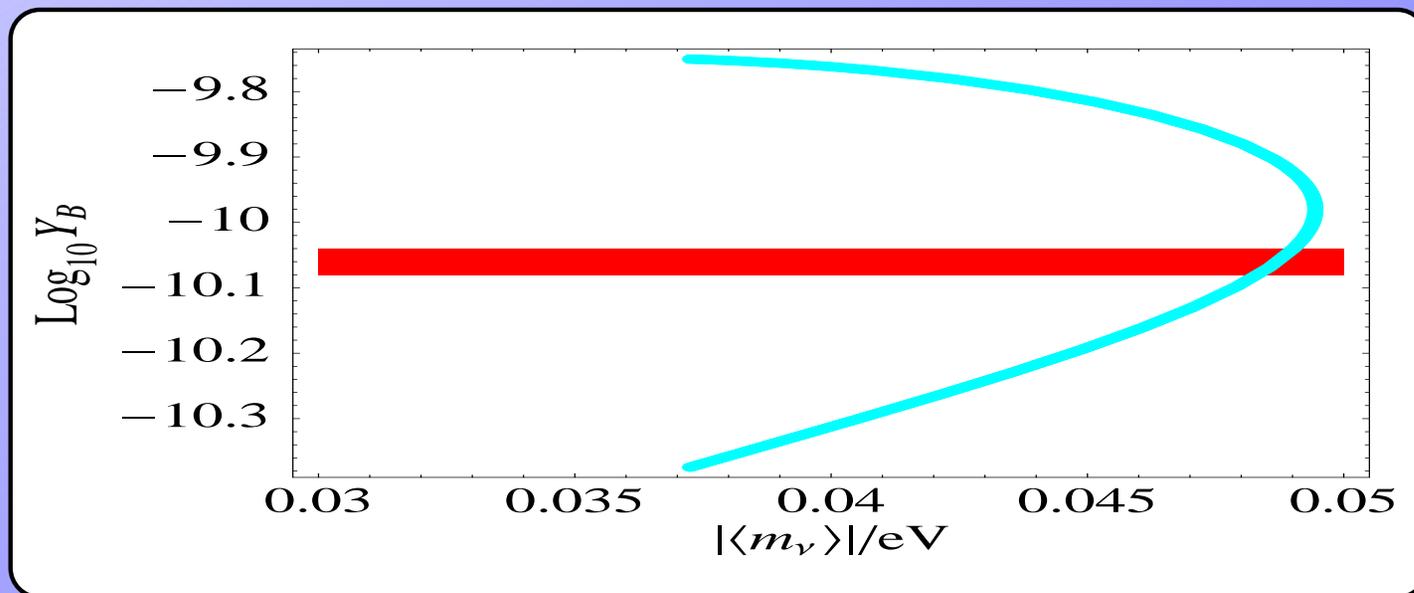


## IH spectrum

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

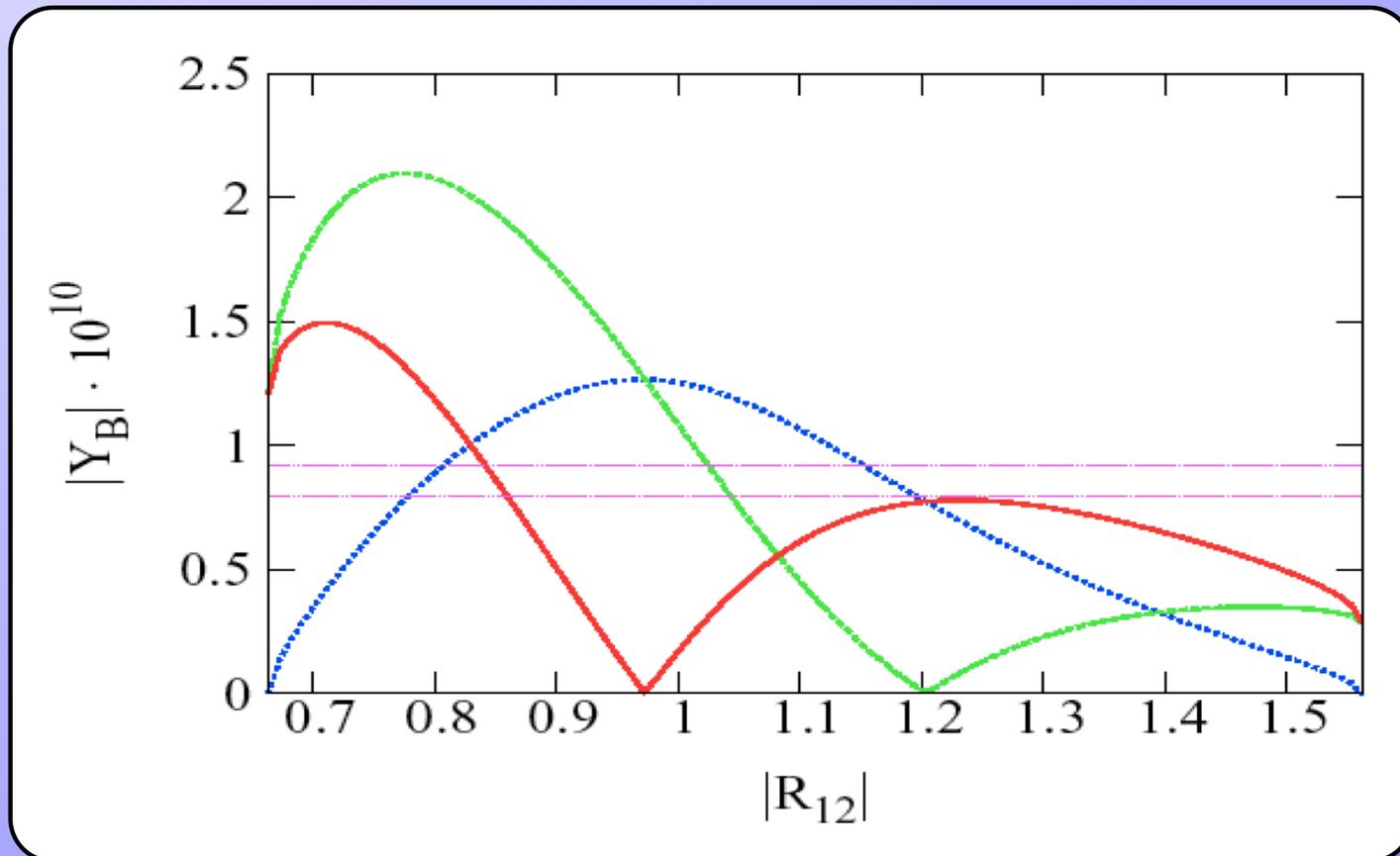
$$|Y_B| \simeq 2.2 \times 10^{-12} \left( \frac{\sqrt{\Delta m_{\text{atm}}^2}}{0.05 \text{ eV}} \right) \left( \frac{M_1}{10^{11} \text{ GeV}} \right).$$

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

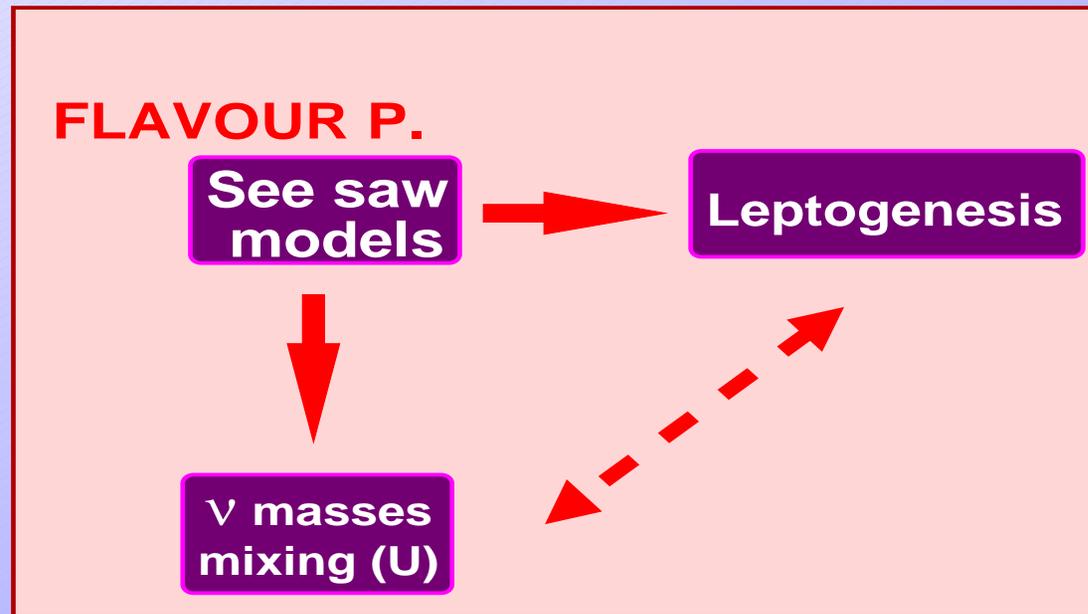


## Interplay between low energy and high energy CP-violation

In general the lepton asymmetry receives contributions both from  $\delta$  and  $\alpha_{ij}$ , and from phases in  $R$ .



## 8 – Conclusions



In presence of **flavour effects**,

low energy phases enter directly 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**.