LEPTOGENESIS AND LOW ENERGY NEUTRINO PHYSICS

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1 – THE FACTS: neutrinos oscillate

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

Neutrino oscillations play

a crucial role in our understanding

of particle physics as they imply that

neutrinos have MASS and MIX (CPV ?)!

2 – THE FACTS: the baryon asymmetry

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

$$\boxed{\eta_B \simeq \eta_B - \eta_{\bar{B}} = n_B/n_\gamma}$$

- Observation of the acoustic peaks in CMB:

$$\boxed{\eta_B^{\mathrm{CMB}} = \left(6.1^{+0.3}_{-0.2}\right) \times 10^{-10}}$$

at $T^{\mathrm{CMB}} \sim 1$ eV which corresponds to $t^{\mathrm{CMB}} \sim 10^{13}$ s.

- From the abundances of light elements in BBN:

$$\boxed{\eta_B^{\mathrm{BBN}} = (2.6 - 6.2) \times 10^{-10}}$$

at $T^{\mathrm{BBN}} \sim 1$ MeV which is $t^{\mathrm{BBN}} \sim 10$ s.

Remarkable agreement!

Measuring CPV at low energy

(in neutrino oscillation experiments and/or $(\beta\beta)_{0\nu}$-decay)

and observing lepton number violation,

can it provide some information on the origin of matter

(baryon asymmetry)?

3 – Outline

- 1. 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

- 2. The see-saw mechanism and leptogenesis

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

- Conclusions

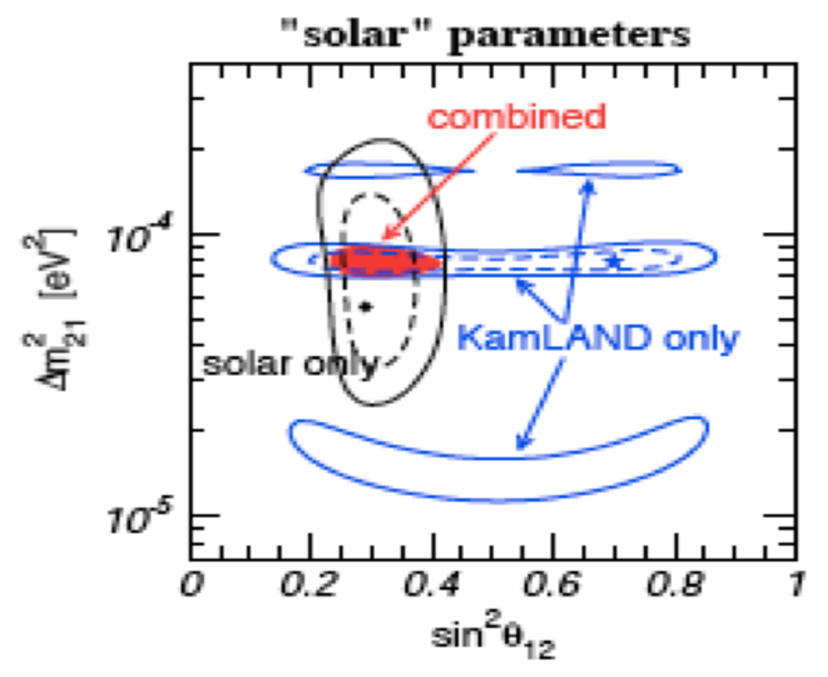
4 – ν-oscillations: present status and questions for the future

The probability of

ν_a oscillating into ν_b is:

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

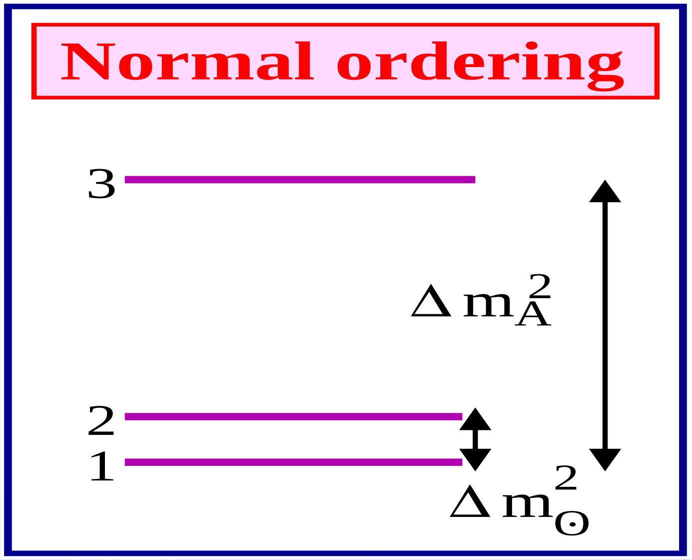
$$\simeq \quad \sin^2 2\theta \quad \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

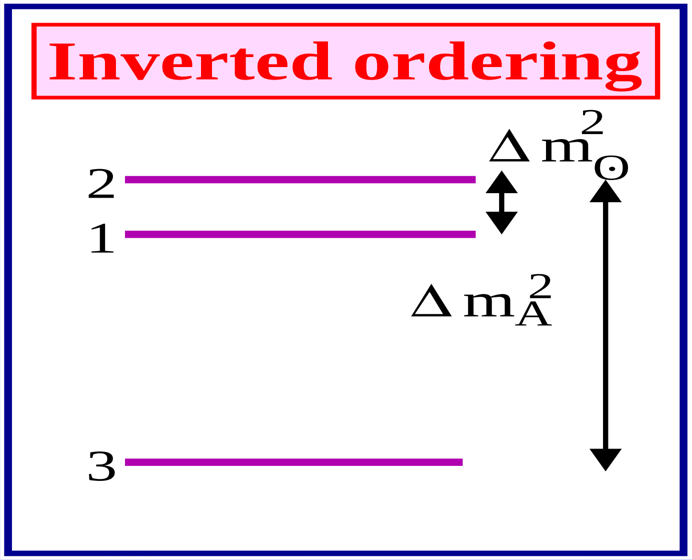


[T. Schwetz, hep-ph/0606060]

- Solar neutrino and KamLAND experiments: $\Delta m^2_{\odot}$, θ_{12}
- Atmospheric neutrino, K2K, MINOS experiments: $\Delta m^2_{\rm atm}$, θ_{23}

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





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

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

We can identify 3 types of spectra:

NH: $m_1 \ll m_2 \ll m_3$

IH: $m_3 \ll m_1 \simeq m_2$

QD: $m_1 \sim m_2 \sim m_3$.

Measuring neutrino masses requires to know:

- $m_{\rm MIN}$
- 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.

$$U = \underset{\text{Solar, reactor } \theta_\odot \sim 30^o}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \underset{\text{Atm, Acc. } \theta_A \sim 45^o}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}$$

$$\underset{\text{CPV phase}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}} \underset{\text{Reactor, Acc. } \theta < 12^o}{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \underset{\text{CPV Majorana phases}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}$$

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

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.

- **Leptonic CP-violation**?

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

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. **$\beta\beta_{0\nu}$ decay**

- Absolute value of neutrino masses?

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

- **Leptonic CP-violation**?

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

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

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 $\Delta m^2 < 0$.

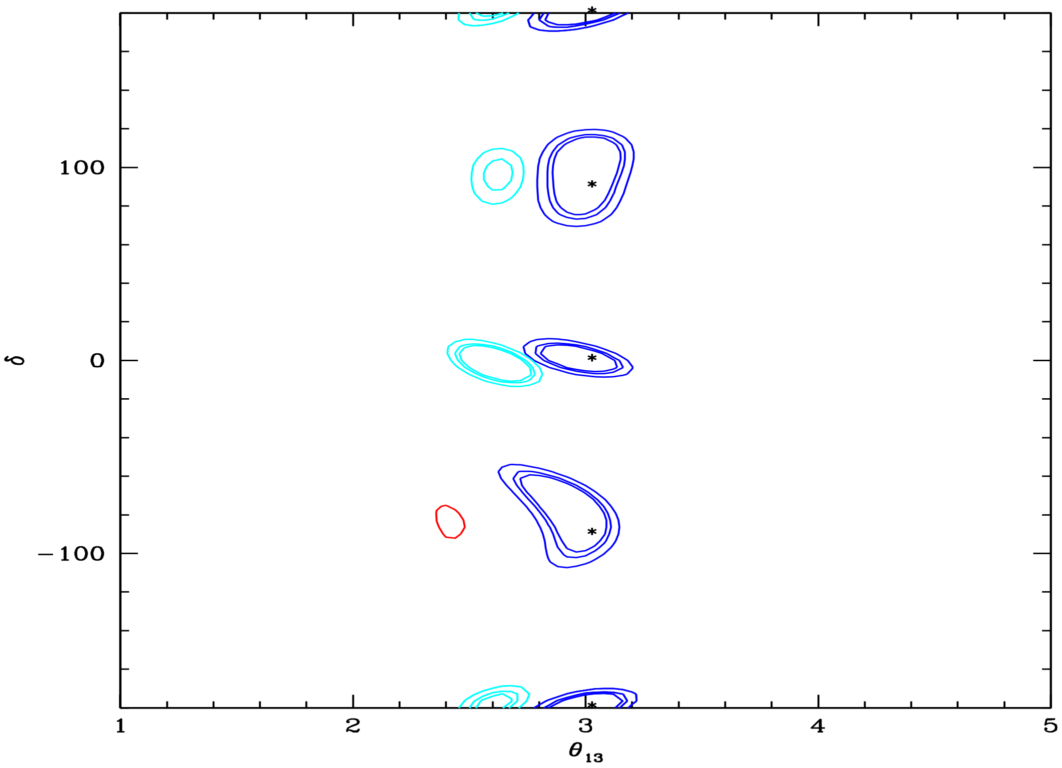
Matter effects imply that

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

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

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

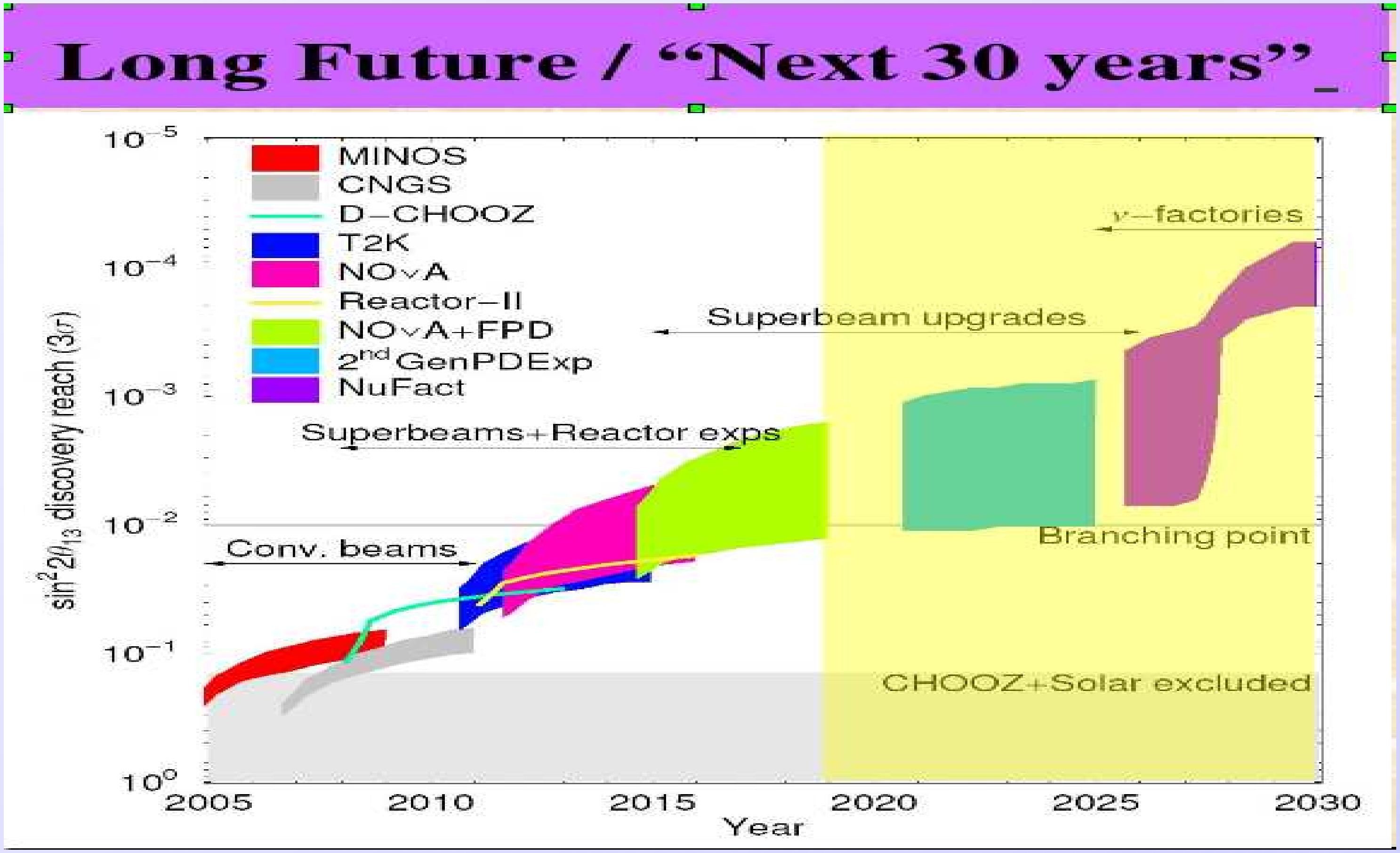
There are degenerate solutions:



1. **Superbeams**: T2K-II, NOνA.

2. **Neutrino factories**.

3. **Beta-beams**.



It is necessary to disentangle

true CP-V effects due to the δ phase

from the ones induced by matter:

problem of DEGENERACIES.

- Sensitivity to CP-violation:

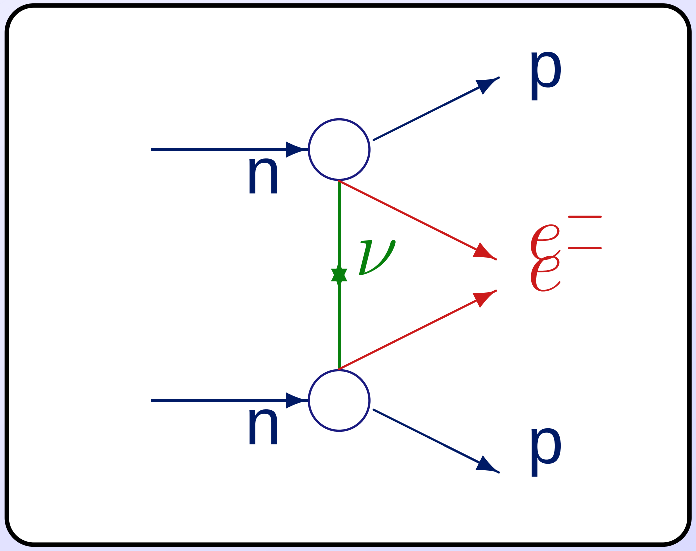
if $\sin^2 2\theta_{13} > 0.01$ in NOνA

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: $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$.



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

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

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

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

$$\boxed{|<m>| \equiv \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \right| \, ,}$$

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

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

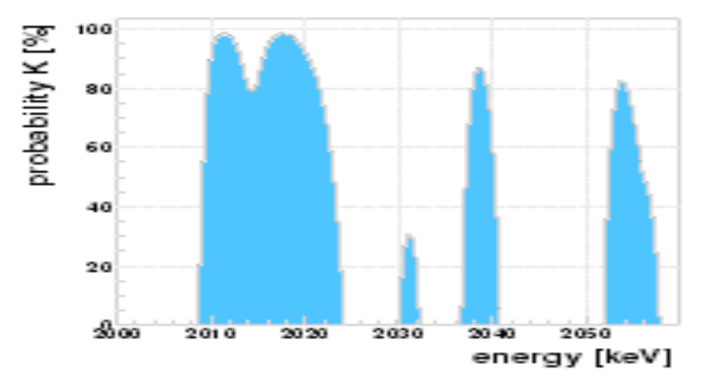
$$0.05 \text{ eV} \leq m_{\bar{\nu}_e} \cos 2\theta_\odot \leq |<m>| \leq m_{\bar{\nu}_e} < 2.2 \text{ eV}$$

The present best limit on $|\!<m>\!|$ reads:

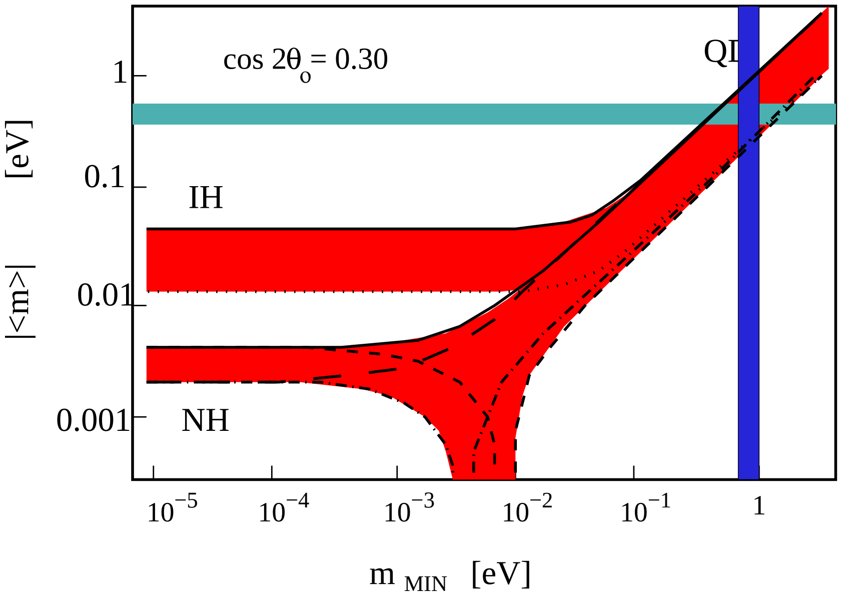
$\|\!<m>\!\| \ < (350 - 1050)\ \mathrm{meV}$	**Heidelberg-Moscow**
$\|\!<m>\!\| \ < (680 - 2800)\ \mathrm{meV}$	**NEMO3**
$\|\!<m>\!\| \ < (200 - 1050)\ \mathrm{meV}$	**CUORICINO**

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,

- For three-neutrino mixing, there are 1 Dirac CPV phase and 2 Majorana phases.
- Neutrino oscillations and $(\beta\beta)_{0\nu}$-decay experiments are sensitive to CP-violating phases.
- A wide experimental programme will aim at measuring δ and, possibly, the Majorana phases (challenging).

What information on the physics at high energy and on the baryon asymmetry can be extracted from establishing CPV?

6 – THE THEORY: The origin of neutrino masses and 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:

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

- **Lepton number is violated.**

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

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

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

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

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

- **See-saw models provide a framework for leptogenesis**.

7 – THE THEORY: Leptogenesis

How to explain the existence of the baryon asymmetry?

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

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

- In the Early Universe, there is a thermal plasma of particles ($ab \leftrightarrow cd$). Its temperature T drops as the Universe expands.
- The Majorana right-handed neutrino N_i are in equilibrium in the Early Universe as far as the processes which produce and destroy them are efficient ($N \leftrightarrow lH$).
- When $T < M_1$, N_1 drops out of equilibrium as it cannot be produced efficiently anymore.
- N_1 decays. If Γ for $N_1 \rightarrow l\Phi$ and $N_1 \rightarrow \bar{l}\bar{\Phi}$ are different, a lepton asymmetry will be generated.
- This lepton asymmetry is then converted into a baryon asymmetry by sphaleron processes.

[Fukugita, Yanagida]

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry:

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

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

$$Y_B = \frac{k}{g^*} c_s \epsilon_1 \sim 10^{-3} - 10^{-4} \epsilon_1$$

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

The one-flavour approximation

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

Only the total decay asymmetry ϵ_1 is relevant.

$\boxed{\epsilon_1}$ depends on the CPV phases in λ:

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

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:

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

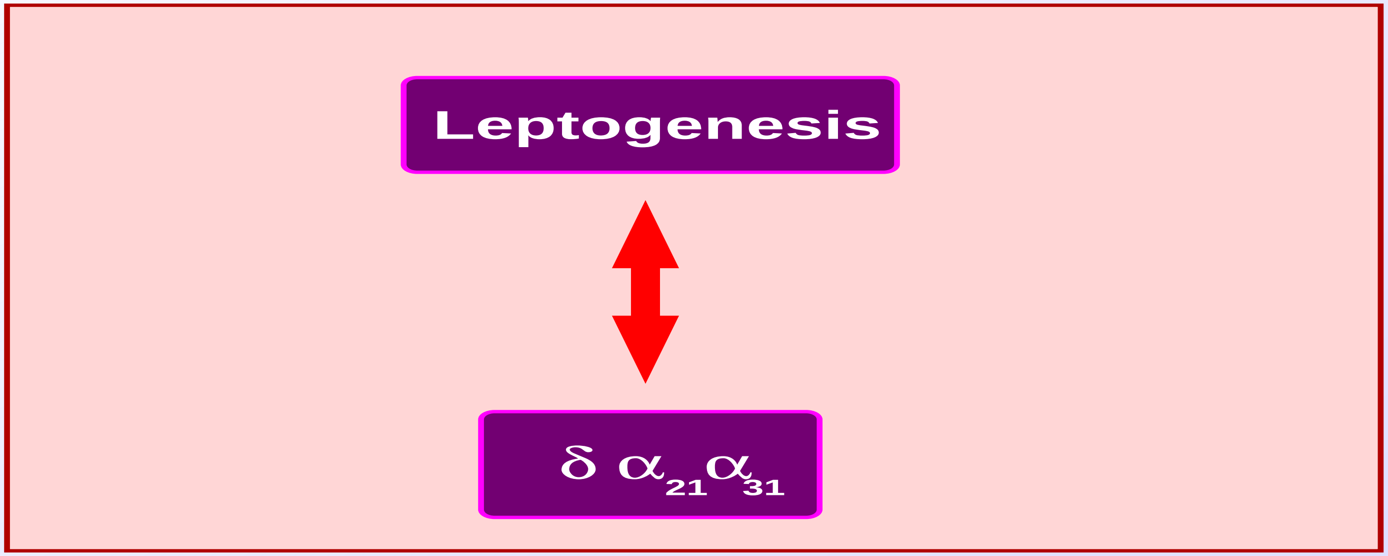
From measuring the CPV phases

at low energy

can one compute the amount

of baryon asymmetry?

7 – THE THEORY: Leptogenesis



Leptogenesis

$\delta \; \alpha_{21} \alpha_{31}$

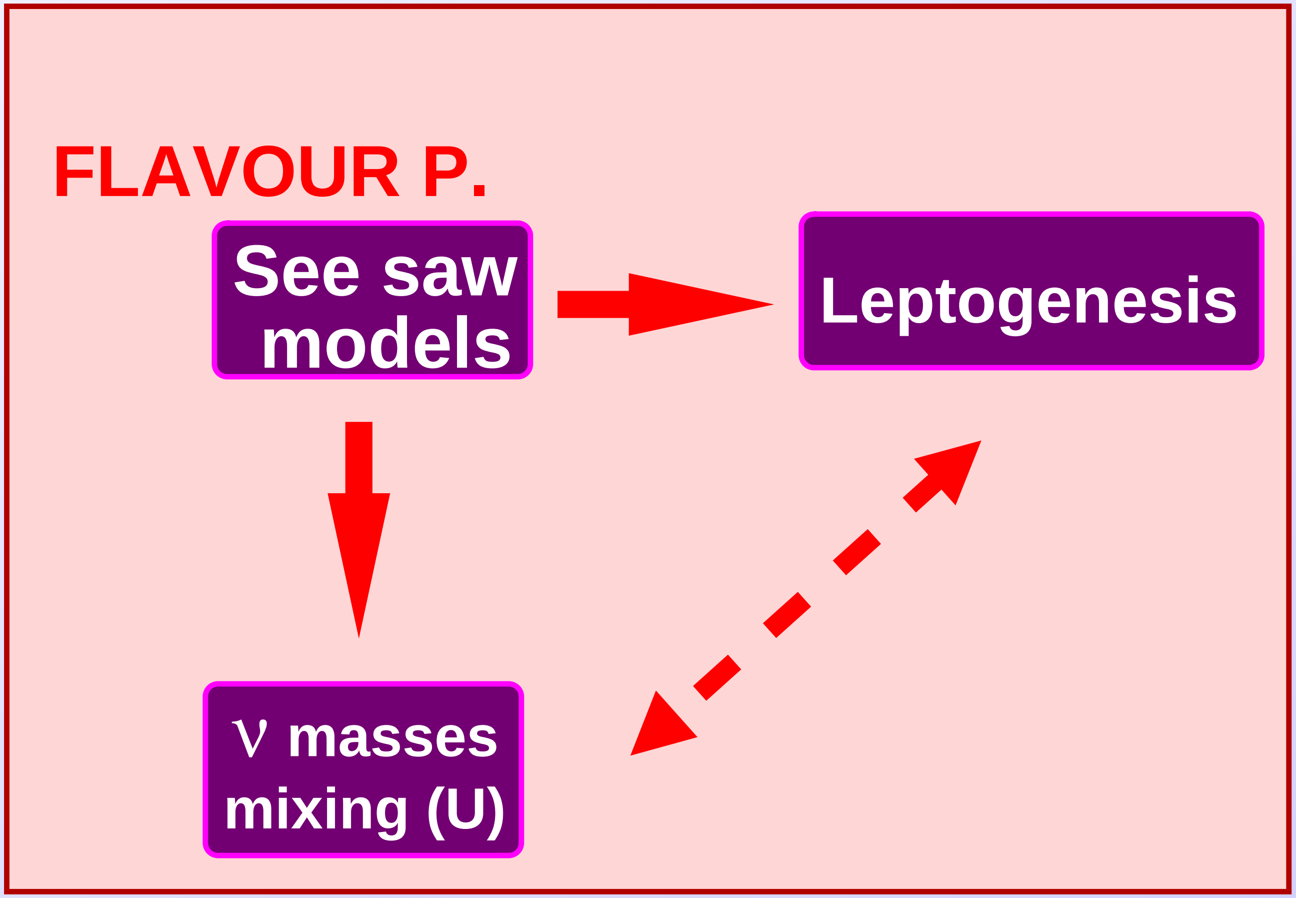
High energy parameters			Low energy parameters		
M_R	3	0	d_m	3	0
λ	9	6	U	3	3

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.



FLAVOUR P.

See saw models

Leptogenesis

ν masses mixing (U)

8 – Observing low-energy CPV implies leptogenesis?

From observing

leptonic CP-violation at low energy,

can we infer that

a baryon asymmetry

(which can be as high as observed)

is generated?

8 – Observing low-energy CPV implies leptogenesis?

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

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

with flavour

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

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

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

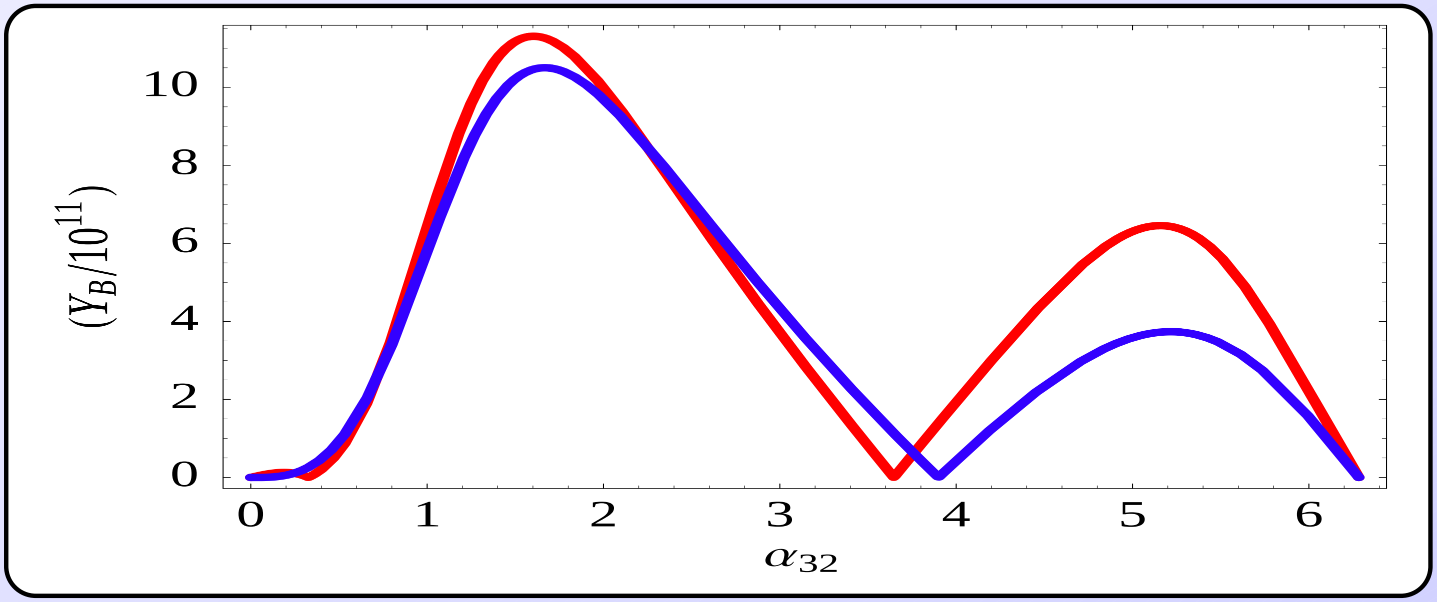
- Maximal asymmetry is obtained in the intermediate regime.

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

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



8 – Observing low-energy CPV implies leptogenesis?

Leptogenesis due uniquely to the Dirac phase.

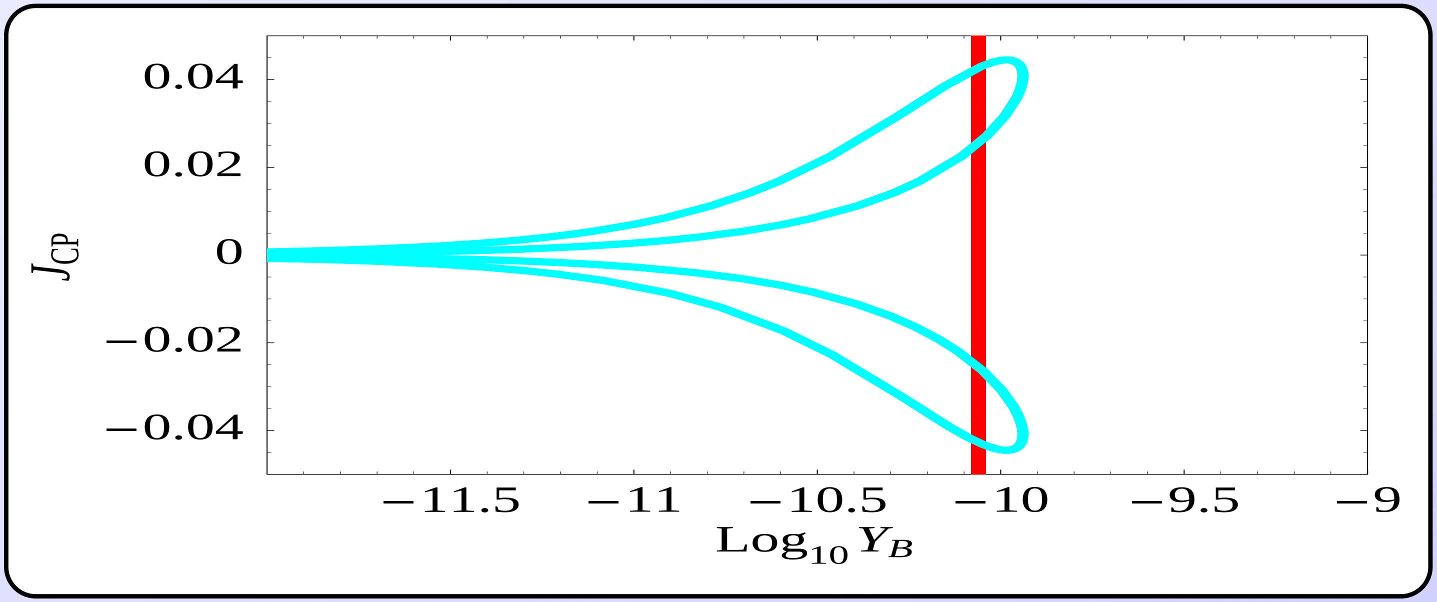
$$\boxed{|Y_B| \propto c_{23}^2\, s_{12}\, s_{13}\, |\sin\delta|.}$$

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

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

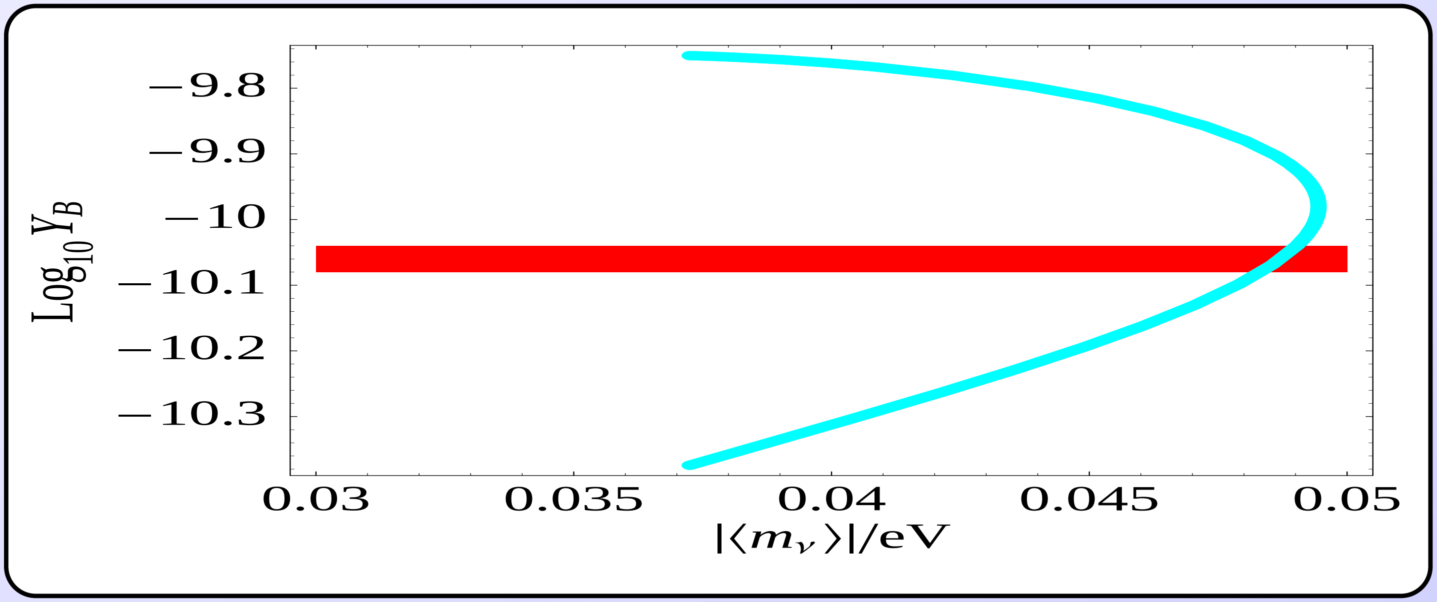


IH spectrum

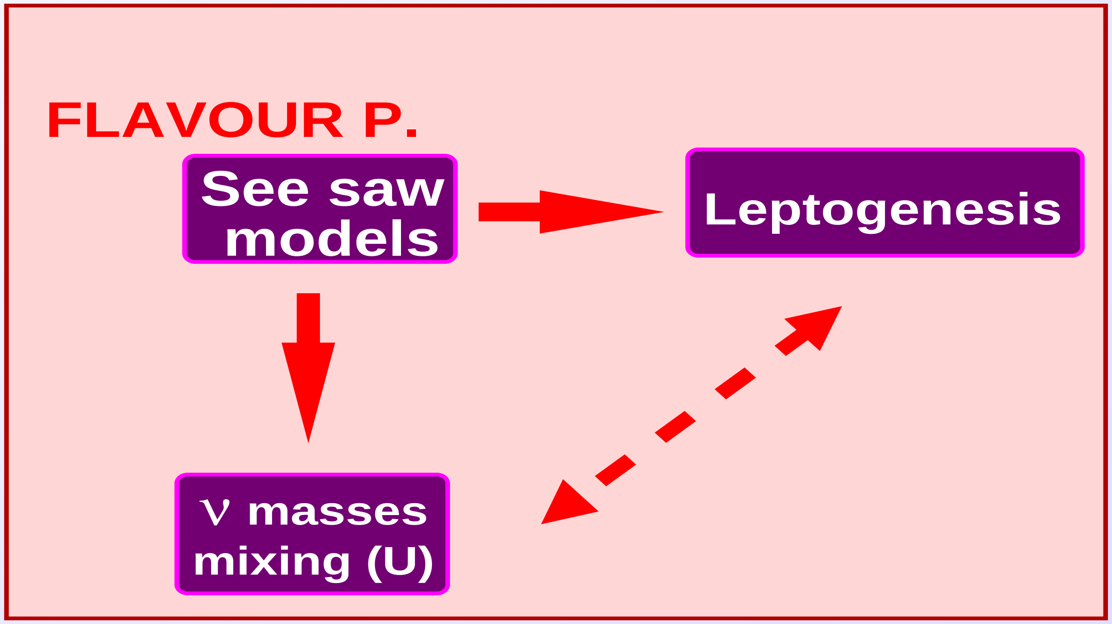
$$\epsilon_l \simeq \frac{3M_1\sqrt{\Delta m^2_{\rm atm}}}{32\pi v^2}\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)\left(\frac{\Delta m^2_\odot}{\Delta m^2_{\rm atm}}\right)^{\frac{1}{4}}\frac{|R_{11}R_{12}|}{|R_{11}|^2+|R_{12}|^2}\,{\rm Im}\,\left(U^*_{l1}U_{l2}\right).$$

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

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



9 – 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.