NEUTRINOS AS A PROBE OF CP VIOLATION AND LEPTOGENESIS

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1 – Outline

- Leptonic Dirac and Majorana CP-violation: theoretical aspects

- Determining the leptonic CPV phases in future experiments:

1) long base-line neutrino oscillation experiments

2) neutrinoless double beta decay experiments

- The see-saw mechanism and leptogenesis

- Possible connection between Low energy and High energy (leptogenesis) CP-violation

- Conclusions

2 – Dirac and Majorana CPV phases

In the case of 3 neutrino mixing, the unitary lepton mixing matrix 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.

If CP is conserved we have $\alpha_{21}, \alpha_{31} = 0$ (equal CP-parities) or $\alpha_{21}, \alpha_{31} = \pm\pi$ (opposite CP-parities).

It is possible to define rephasing invariants associated with CP-V phases.

- $\boxed{J_{CP}}$ is related to the δ phase.

$$\boxed{\begin{aligned} J_{CP} &= \mathrm{Im}(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) \\ &= \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta \end{aligned}}$$

[C. Jarlskog '85; P.I. Krastev and S.T. Petcov '88]

It controls the magnitude of CP and T violating effects in ν-oscillations.

- $\boxed{S_1}$ and $\boxed{S_2}$ are linked to the two Majorana CP-violating phases.

$$\boxed{S_1 = \mathrm{Im}(U_{e1}U^*_{e3})} \text{ and } \boxed{S_2 = \mathrm{Im}(U_{e2}U^*_{e3})}$$

[see e.g., J.F. Nieves and P.B. Pal; J.A. Aguilar-Saavedra and G.C. Branco]

They enter in neutrinoless double beta decay [S.M. Bilenky, S.T. Petcov and S.P.].

3 – Measuring CP-V phases

The δ phase

The Dirac phase δ can be measured in ν-oscillation experiments.

A measure of CP- violating effects is provided by the CP-asymmetry (in vacuum):

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

CP- (T-) violating effects in neutrino oscillations are controlled by $\sin\theta_{13}$.

The CP-asymmetry will be searched for in future long base-line experiments, looking for $\nu_\mu \longrightarrow \nu_e(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$, $(\nu_e \longrightarrow \nu_{\mu,\tau}(\bar{\nu}_e \longrightarrow \bar{\nu}_{\mu,\tau}))$.

These oscillations take place in matter (Earth).

The Earth matter (e^-, p and n) is not charge-symmetric $\Rightarrow$ Matter effects violate CP ($A \equiv \sqrt{2} G_F \bar{n}_e$).

The probability can be approximated as (for $\Delta m^2_{12} \sim 0$):

$$\boxed{P_{e\mu} = \sin^2\theta_{23}\sin^2 2\theta^m_{13}\sin^2\frac{\Delta^m_{13}L}{2}}$$

The mixing angle changes with respect to the vacuum case:

$$\boxed{\sin 2\theta_m = \frac{(\Delta m^2/2E)\sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E}\cos 2\theta - A\right)^2}}}$$

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

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:

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

It is necessary to disentangle

true CP-V effects due to the δ phase

from the ones induced by matter.

There are degenerate solutions:

$$\left.\begin{array}{l} \Delta m^2_{31}\ ,\ \theta_{13}\ ,\ \delta\ ,\ \theta_{23} \\ \Delta m^2_{31}{}',\ \theta'_{13}\ ,\ \delta',\ \theta'_{23} \end{array}\right\} \longrightarrow P, \bar{P}$$

Degeneracies worsen the sensitivity of future experiments to θ_{13}, the type of hierarchy and CP-violation. It is crucial to resolve them.

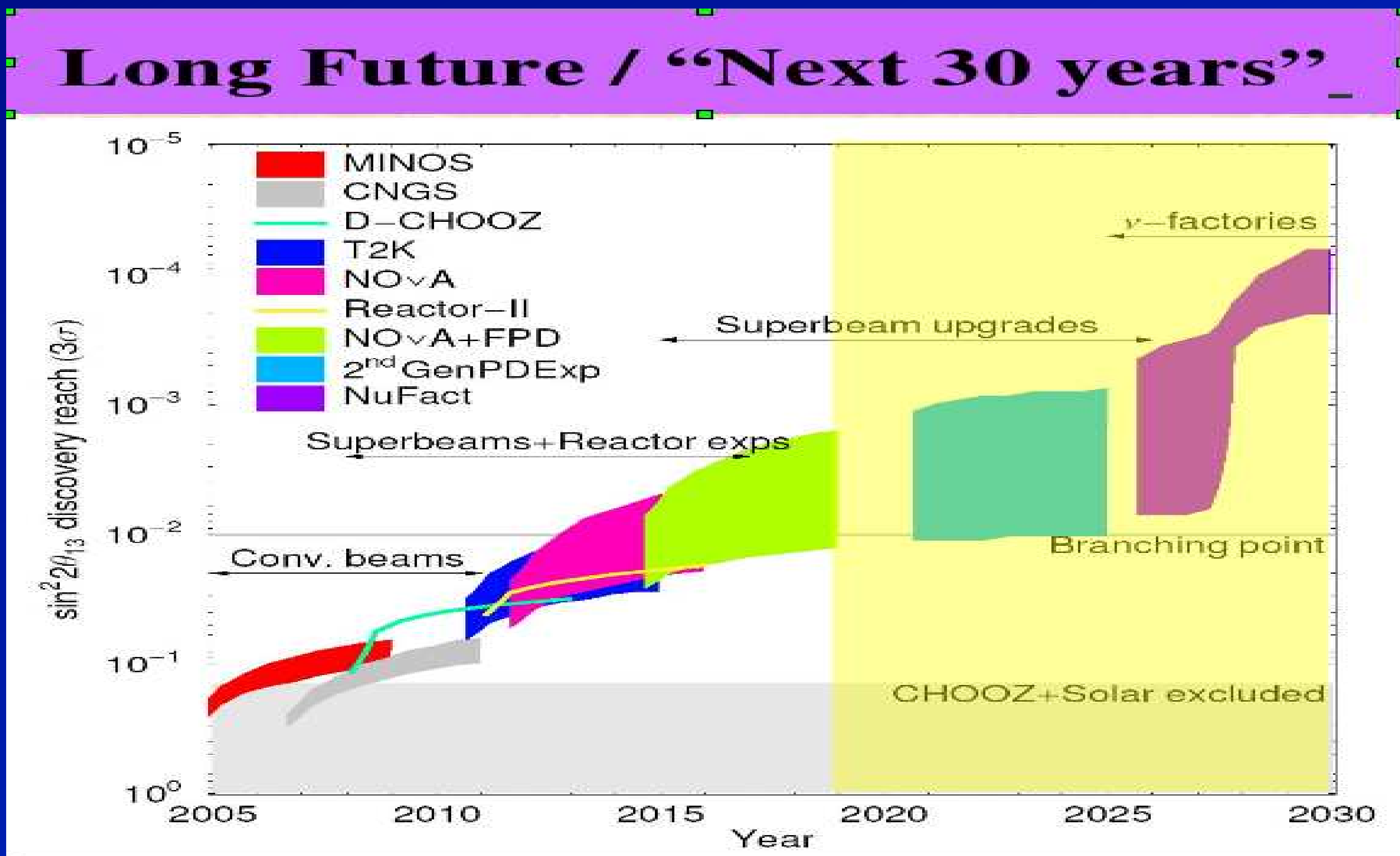
Many approaches have been suggested. For example: combination of different channels, gold ($\nu_\mu \to \nu_e$) + silver channels ($\nu_e \to \nu_\tau$) [Burguet-Castell et al.]; use different energies and/or baselines: NUMI + T2K [Minakata, Nunokawa, Parke; Mena, Parke]; use energy spectrum [Rubbia]; reactors neutrinos + LBL exp. [Minakata, Sugiyama, Yasuda]; atmospheric neutrinos + LBL [Huber, Schwetz, Winter]; use two detectors in the neutrino mode only in NOνA [Mena, Palomares-Ruiz, SP]; use two detectors in T2K [Hagiwara, Okamura, Senda; Ishitsuka et al.]...

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.**

1. Superbeams.

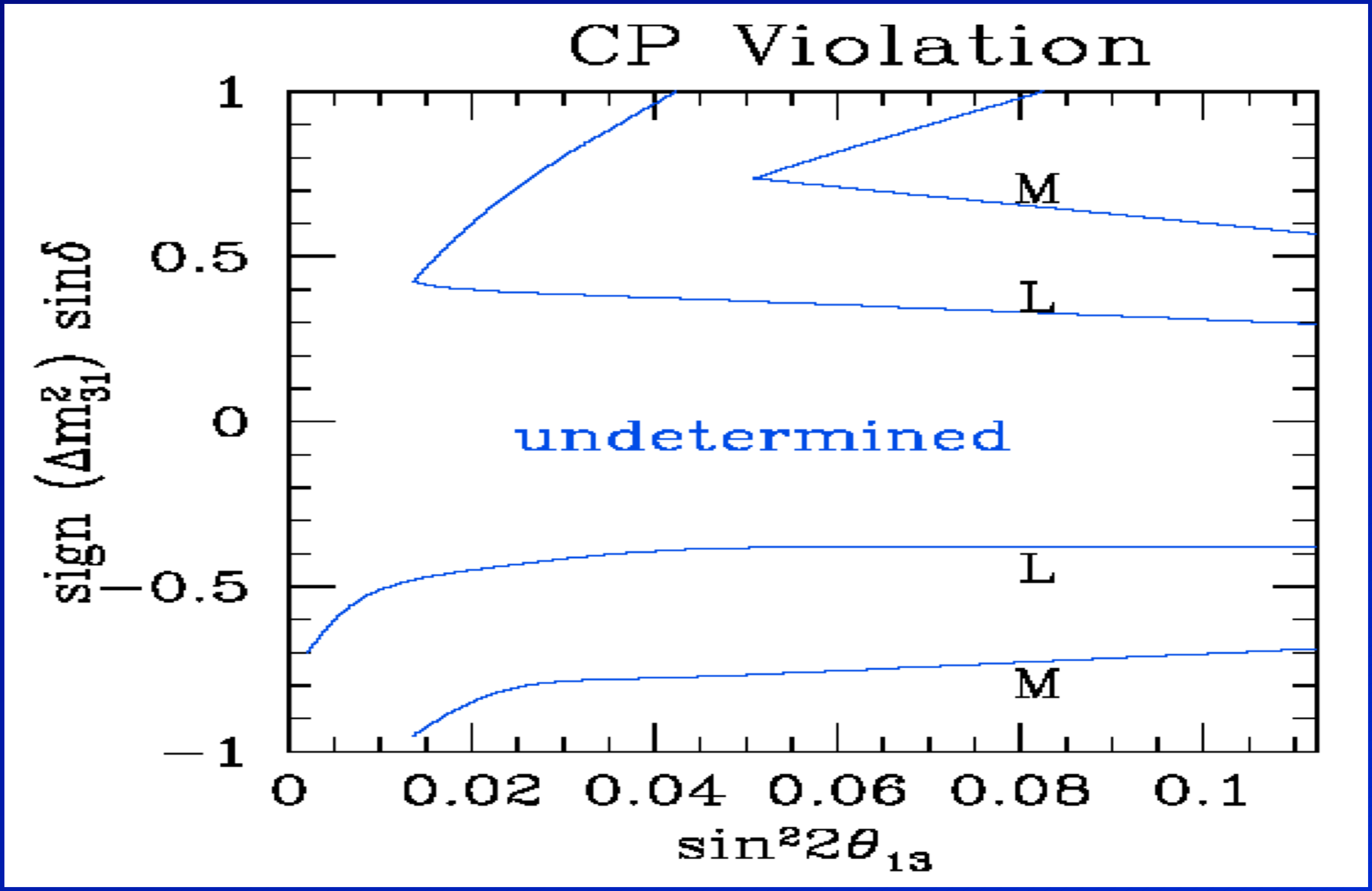
2. Neutrino factories.

3. Beta-beams.



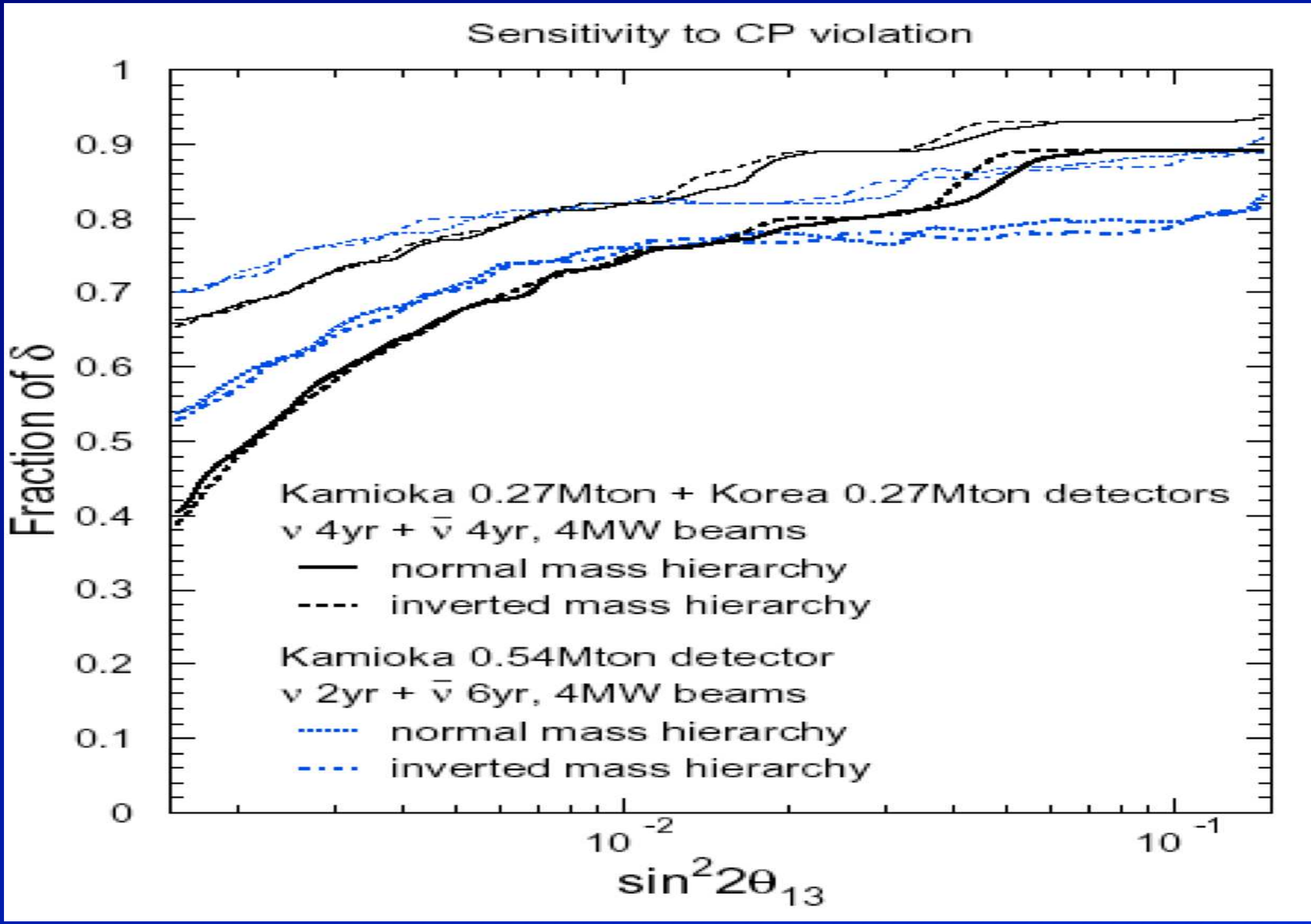
Superbeams

NOνA: off-axis neutrino oscillation experiment at Fermilab (see B. Choudhary's talk).



[O. Mena and S. Parke]

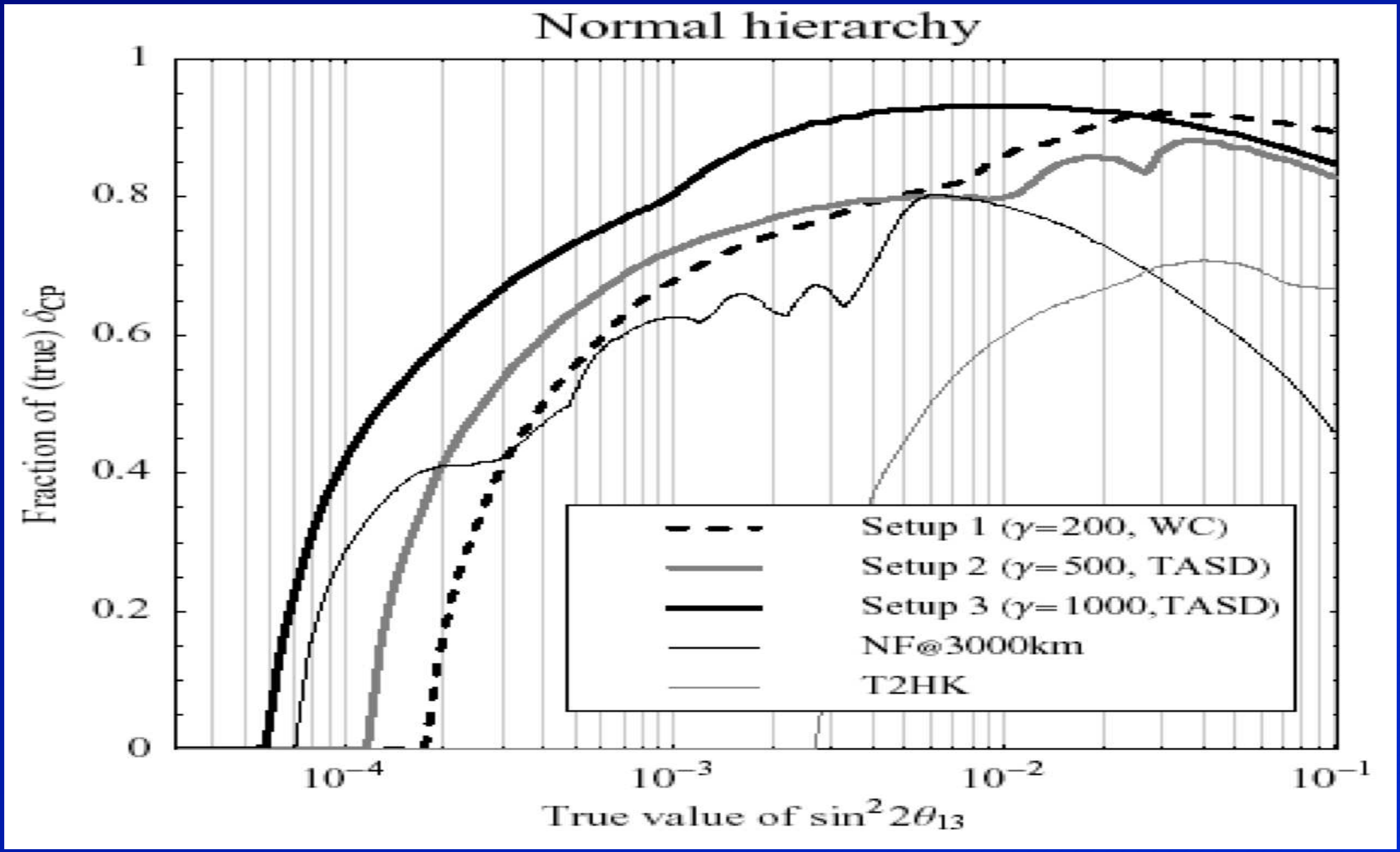
T2K-II: ν_μ off-axis beam in Japan from Tokai to Super-K and Hyper-K (phase II). (see T. Kajita's talk)



[M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa]

Neutrino factory and beta-beams

For smaller values of $\sin^2\theta_{13}$, more sensitive machines are required.



[P. Huber, M. Lindner, M. Rolinec and W. Winter]

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

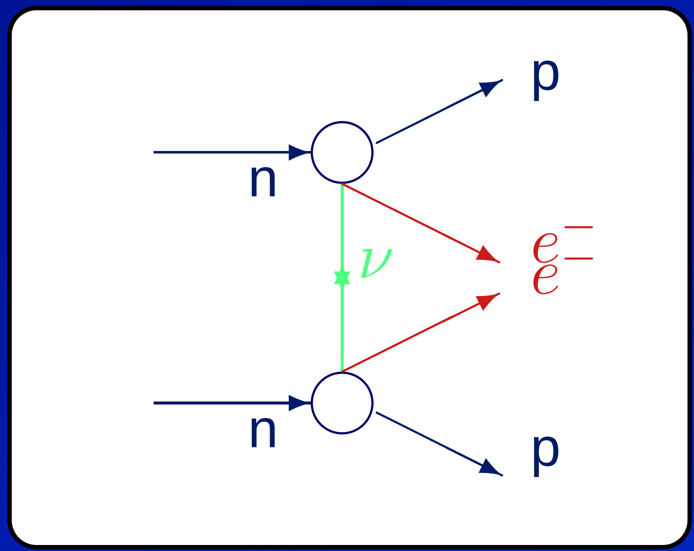
if $\sin^2 2\theta_{13} > 0.003$ in T2K-II

if $\sin^2 2\theta_{13} > 10^{-4}$ at a neutrino factory or β-beam.

Majorana phases

Majorana phases can be measured only in processes which violate the lepton number by 2 units ($\Delta L = 2$).

By far, the most sensitive of these processes is neutrinoless double beta decay: $(A, Z) \longrightarrow (A, Z+2) + 2e^-$.



$(\beta\beta)_{0\nu}$-decay has a special role in the study of neutrino properties, as it probes the violation of **global lepton number**, and it might provide information on the **neutrino mass spectrum, absolute neutrino mass scale and CP-V**.

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

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

- M_F, M_{GT} are nuclear matrix elements.
- $| < m > |$ **is the effective Majorana mass parameter**:

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

For light neutrinos, $|{<}\, m \,{>}|$ contains all the dependence of $\mathrm{T}_{0\nu}^{1/2}$ on the neutrino parameters.

$U_{\mathrm{e}j}$ are the elements of the lepton mixing matrix U_{PMNS}, m_j the masses of the massive neutrinos ν_j, α_{21} and α_{31} the CP-violating phases.

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

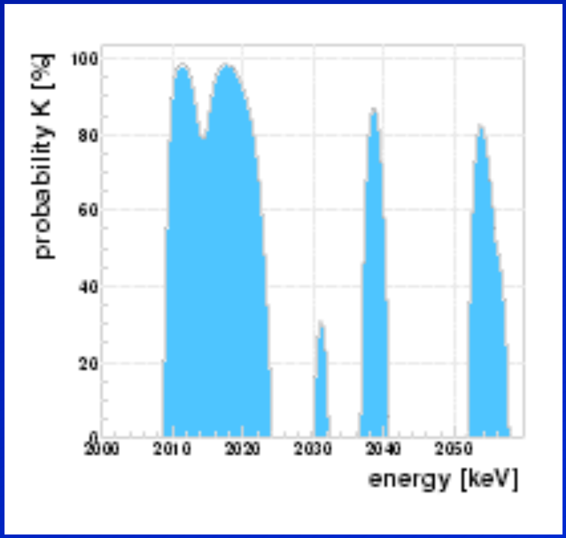
$$|<m>| \ < (350 - 1050) \ \mathrm{meV}$$ **Heidelberg-Moscow**

$$|<m>| \ < (680 - 2800) \ \mathrm{meV}$$ **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

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



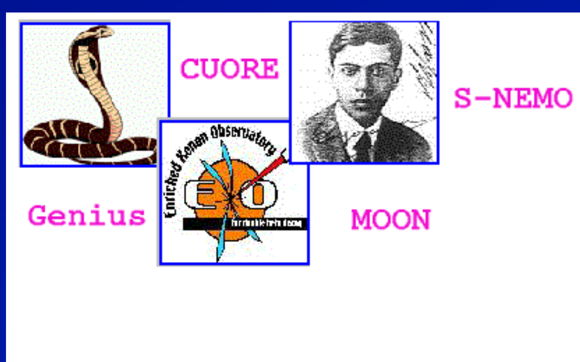
It is still a controversial even if very interesting result.

There are prospects to improve the present limit and test the discovery claim down to $|\!<m>\!| \ \sim 200 - 300\ \mathrm{meV}$ in the present experiments NEMO3 and Cuoricino

and by one order of magnitude,

$|\!<m>\!| \ \sim 10 - 30\ \mathrm{meV}$,

in the new generation of experiments which is now under R&D and construction (CUORE, GENIUS, Majorana, SuperNEMO, EXO, GERDA, COBRA).



Mass quasi degeneracy (QD)

$m_1 \simeq m_2 \simeq m_3 \equiv m_{\bar{\nu}_e}$

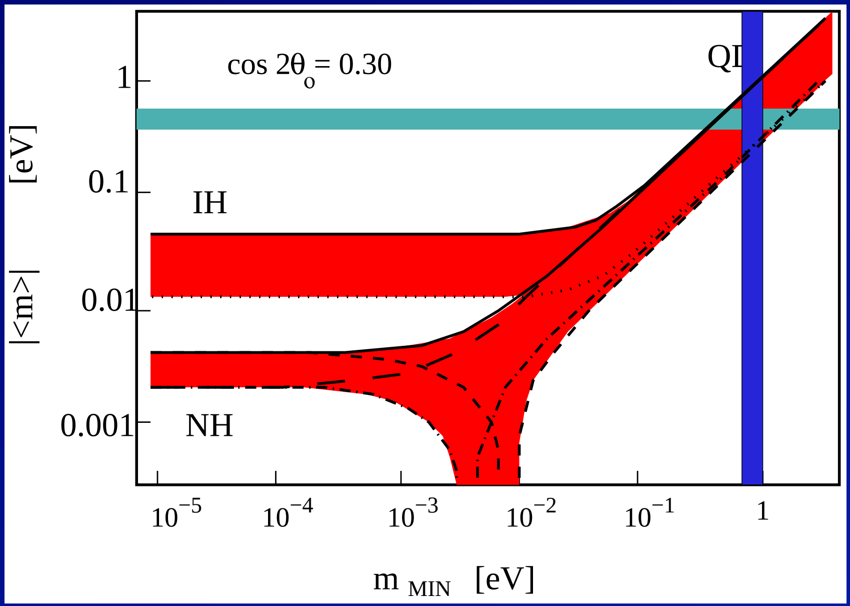
$$\boxed{|{<}\, m\, {>}| \;\simeq m_{\bar{\nu}_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}} \right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|}$$

$|{<}\, m\, {>}|$ has both a lower and an upper bound:

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

All the allowed range for $|{<}\, m\, {>}|$ is in the range of sensitivity of present and upcoming $(\beta\beta)_{0\nu}$-decay experiments.

Analogous expressions can be found for the NH ($m_1 \ll m_2 \ll m_3$) and IH ($m_3 \ll m_1 \sim m_2$) mass spectra. The expected values of $|{<}\, m\, {>}|$ are smaller than in the QD case.



In principle, a measurement of $|<m>|$

combined with a measurement of m_1

(in tritium β-decay exp. and/or cosmology)

would allow to establish if

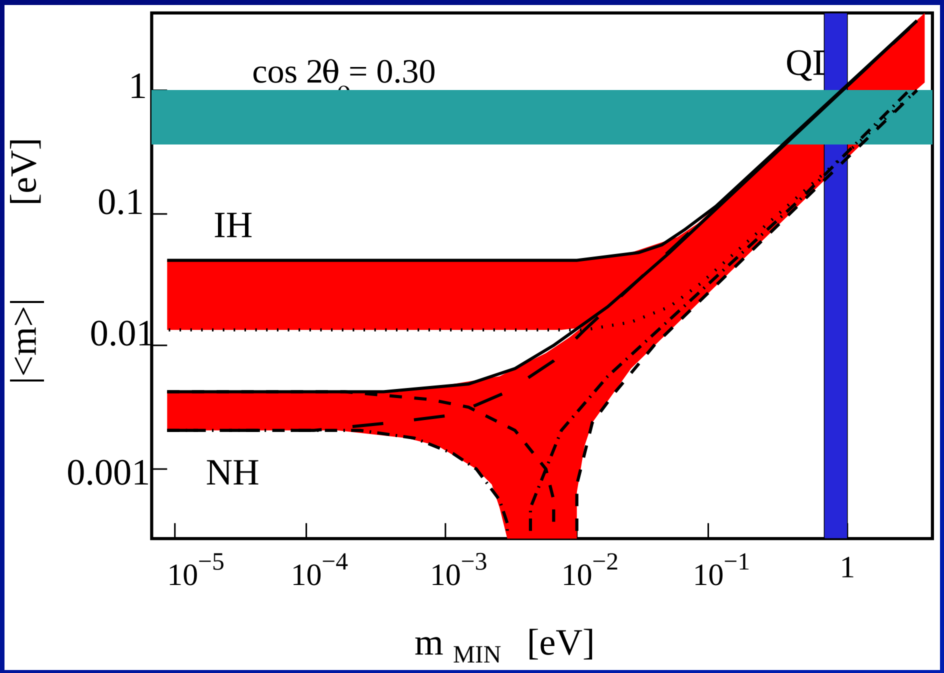
CP is violated

and to constrain the CPV phases,

once the ν mass spectrum is known.

For ex., for the QD spectrum, we have:

$$\sin^2 \alpha_{21}/2 \simeq \left(1 - \frac{|<m>|^2}{{m_{\bar{\nu}_e}}^2}\right) \frac{1}{\sin^2 2\theta_\odot}.$$



Due to the experimental errors and

nuclear matrix elements uncertainties,

determining that

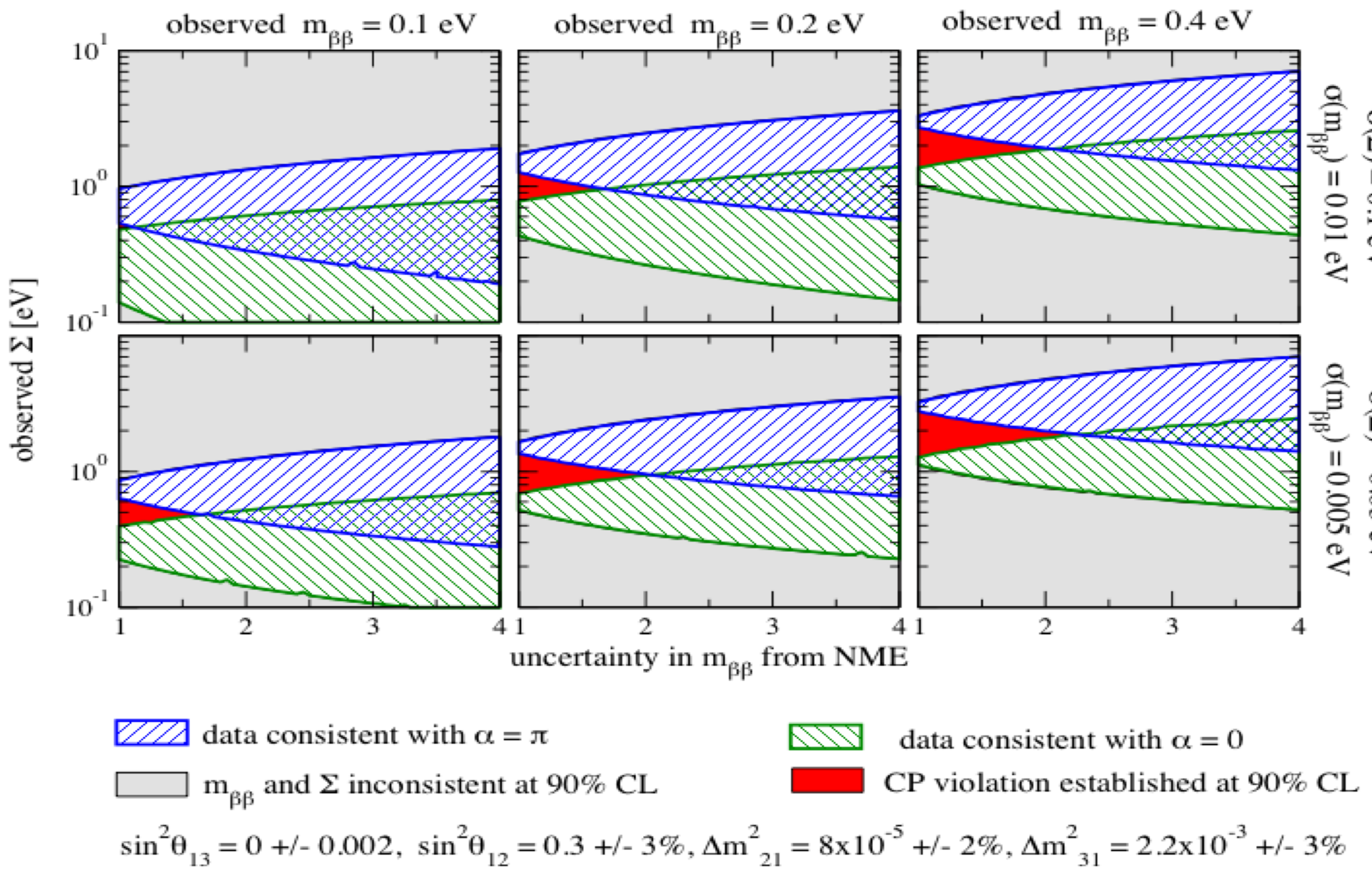
CP is violated in the lepton sector

due to Majorana CPV phases is

challenging.

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

The uncertainty in the nuclear matrix elements plays a crucial role.



[S.P., S. Petcov, T. 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 $\left|<m>\right|$ and neutrino masses;

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

From probing

leptonic CP-violation at low energy,

which information

can we obtain

about the physics at high energy

and in particular about leptogenesis?

4 – 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]

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:

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

- **Lepton number is violated.**
- The see-saw mechanism can be embedded in GUT theories (see R. Mohapatra's talk).

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

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

$$\boxed{\begin{aligned} &M_1 \simeq M_R \\ &m_2 \simeq \frac{m_D^2}{M_R} \sim \frac{1\ \mathrm{GeV}^2}{10^9\ \mathrm{GeV}} \sim 1\,\mathrm{eV} \end{aligned}}$$

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

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

- Light neutrinos are predicted to be Majorana particles.

Leptogenesis takes place in the context of see-saw models (see E. Ma's and T. Hambye's talks). 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.

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

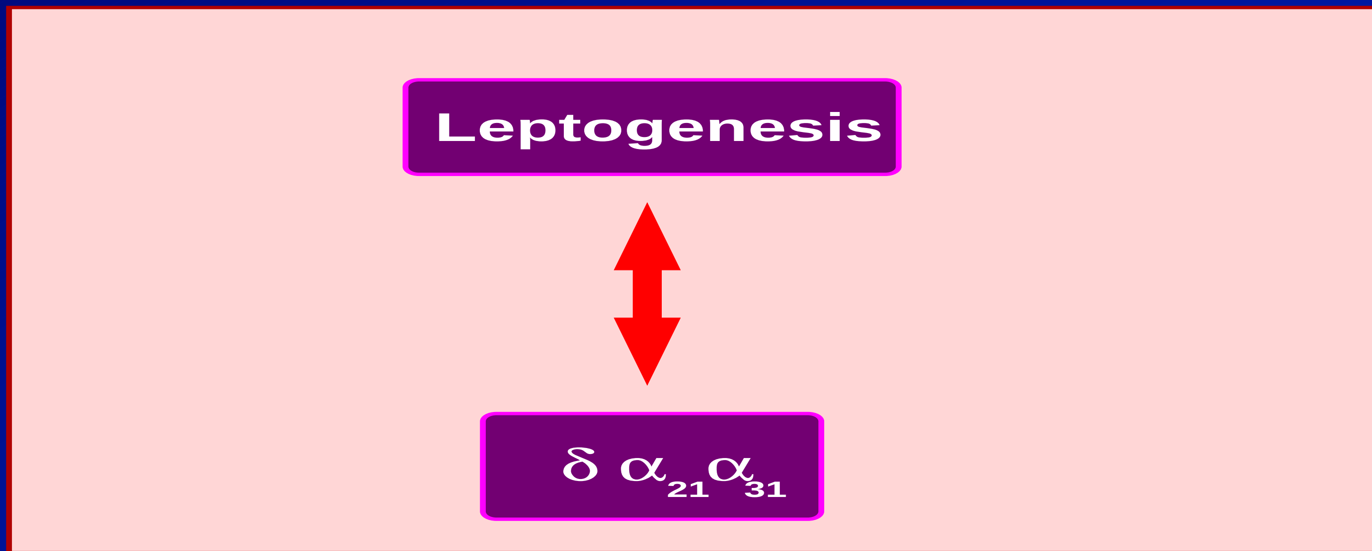
The baryon asymmetry is given by:

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

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

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

5 – 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
Y_ν	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 the biunitary parameterization, $Y_\nu = V_R^\dagger(\beta_1, \beta_2, \beta_3) y V_L(\alpha_1, \alpha_2, \alpha_3)$:

$$\boxed{\begin{array}{ll} \epsilon_1 \propto \mathrm{Im}(V_R^\dagger y^2 V_R)^2_{1j} & \Rightarrow \epsilon_1(\beta_1, \beta_2, \beta_3) \\ m_\nu = V_L^\dagger y V_R M_R^{-1} V_R^T y V_L^* & \Rightarrow m_\nu(\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \beta_3) \end{array}}$$

[Davidson, Ibarra; Ellis et al.; SP, Petcov, Rodejohann]

- ϵ_1 depends only on the mixing in the right-handed sector.

m_ν depends on all the parameters in Y_ν, both the mixing in the left and right-handed sector.

- Additional information can be obtained in **LFV charged lepton decays** which depend on V_L (see for example S. Petcov et al. 2005).

Even if the soft breaking terms are diagonal at the SUSY breaking scale M_X, the radiative corrections due to Y_ν induce off-diagonal soft terms.

$$BR(l_i \to l_j \gamma) \propto |P_{ij}|^2$$

$$P = Y_\nu^\dagger \log \frac{M_X}{M} Y_\nu \sim V_L^\dagger y^2 V_L.$$

-

if there is CPV in V_R (leptogenesis), we can expect to have CPV in m_ν.

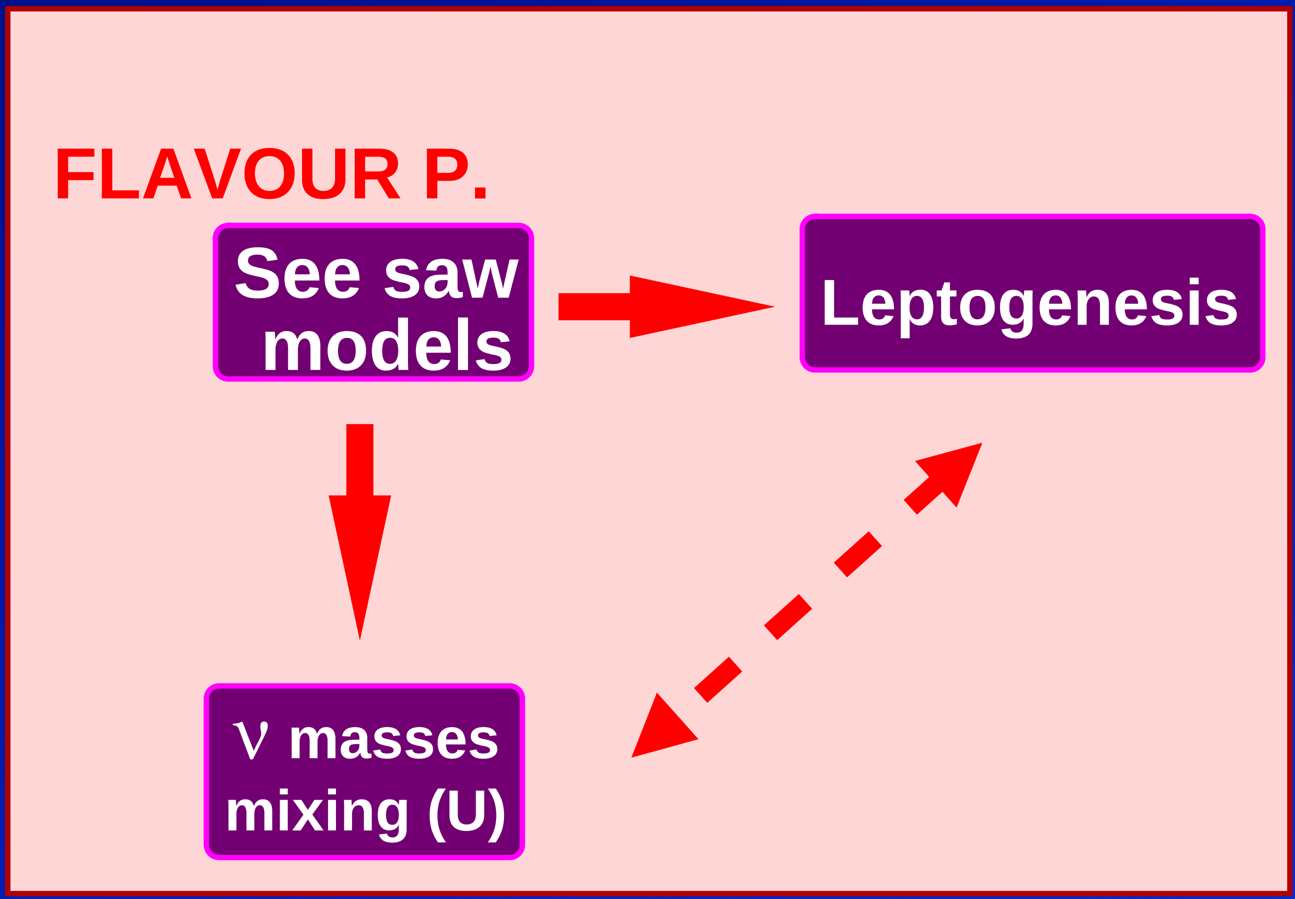
$$
\begin{aligned}
J_{CP} & \propto Im\left(h_{12} h_{23} h_{31}\right) \\
& \propto Im\Big((V_L^T y V_R^* M_R^{-1} V_R^\dagger y^2 V_R M_R^{-1} V_R^T y V_L)_{12} \\
& \quad (V_L^T y V_R^* M_R^{-1} V_R^\dagger y^2 V_R M_R^{-1} V_R^T y V_L)_{23} \\
& \quad (V_L^T y V_R^* M_R^{-1} V_R^\dagger y^2 V_R M_R^{-1} V_R^T y V_L)_{31} \Big)
\end{aligned}
$$

[Branco et al.]

Even if $\delta = 0$ at high scale, RGE's effects can generate it at low energy.

In understanding the origin of the flavour structure, the see-saw models have a reduced number of parameters. In many cases,

it is possible to link directly Dirac and Majorana phases to leptogenesis.



- Minimal see-saw model:

With only 2 heavy neutrinos, all the high energy parameters (8 + 3) can be reconstructed by using U and P. With additional 2 texture zeros, there is only one phase. It can be shown that:

$$\epsilon_1 \propto \sin 2\delta$$
$$J_{CP} = \mathrm{Im}(Y_{12} Y_{23} Y_{31}) \propto -\sin 2\delta$$

[Frampton, Glashow, Yanagida; Ibarra, Ross; Ibarra]

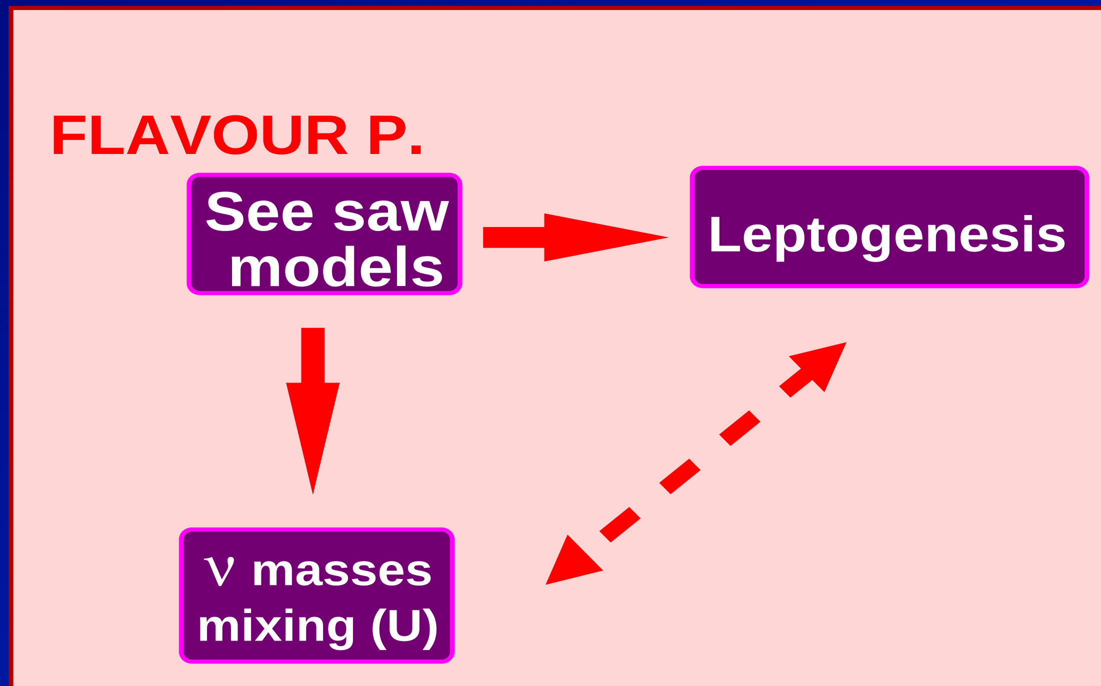
- Mixing only in the right-handed sector:

$V_L = 1$. In this case the only phases are the ones in V_R.

$$\epsilon_1 = \epsilon_1(\beta_1, \beta_2, \beta_3)$$
$$J_{CP} = \mathrm{Im}(Y_{12} Y_{23} Y_{31}) = J_{CP}(\beta_1, \beta_2, \beta_3)$$
$$\alpha_{21,31} = \alpha_{21,31}(\beta_1, \beta_2, \beta_3)$$

[Branco et al.]

6 – Conclusions



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 indication, even if not a proof, of leptogenesis

as the explanation for the observed baryon asymmetry of the Universe.

6 – Conclusions

The oscillation probability for $\nu_\mu \longrightarrow \nu_e$ is given by:

$$\boxed{\begin{aligned} P(\bar{P}) \simeq \quad & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A\mp\Delta_{13})L}{2} \\ & + \tilde{J}\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{A\mp\Delta_{13}} \sin\frac{AL}{2} \sin\frac{(A\mp\Delta_{13})L}{2} \cos\left(\mp\delta + \frac{\Delta_{13}L}{2}\right) \\ & + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2} \end{aligned}}$$

We identify 2-, 4- and 8- fold degeneracies [Barger, Marfatia, Whisnant]:

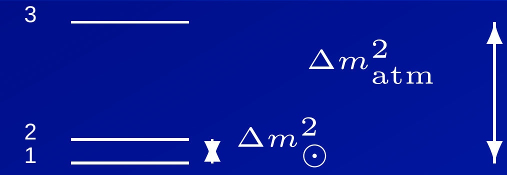
- (θ_{13}, δ) degeneracy [Koike, Ota, Sato; Burguet-Castell et al.] :

$$\begin{aligned} \delta' & = \pi - \delta \\ \theta'_{13} & = \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m_{12}^2 L}{4E} \cot\theta_{23} \cot\frac{\Delta m_{13}^2 L}{4E} \end{aligned}$$

- $(\mathrm{sign}(\Delta m_{13}^2), \delta)$ degeneracy [Minakata, Nunokawa]: $\begin{array}{ll} \delta' & \pi - \delta \\ \mathrm{sign}'(\Delta m_{13}^2) & -\mathrm{sign}(\Delta m_{13}^2) \end{array}$

- $\theta_{23}, \pi/2 - \theta_{23}$ degeneracy [Fogli, Lisi].

NH spectrum: $m_1 \ll m_2 \ll m_3$

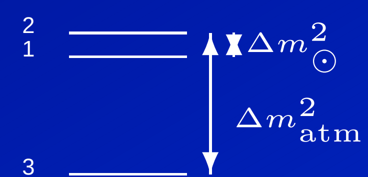


$$|\!<\!m\!>\!| \;\simeq\; \left| \sqrt{\Delta m^2_{\odot}} \cos^2\theta_{13} \sin^2\theta_{\odot} + \sqrt{\Delta m^2_{\mathrm{atm}}} \sin^2\theta_{13} e^{i\alpha_{32}} \right|$$

$|\!<\!m\!>\!|$ has both an upper and lower bound:

$$\text{few} \times 10^{-4}\ \text{eV} \;\lesssim |\!<\!m\!>\!| \;\lesssim 8.5 \times 10^{-3}\ \text{eV}$$

IH spectrum: $m_3 \ll m_1 \sim m_2$



$$\sqrt{\Delta m^2_{\mathrm{atm}}} \cos 2\theta_{\odot} \le |\!<\!m\!>\!| \;\simeq\; \sqrt{\left(1 - \sin^2(2\theta_{\odot}) \sin^2\frac{\alpha_{21}}{2}\right) \Delta m^2_{\mathrm{atm}}} \le \sqrt{\Delta m^2_{\mathrm{atm}}}$$

$|\!<\!m\!>\!|$ has a significant lower bound

$$0.01\ \text{eV} \;\lesssim |\!<\!m\!>\!| \;\lesssim 0.08\ \text{eV}$$

$|\!<\!m\!>\!|$ is in the range of sensitivity of the upcoming $(\beta\beta)_{0\nu}$-decay experiments.