LEPTOGENESIS AND LOW ENERGY NEUTRINO PHYSICS

COSMO07

U. of Sussex - 23 August 2007

Silvia Pascoli

IPPP - Durham U.

1 – Outline

- A. Present status of neutrino physics and future questions:

Determining the leptonic CPV phases in future experiments:

1) long base-line neutrino oscillation experiments

2) neutrinoless double beta decay experiments

- B. The see-saw mechanism and leptogenesis

- C. Connection between Low energy and High energy (leptogenesis) CP-violation: flavour effects (new perspective)

- Conclusions

2 – Present status of neutrino physics

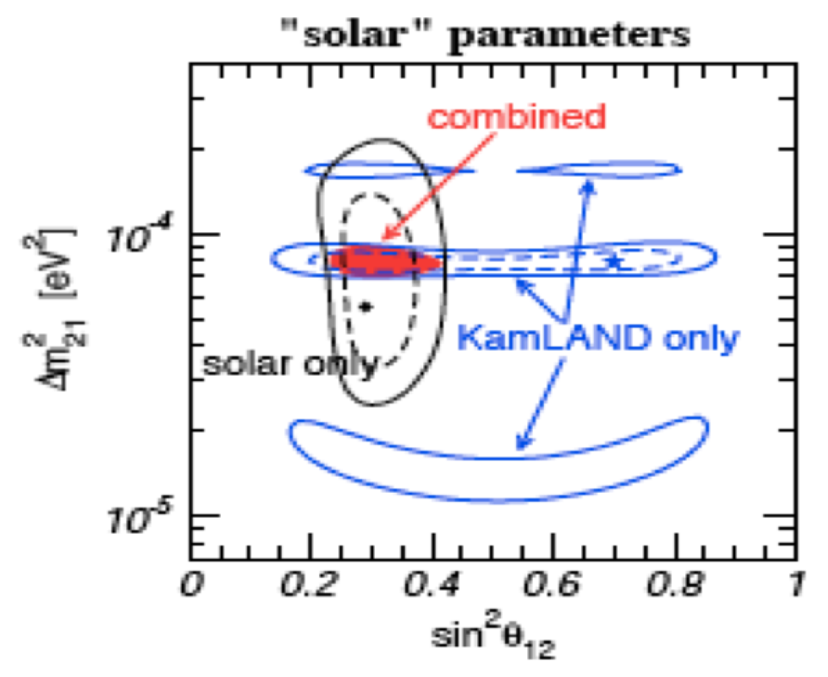
There is strong evidence for neutrino oscillations ($\nu_a \longrightarrow \nu_b$) from solar, atmospheric neutrino experiments as well as KamLAND, K2K, MINOS.

The probability of

ν_a oscillating into ν_b is:

$$P(\nu_a \longrightarrow \nu_b) = |\langle\nu_b|\nu, t\rangle|^2$$

$$\simeq \quad \sin^2 2\theta \quad \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$



[T. Schwetz, hep-ph/0606060]

Neutrino oscillations play

a crucial role in our understanding

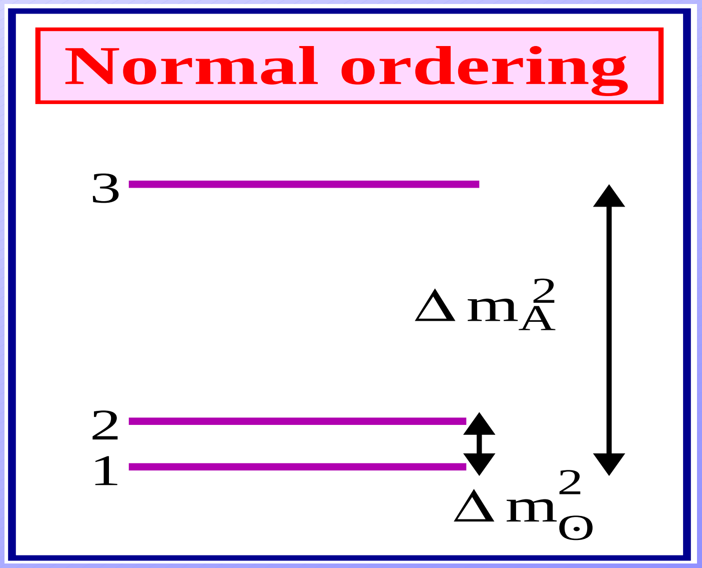
of particle physics as they imply that

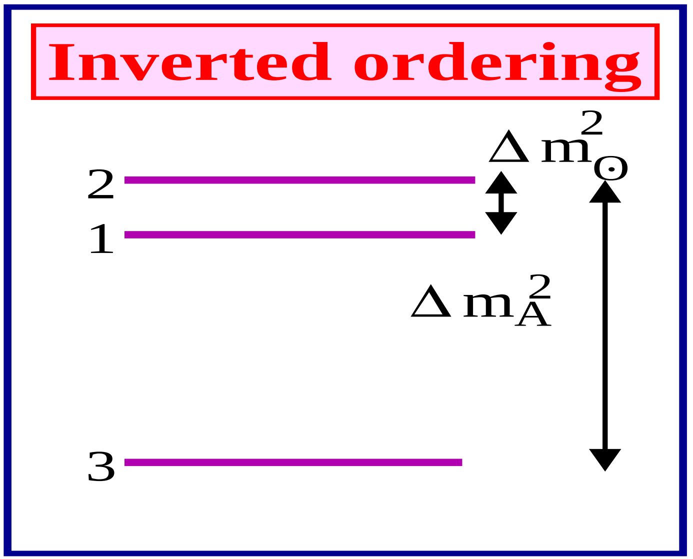
neutrinos have MASS and MIXING!

Physics beyond the Standard Model is required

to explain neutrino masses.

$$\Delta m^2_\odot = 8.0 \times 10^{-5}\ \mathrm{eV}^2 \ll \Delta m^2_{\mathrm{atm}} = 2.5 \times 10^{-3}\ \mathrm{eV}^2 \ \Rightarrow \mathbf{3}\ \nu.$$





$$m_1 = m_{\mathrm{MIN}}$$
$$m_2 = \sqrt{m_{\mathrm{MIN}}{}^2 + \Delta m^2_\odot}$$
$$m_3 = \sqrt{m_{\mathrm{MIN}}{}^2 + \Delta m^2_{\mathrm{atm}}}$$

$$m_3 = m_{\mathrm{MIN}}$$
$$m_1 = \sqrt{m_{\mathrm{MIN}}{}^2 + \Delta m^2_{\mathrm{atm}} - \Delta m^2_\odot}$$
$$m_2 = \sqrt{m_{\mathrm{MIN}}{}^2 + \Delta m^2_{\mathrm{atm}}}$$

Measuring neutrino masses requires to know m_{MIN} and sign(Δm^2_{31}).

Mixing is described by a unitary matrix:

$$|\nu_l\rangle = \sum_i U_{li} |\nu_i\rangle$$

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix.

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar, reactor $\theta_\odot \sim 30^o$ **Atm, Acc.** $\theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase **Reactor, Acc.** $\theta < 12^o$ **CPV Majorana phases**

If $U \neq U^*$, there is leptonic CP-violation.

3 – Questions for the future

- What is the **nature** of neutrinos?

Whether they Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$). Majorana neutrinos violate the lepton number.

- Absolute value of neutrino masses?

Needed the type of hierarchy and the mass scale of the lightest neutrino.

- CP-violation?

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

4 – Questions for the future

- What is the **nature** of neutrinos?

Whether they Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$). Majorana neutrinos violate the lepton number. $\boxed{\beta\beta_{0\nu}\ \textbf{decay}}$

- Absolute value of neutrino masses?

Needed the type of hierarchy and the mass scale of the lightest neutrino: $\boxed{\beta\beta_{0\nu}\ \textbf{decay, LBL oscillations, } {}^3\textbf{H}\ \beta\ \textbf{decay}}$

- CP-violation?

$\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$. $\boxed{\textbf{LBL oscillations, } \beta\beta_{0\nu}\ \textbf{decay}}$

5 – Measuring CP-V phases

The δ phase

δ can be measured in LBL appearance ν-oscillation experiments.

A measure of CP- violating effects is provided by:

$$A_{CP} = \frac{P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})}{P(\nu_l \to \nu_{l'}) + P(\bar{\nu}_l \to \bar{\nu}_{l'})} \propto J_{CP} \propto \sin\theta_{13} \sin\delta$$

These oscillations take place in matter (Earth), (e^-, p and n),

$\Rightarrow$ Matter effects violate CP.

For $\Delta m^2 > 0$, the probability gets enhanced for neutrinos and suppressed for antineutrinos. Viceversa, for $\Delta m^2 < 0$.

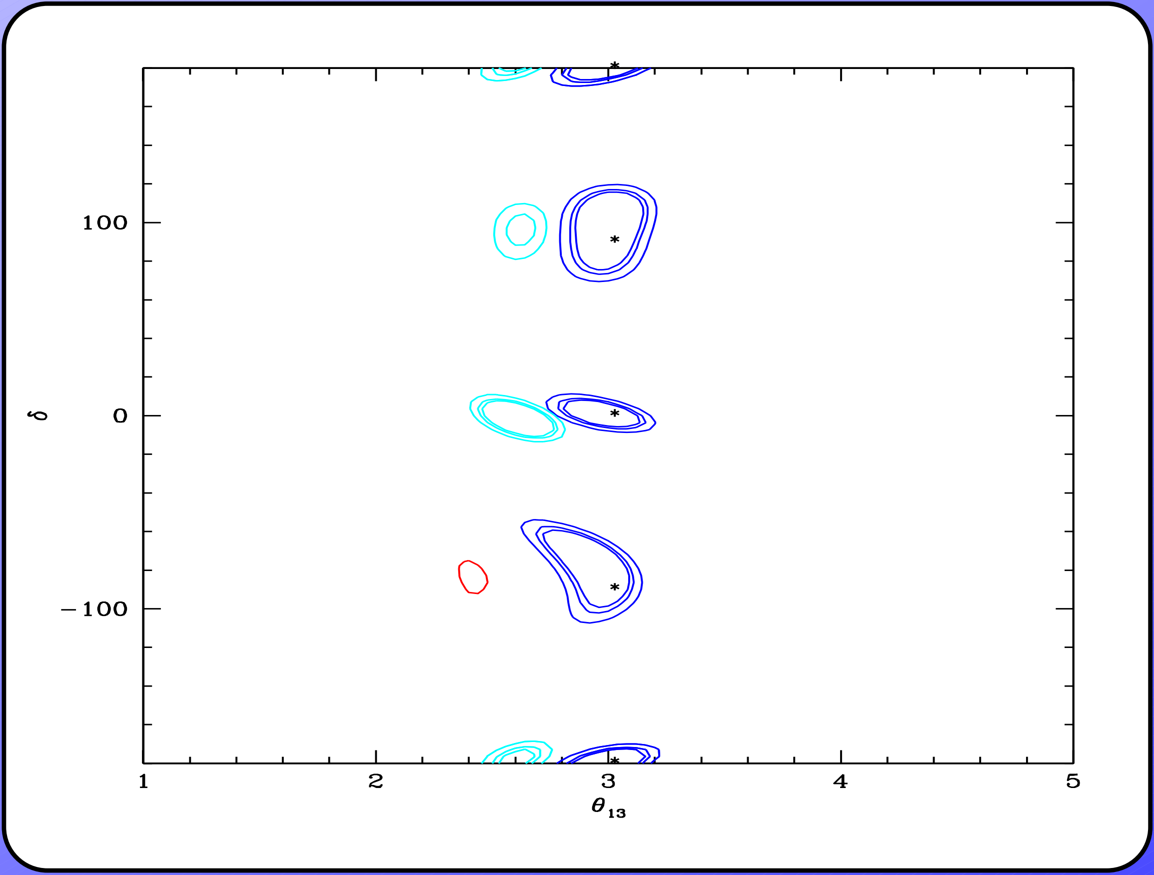
Matter effects imply that

$$\boxed{P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})}$$

If U is complex ($\delta \neq 0, \pi$), we have CP-violation:

$$\boxed{P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})}$$

There are degenerate solutions:



It is necessary to disentangle true CP-V effects due to the δ phase from the ones induced by matter: problem of DEGENERACIES.

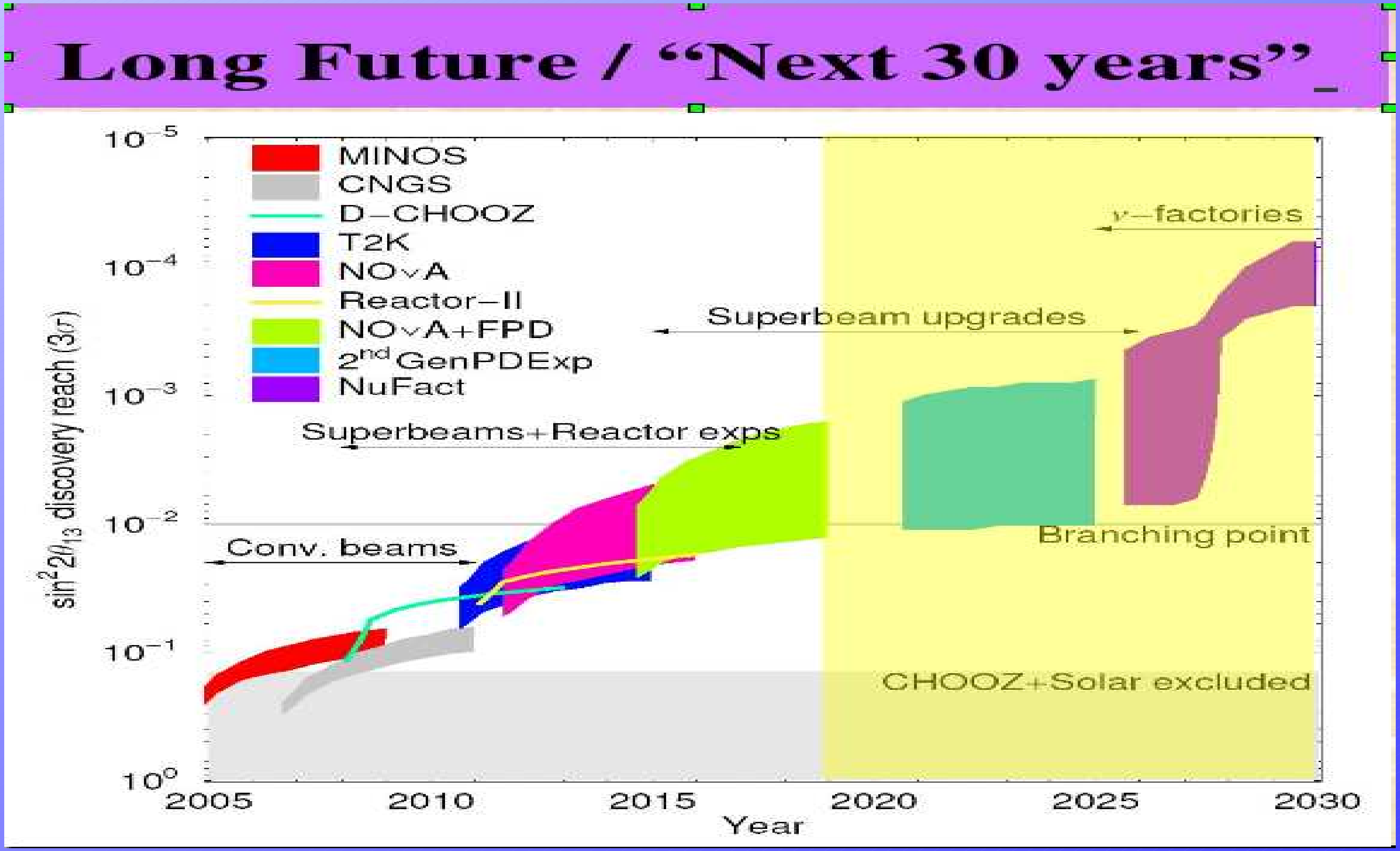
Combining different experiments or choosing specific experimental set-ups, **it may be possible to resolve the degeneracies among different parameters and uniquely determine the existence of CP-V in the lepton sector due to the δ phase.**

5 – Measuring CP-V phases

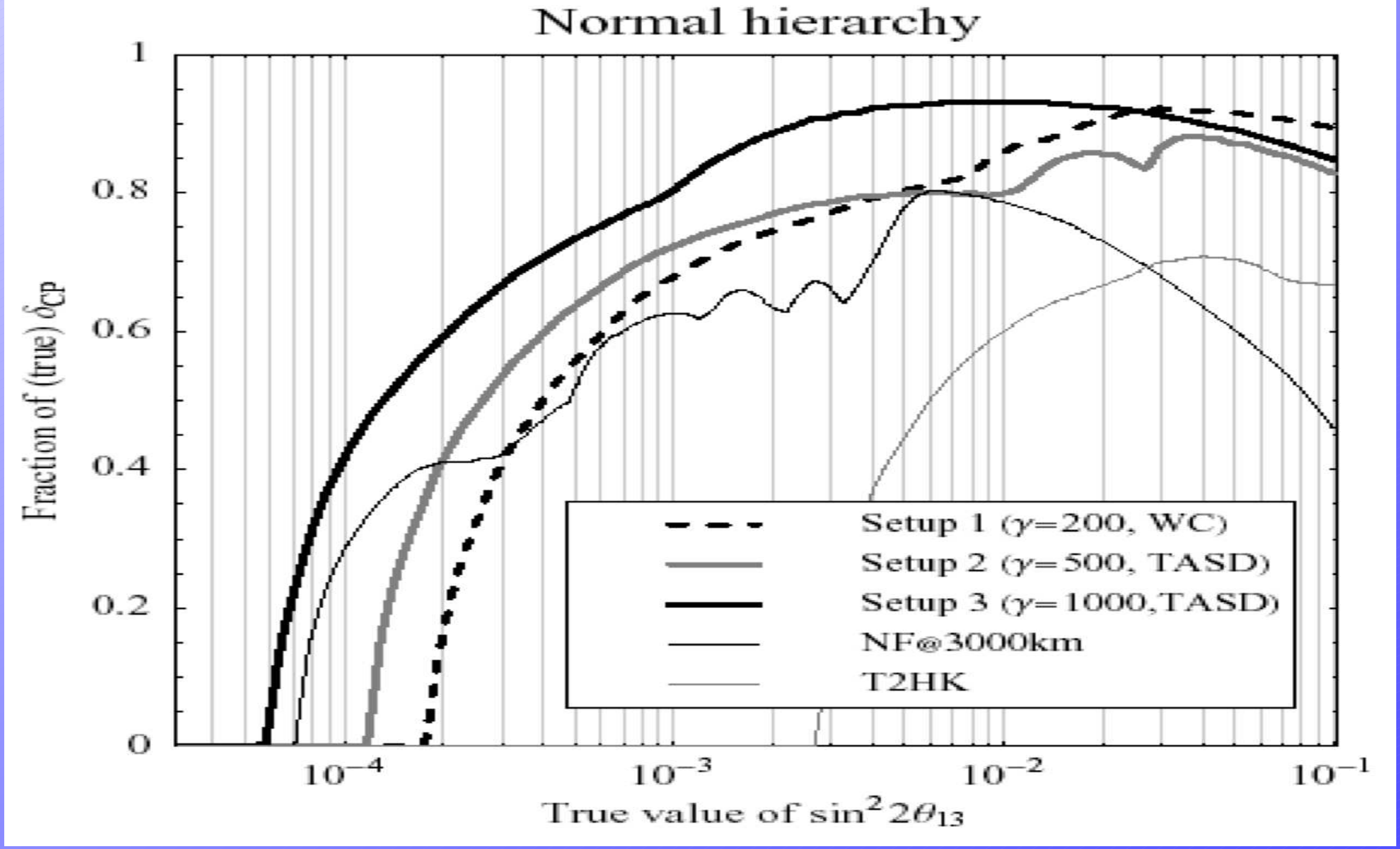
1. **Superbeams**.

2. **Neutrino factories**.

3. **Beta-beams**.



Superbeams (NOνA, T2K) will have sensitivity to CPV for $\sin^2 2\theta_{13} \gg 10^{-3}$. For smaller values, more sensitive machines are required.



[P. Huber, M. Lindner, M. Rolinec and W. Winter; See also, Mena et al.; Barger et al.]

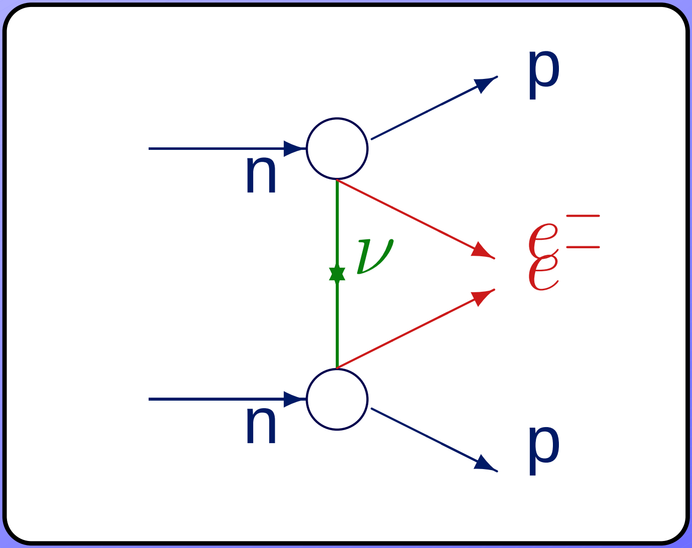
In summary,

- neutrino oscillations experiments are sensitive to δ.
- The search for CP-violation is affected by degeneracies with other unkown parameters which have to be extracted in the analysis of the same data: δ, $\sin^2\theta_{13}$, sign(Δm^2_{13}), θ_{23}.
- Sensitivity to CP-violation:

if $\sin^2 2\theta_{13} > 0.01$ in NOνA
if $\sin^2 2\theta_{13} > 0.003$ in T2K-II
if $\sin^2 2\theta_{13} > 10^{-4}$ at a neutrino factory or β-beam.

Majorana phases

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



$(\beta\beta)_{0\nu}$-decay has a special role in the study of neutrino properties, as it probes the violation of **global lepton number**.

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

$$\boxed{[\mathrm{T}^{1/2}_{0\nu}(0^+ \to 0^+)]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |{<}\, m \,{>}|^{\,2}}$$

- $\mathbf{M}_F$, $\mathbf{M}_{GT}$ are nuclear matrix elements.
- $|<m>|$ **is the effective Majorana mass parameter**:

$$\boxed{|{<}\, m \,{>}| \; \equiv \left| m_1 |U_{\mathrm{e}1}|^2 + m_2 |U_{\mathrm{e}2}|^2 e^{i\alpha_{21}} + m_3 |U_{\mathrm{e}3}|^2 e^{i\alpha_{31}} \right| ,}$$

For QD spectrum ($m_1 \simeq m_2 \simeq m_3$):

$$|{<}\, m \,{>}| \; \simeq m_{\bar{\nu}_e} |\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}|$$

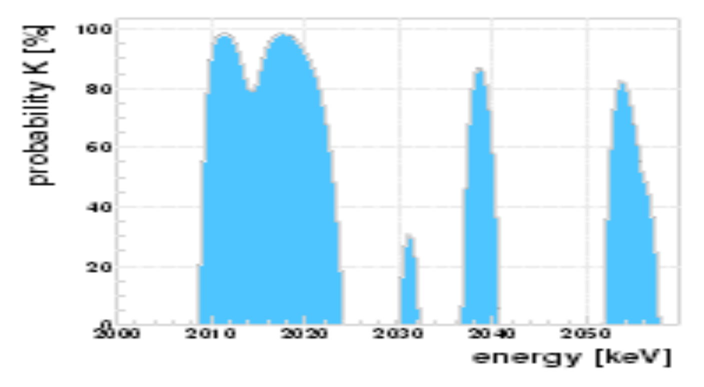
$$0.05 \;\; \mathrm{eV} \;\; \le m_{\bar{\nu}_e} \cos 2\theta_\odot \le |{<}\, m \,{>}| \;\; \le m_{\bar{\nu}_e} < 2.2 \;\; \mathrm{eV}$$

The present best limit on $|{<}m{>}|$ reads:

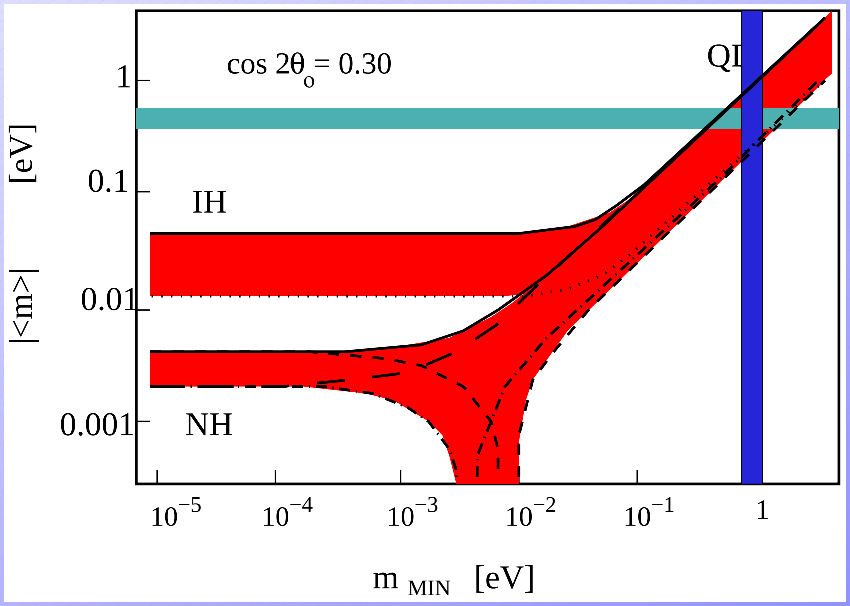
$|{<}m{>}| \ < (350 - 1050)\ \mathrm{meV}$	**Heidelberg-Moscow**
$|{<}m{>}| \ < (680 - 2800)\ \mathrm{meV}$	**NEMO3**
$|{<}m{>}| \ < (200 - 1050)\ \mathrm{meV}$	**CUORICINO**

Recently a claim of $(\beta\beta)_{0\nu}$decay discovery has been published [Klapdor-Kleingrothaus et al. 2004]. It implies

$$\boxed{|{<}m{>}| \ \simeq 200 - 600\ \mathrm{meV}}$$



A new generation of experiments (CUORE, GERDA, COBRA, SuperNEMO, Majorana, EXO) will reach the $|{<}m{>}| \ \sim 10 - 30\ \mathrm{meV}$ sensitivity.



A measurement of $|<m>|$

combined with a measurement

of m_1 (in tritium

β-decay exp. and/or cosmology)

might allow to establish if

CP is violated.

Due to the experimental errors and nuclear matrix elements uncertainties, determining that CP is violated in the lepton sector due to Majorana CPV phases is challenging.

[Barger et al.; S.P., Petcov, Rodejohann; S.P., Petcov, Schwetz]

In summary,

- $(\beta\beta)_{0\nu}$-decay experiments are in principle sensitive to one Majorana CP-violating phase.

- Establishing CPV due to Majorana CPV phases is challenging and would require: [S.P., S. Petcov, T. Schwetz]

i) small experimental errors on $|<m>|$ and neutrino masses;

ii) an uncertainty in the NME which accounts to a factor ζ in $|<m>|$, $\zeta \ll (\cos 2\theta_{\odot})^{-1}$.

6 – 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]

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:

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

- **Lepton number is violated.**

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

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

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

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

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

- Light neutrinos are predicted to be Majorana particles.

Leptogenesis takes place in the context of see-saw models. As the Universe expands, N's go out of equilibrium ($T < M/$ few). Their decays produce a lepton asymmetry, which is then converted into a baryon asymmetry by sphaleron processes. 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.

Leptogenesis takes place in the context of see-saw models. As the Universe expands, N's go out of equilibrium ($T < M/$ few). Their decays produce a lepton asymmetry, which is then converted into a baryon asymmetry by sphaleron processes. Leptogenesis can succesfully explain the observed baryon asymmetry of the Universe.

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

It requires:

- out of equilibrium; Expansion of the Universe
- L violation;
- C and CP violation.

Leptogenesis takes place in the context of see-saw models. As the Universe expands, N's go out of equilibrium ($T < M/$ few). Their decays produce a lepton asymmetry, which is then converted into a baryon asymmetry by sphaleron processes. 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; $\boxed{(\beta\beta)_{0\nu}\text{-decay}}$
- C and CP violation.

Leptogenesis has been implemented in different type of see-saw models.

- Leptogenesis in Type I see saw with Hierarchical RH neutrinos
- Resonant leptogenesis
- Leptogenesis in Type II see-saw
- Other models....

Here I restrict the discussion to the ”simplest” case of Type I seesaw with hierarchical right-handed neutrinos ($M_1 \ll M_2 \ll M_3$).

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:

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

$\boxed{\epsilon_1}$ is the decay asymmetry which depends on the CPV phases in λ:

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

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.]

We take hierarchical right handed ($M_1 \ll M_2 \ll M_3$) neutrinos with $10^9 < M_1 < 10^{12}$ GeV.

The flavour CP-asymmetry:

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

Washout effects are flavour dependent and controlled by:

$$\widetilde{m_l} \equiv \frac{|\lambda_{1l}|^2\, v^2}{M_1}$$

The baryon asymmetry is finally given by:

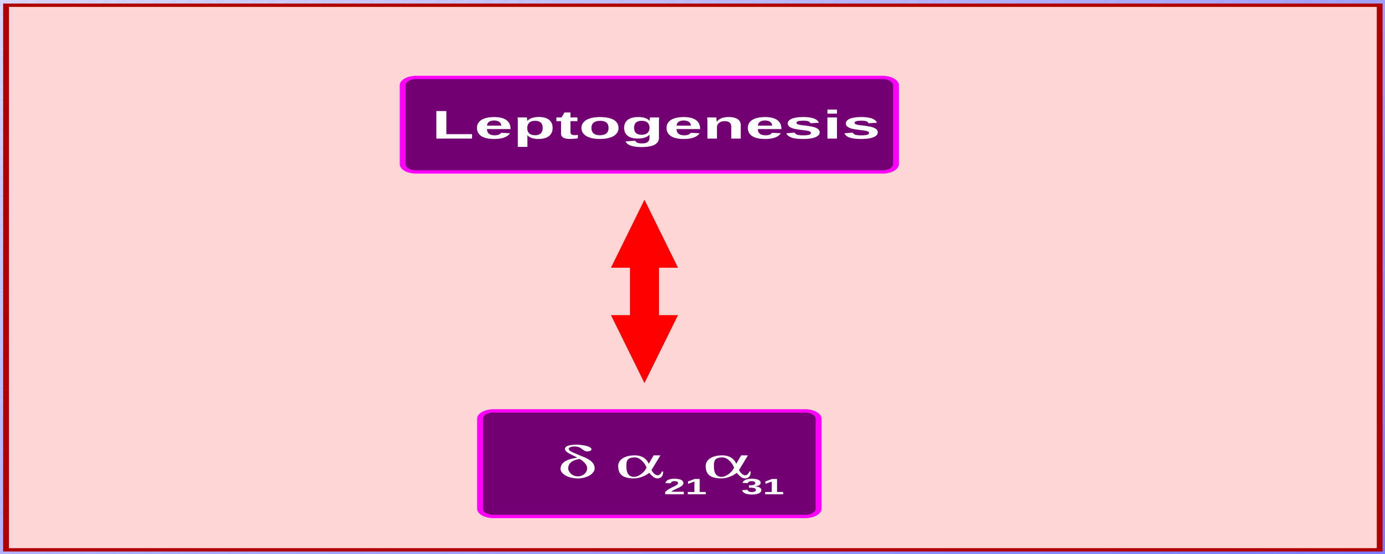
$$\boxed{Y_B \simeq -\frac{12}{37 g_*}\left(\epsilon_\tau \eta\left(\frac{390}{589}\,\widetilde{m_\tau}\right) - \epsilon_2 \eta\left(\frac{417}{589}\,\widetilde{m_2}\right)\right)}$$

From measuring the CPV phases

at low energy

can one compute the amount

of baryon asymmetry?

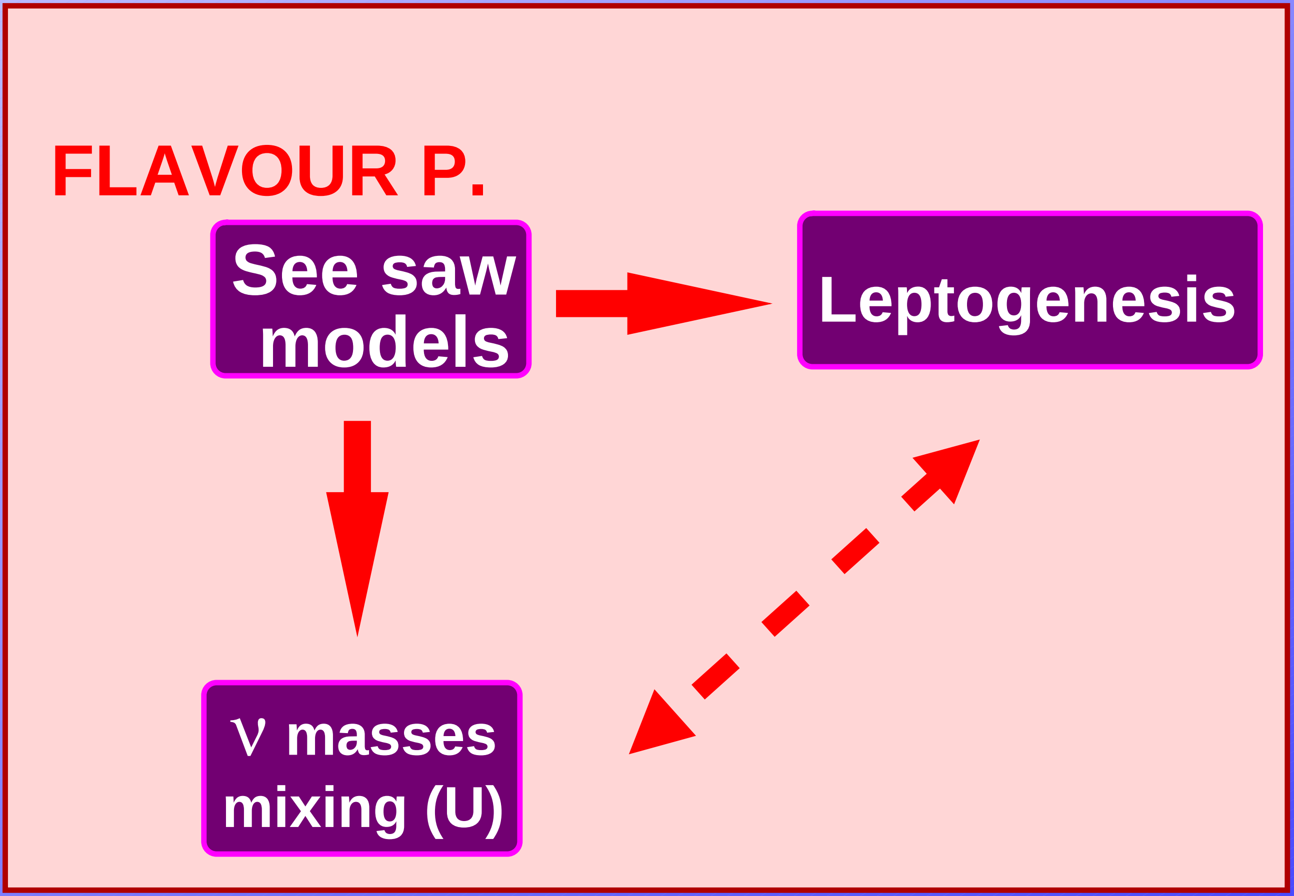


High energy parameters			Low energy parameters		
M_R	3	0	d_m	3	0
λ	9	6	U	3	3

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.



7 – Observing low-energy CPV implies leptogenesis?

From observing

leptonic CP-violation at low energy,

can we infer that

a lepton asymmetry is generated?

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

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

with flavour

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

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

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

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

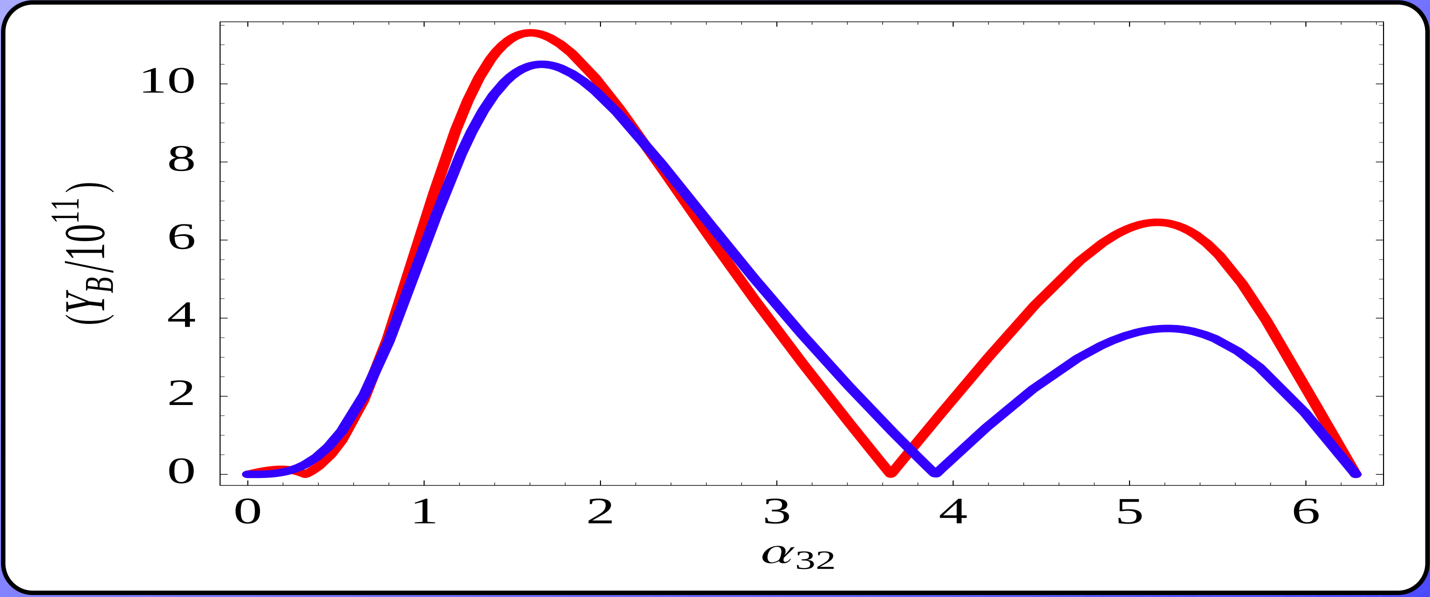
- Maximal asymmetry is obtained in the intermediate regime.

Leptogenesis due to the Majorana phase.

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

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

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



7 – Observing low-energy CPV implies leptogenesis?

Leptogenesis due uniquely to the Dirac phase.

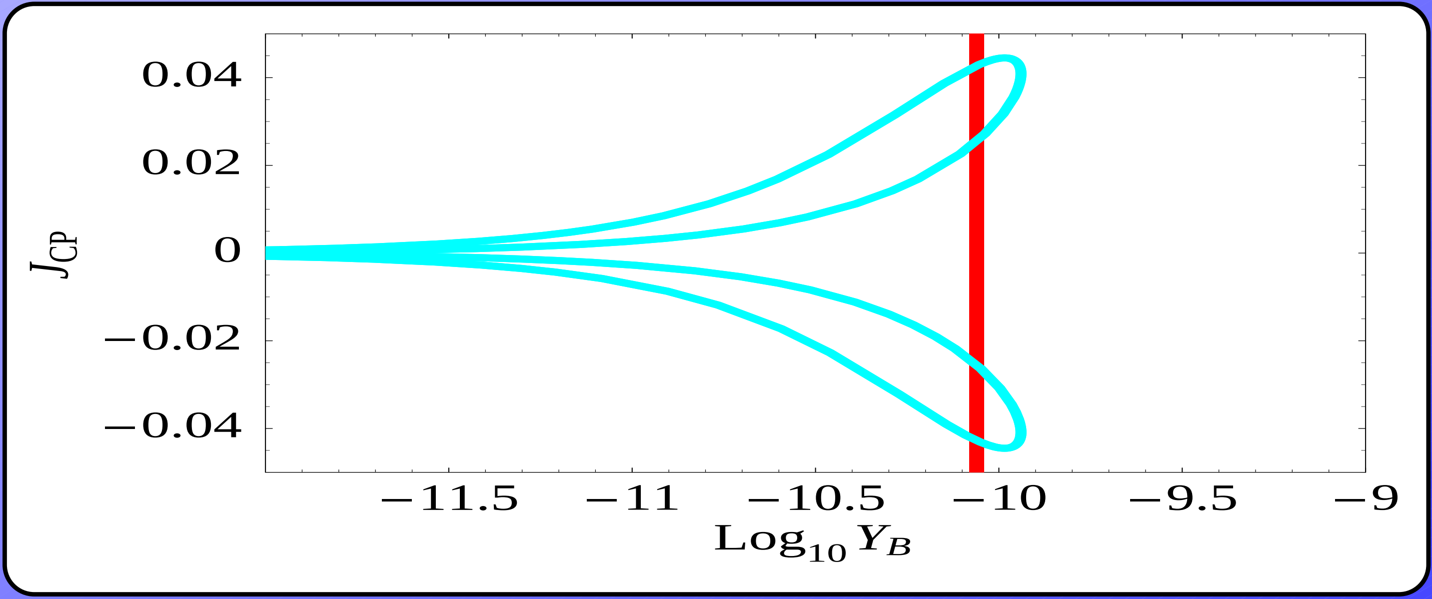
$$\boxed{|Y_B| \propto c_{23}^2\, s_{12}\, s_{13}\ |\sin\delta|.}$$

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

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



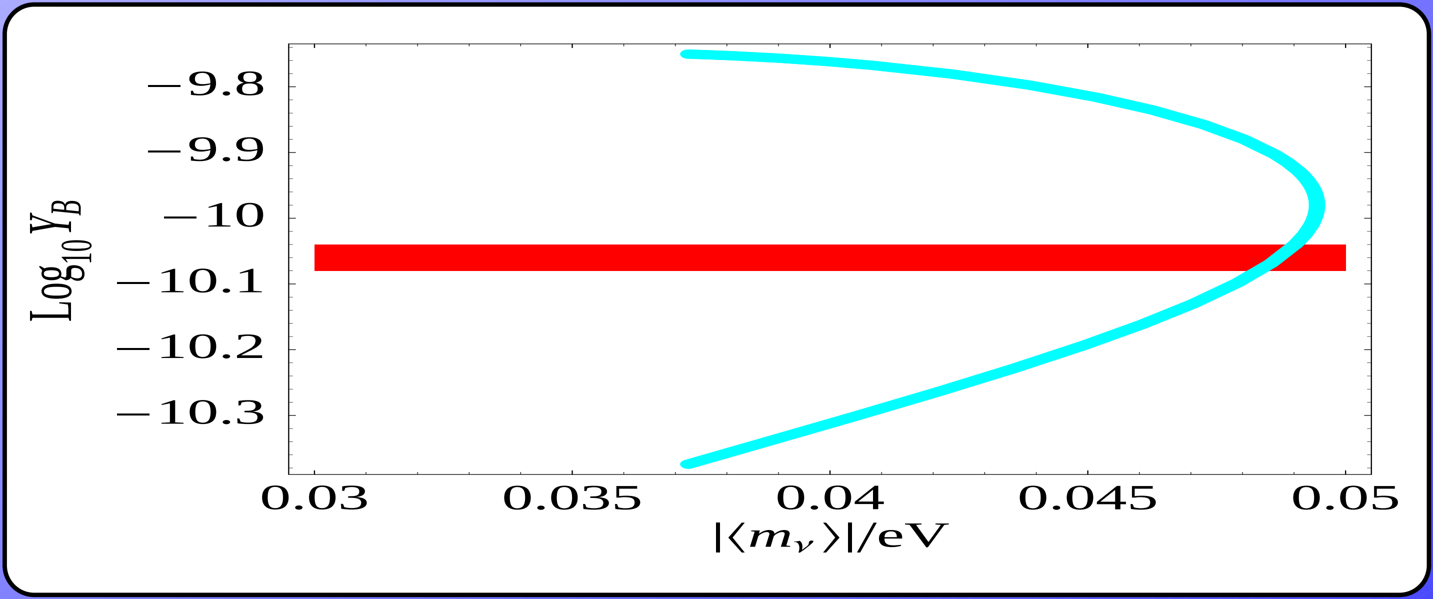
7 – Observing low-energy CPV implies leptogenesis?

IH spectrum

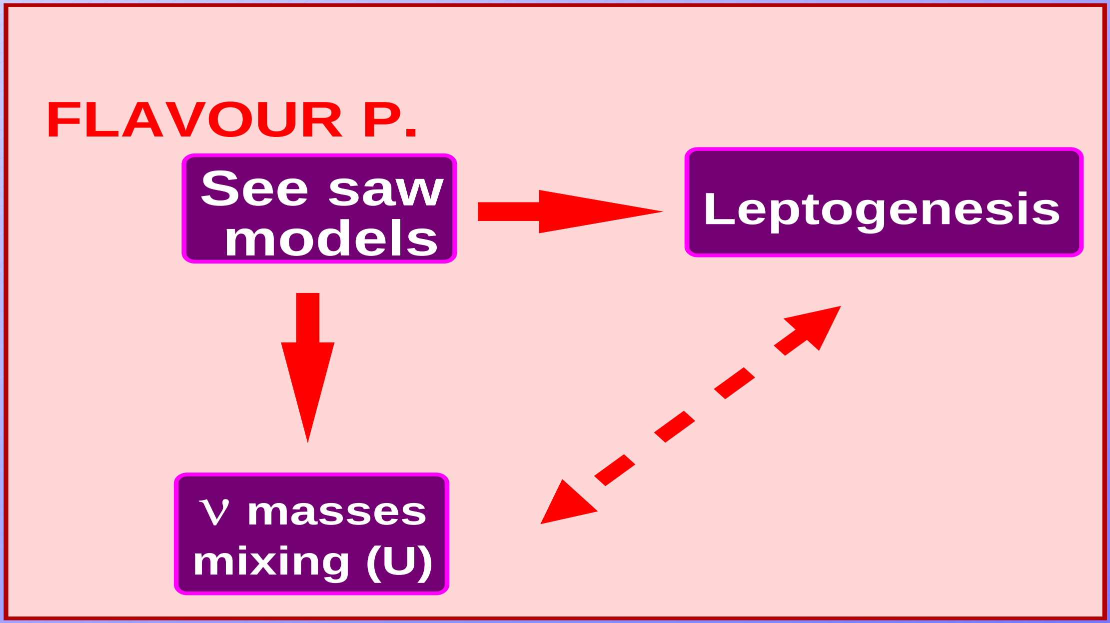
$$\epsilon_l \simeq \frac{3M_1\sqrt{\Delta m^2_{\rm atm}}}{32\pi v^2}\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)^{\frac{1}{4}}\frac{|R_{11}R_{12}|}{|R_{11}|^2+|R_{12}|^2}\,{\rm Im}\,(U^*_{l1}U_{l2})\,.$$

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

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



8 – Conclusions



FLAVOUR P.

See saw models

Leptogenesis

ν masses mixing (U)

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.