Leptonic CP violation and the matter/antimatter asymmetry of the Universe

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Silvia Pascoli

IPPP – Durham University

Outline

1. The facts: neutrino masses and the baryon asymmetry

2. Baryogenesis and Leptogenesis

3. Leptogenesis in BSM models of neutrino masses

4. Is there a connection between low energy CPV and leptogenesis?

3. Conclusions

The facts

1. Neutrino oscillations imply that **neutrinos have mass and mix (CPV?)!** This requires new physics BSM which might be lepton number violating.

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$	$0.311^{+0.013}_{-0.013}$	$0.273 \to 0.354$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$	$33.87^{+0.82}_{-0.80}$	$31.52 \to 36.49$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$	$0.416^{+0.036}_{-0.029} \oplus 0.600^{+0.019}_{-0.026}$	$0.341 \to 0.670$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$	$40.1^{+2.1}_{-1.6} \oplus 50.7^{+1.2}_{-1.5}$	$35.7 \to 55.0$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$	$0.0255^{+0.0024}_{-0.0024}$	$0.0181 \to 0.0327$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$	$9.20^{+0.41}_{-0.45}$	$7.73 \to 10.42$
$\delta_{\rm CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$	298^{+59}_{-145}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$	$7.51^{+0.21}_{-0.15}$	$7.04 \to 8.12$
$\frac{\Delta m^2_{31}}{10^{-3}\ {\rm eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$	$+2.489^{+0.055}_{-0.051}$	$+2.294 \to +2.715$
$\frac{\Delta m^2_{32}}{10^{-3}\ {\rm eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$	$-2.468^{+0.073}_{-0.065}$	$-2.678 \to -2.252$

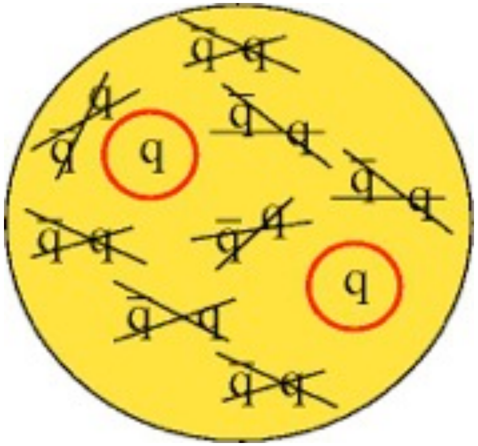
2 other CPV Majorana phases.

M. C. Gonzalez-Garcia et al., 1209.3023

The facts

2. There is evidence of the baryon asymmetry:

In the Early Universe



As the temperature drops, only quarks are left:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.14 \pm 0.08) \times 10^{-10}$$

Planck, 1303.5076

Is there a link between light neutrino physics and the baryon asymmetry?

The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

- C, CP violation;

- departure from thermal equilibrium.

The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

If neutrinos are Majorana particles, L is violated. Conversely, Majorana masses require L violation.

See-saw models require L violation (typically the Majorana mass of a heavy right-handed neutrino). They can be embedded in GUT or at the TeV scale or below.

In the SM also L is violated at the non-perturbative level. A lepton asymmetry is partially converted into a baryon asymmetry for T>100 GeV by sphaleron effects.

The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- C, CP violation;

If C were conserved:

$$\Gamma(X^c \to Y^c + B^c) = \Gamma(X \to Y + B)$$

and no baryon asymmetry generated:

$$\frac{dB}{dt} \propto \Gamma(X^c \to Y^c + B^c) - \Gamma(X \to Y + B)$$

We have observed CPV in quark sector (too small) and we can search for it in the leptonic sector.

The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- out of equilibrium

In equilibrium

$$\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$$

A generated baryon asymmetry is cancelled exactly by the antibaryon asymmetry.
When particles get out of equilibrium, this does not happen.

$$T < M_X$$

A successful model of baryogenesis:

Leptogenesis in models at the origin of neutrino masses

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Leptogenesis in models at the origin of neutrino masses

Provides a source of L violation

Neutrino masses BSM

In the SM, neutrinos do not acquire mass and mixing:

$$m_\nu \bar{\nu}_L \cancel{\nu_R}$$

Dirac mass

$$M \cancel{\nu_L^T C} \nu_L$$

Majorana mass

Dirac Masses:

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \mathrm{h.c.}$$

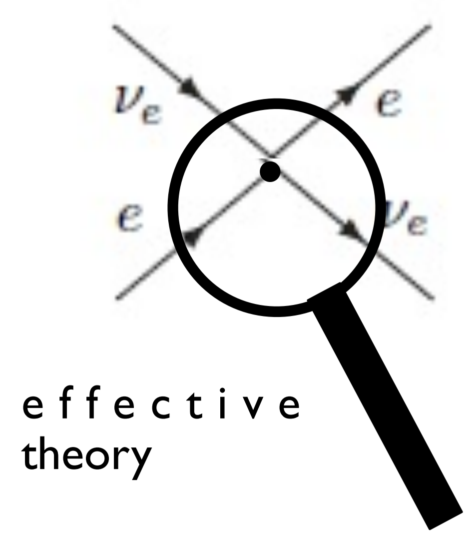
$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$$

Lepton number violation!

Majorana Masses:

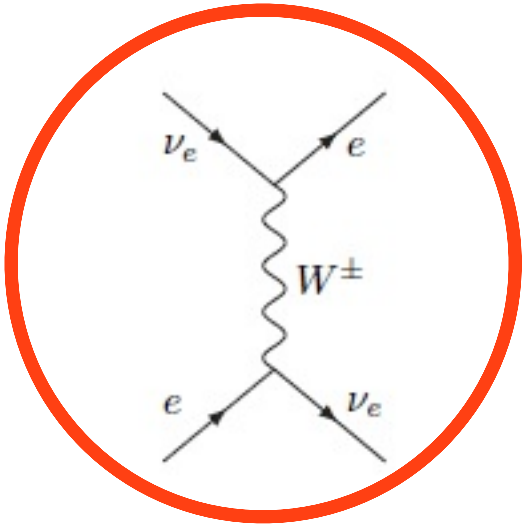
$$-\mathcal{L} = \lambda \frac{\nu_L H \, \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$

A D=5 **Majorana mass** can arise as the **low energy realisation of a higher energy theory (new mass scale!)**.



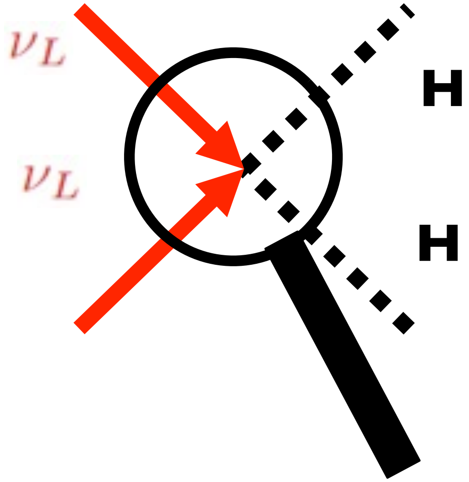
effective theory

$$\mathcal{L} \propto G_F(\bar{e}_L\gamma_\mu\nu_L)(\bar{\nu}_L\gamma^\mu e_L)$$



Standard Model: W exchange

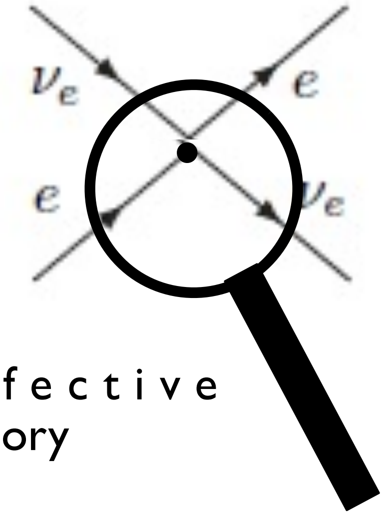
$$\mathcal{L}_{SM} \propto g\bar{\nu}_L\gamma^\mu e_L W_\mu \Rightarrow G_F \propto \frac{g^2}{m_W^2}$$



Neutrino mass

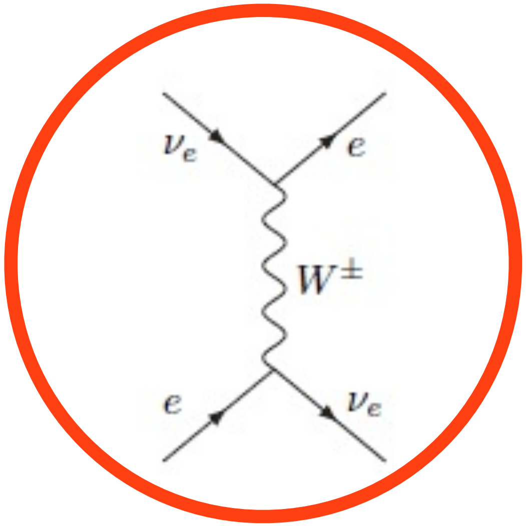
$$-\mathcal{L} = \lambda\frac{\nu_L H\,\nu_L H}{M} = \frac{\lambda v^2}{M}\nu_L^T C\nu_L$$

New theory: new particle exchange with mass M



effective theory

$$\mathcal{L} \propto G_F(\bar{e}_L\gamma_\mu\nu_L)(\bar{\nu}_L\gamma^\mu e_L)$$



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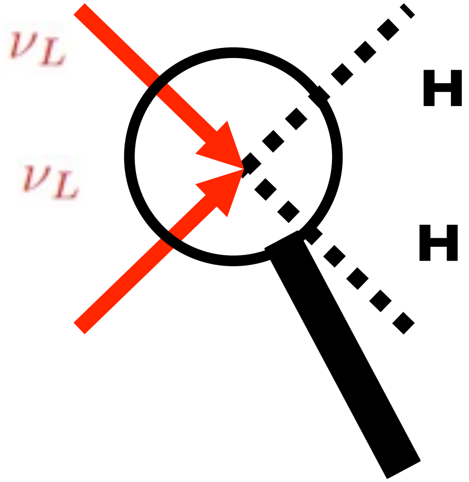
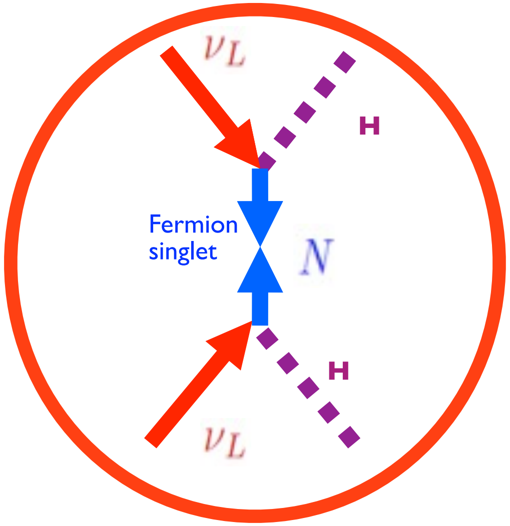


Neutrino mass

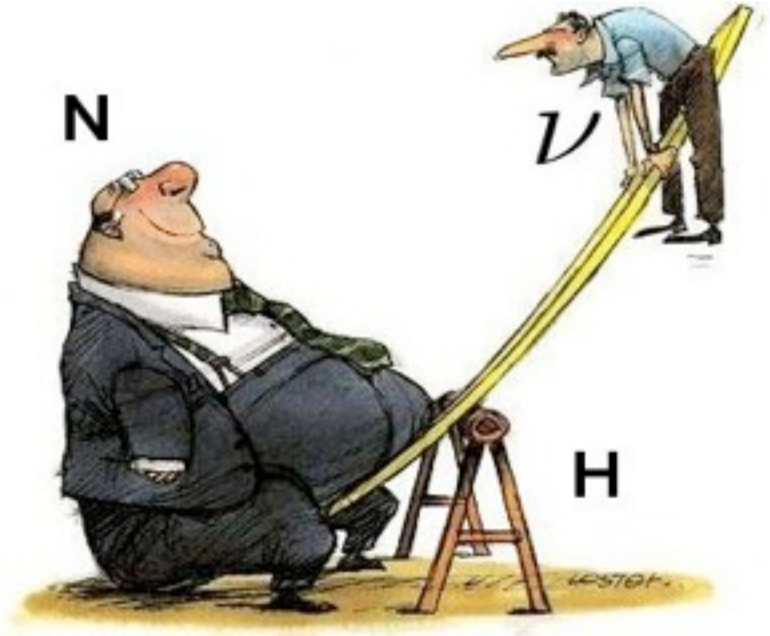
$$-\mathcal{L} = \lambda\frac{\nu_L H\,\nu_L H}{M} = \frac{\lambda v^2}{M}\nu_L^T C\nu_L$$



See-saw type I mechanism

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

The simplest see saw mechanism: type I



- Introduce a right handed neutrino **N**

Couple it to the Higgs and left handed neutrinos

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

When the Higgs gets a vev:

$$\mathcal{L} = \begin{pmatrix} \nu_L^T & N^T \end{pmatrix} \begin{pmatrix} 0 & Y_\nu v \\ Y_\nu^T v & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

$$m_\nu = U^* m_i U^\dagger = -Y_\nu^T M_R^{-1} Y_\nu v^2 \sim \frac{1\,\mathrm{GeV}^2}{10^{10}\,\mathrm{GeV}} \sim 0.1\,\mathrm{eV}$$

The light neutrino acquires a tiny mass!

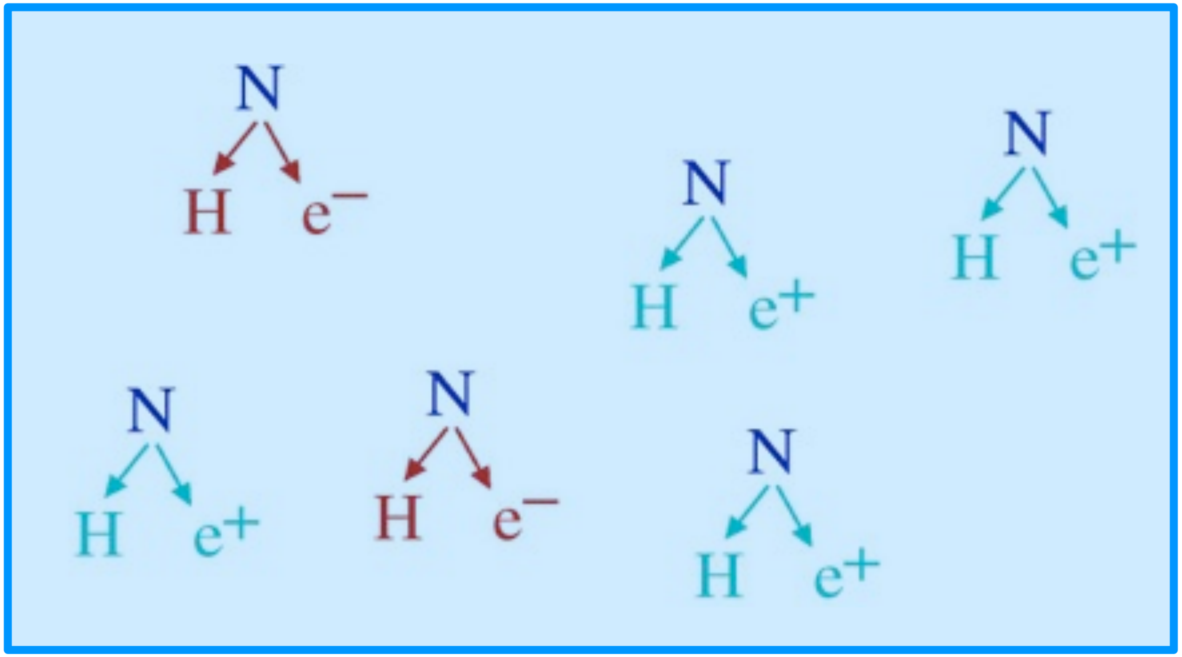
Leptogenesis

At T>M, the right-handed neutrinos N are in equilibrium thanks to processes which produce and destroy them:

$$N \leftrightarrow \ell H$$

When T<M, N drops out of equilibrium

$$N \rightarrow \ell H$$



A lepton asymmetry can be generated if

$$\Gamma(N \rightarrow \ell H) \neq \Gamma(N \rightarrow \ell^c H^c)$$

Sphalerons convert it into a baryon asymmetry.

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry

$$\epsilon \equiv \frac{\Gamma(N \to \ell H) - \Gamma(N^c \to \ell^c H^c)}{\Gamma(N \to \ell H) + \Gamma(N^c \to \ell^c H^c)}$$

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

$$\eta_L = \tilde{k}\epsilon$$

3. convert the lepton asymmetry into the baryon one

$$\boxed{\eta_B = \frac{\tilde{k}}{g^*} c_s \epsilon \sim 10^{-3} - 10^{-4}\epsilon}$$

For T < 10^{12} GeV, flavour effects are important.

Is there a connection between low energy CPV and the baryon asymmetry?

The general picture

ϵ depends on the CPV phases in Y_ν

$$\epsilon \propto \sum_j \Im(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

and in the U mixing matrix via the see-saw formula.

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

Let’s consider see-saw type I with 3 NRs.

High energy

M_R	3	0
Y_ν	9	6

Low energy

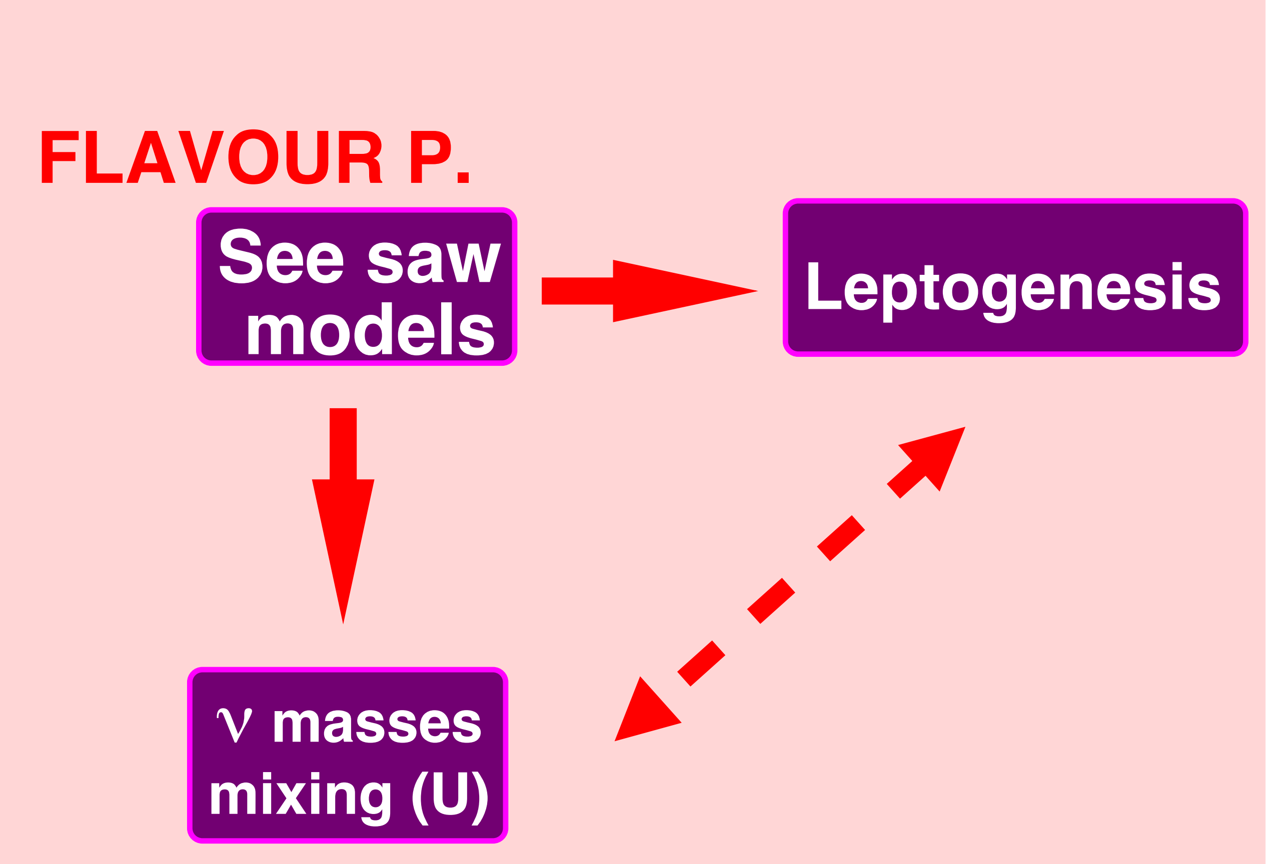
m_i	3	0
U	3	3

3 phases missing!

Specific flavour models

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

It may be possible to predict the baryon asymmetry from the Dirac and Majorana phases.



FLAVOUR P.

See saw models

Leptogenesis

ν masses mixing (U)

Does observing low energy CPV imply a baryon asymmetry?

It has been shown that, thanks to flavour effects, the low energy phases enter directly the baryon asymmetry.

In see-saw type I with flavour effects, if we observe CPV, can we conclude that a lepton asymmetry was generated? And that this could be as large as what observed?

6 CPV phases → $\delta, \alpha_{31}, \alpha_{32}$

→ 3 phases at ~~high energy,~~ not observable

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

No flavour effects

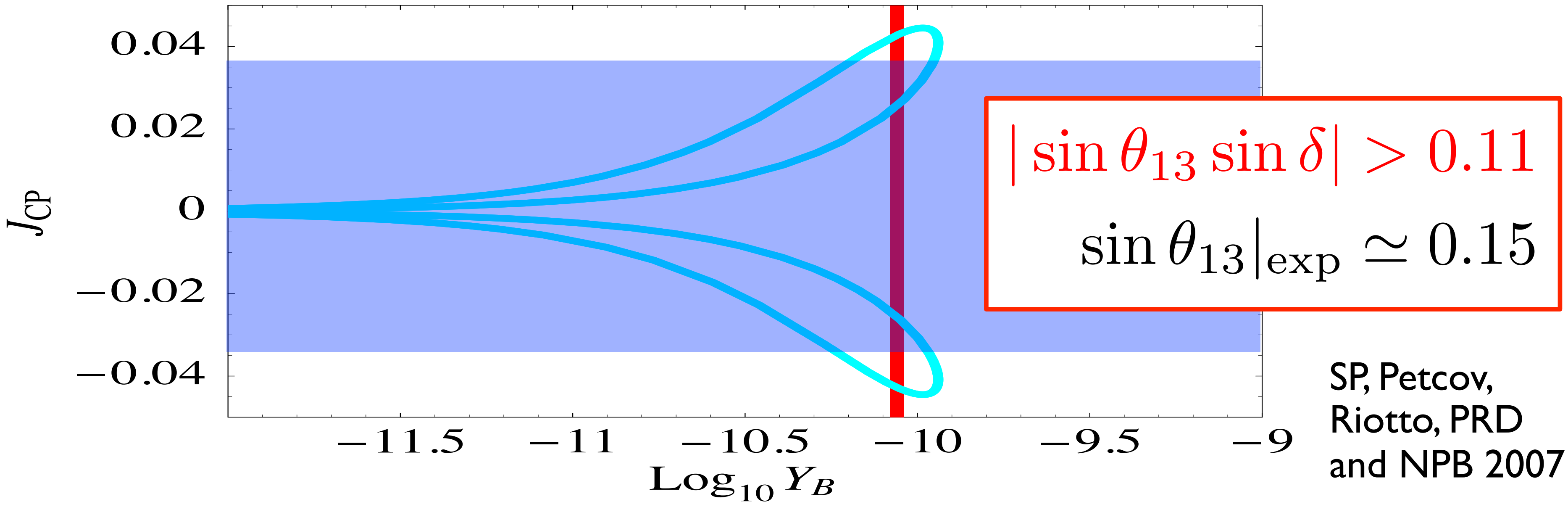
$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} \boxed{U^*_{\alpha\beta} U_{\alpha\rho}} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

With flavour effects, M1<5 10^11 GeV

The CP-asymmetry can depends only on the low energy CPV phases:

in the NH spectrum (m1<<m2<<m3), with M1<<M2<<M3 and M1<5 10^11 GeV,

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



$$|\sin\theta_{13}\sin\delta| > 0.11$$

$$\sin\theta_{13}|_{\rm exp} \simeq 0.15$$

SP, Petcov, Riotto, PRD and NPB 2007

Large theta13 implies that delta can give an even dominant contribution to the baryon asymmetry. Large CPV and NH are needed. For IH or QD spectrum, the CP-asymmetry is suppressed. A more detailed numerical study is ongoing.

Conclusions

- Leptogenesis requires
 - L violation (nu-less double beta decay, colliders...)
 - C/CPV (LBL and nu-less double beta decay (?))
 - out-of-equilibrium (expansion of the Universe)

- In presence of flavour effects (see-saw type I, $M< 10^{12}$ GeV), low energy phases enter directly in leptogenesis.

The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.

The CP-asymmetry in one-flavour approximation

For high T > 10^{12} GeV, charged lepton Yukawa interactions are out-of-equilibrium and flavours are indistinguishable. Only the total decay asymmetry is relevant.

ϵ depends on the CPV phases in

$$\epsilon \propto \sum_j \Im(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

and therefore in the U mixing matrix (but not directly) via the see-saw formula.

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

Taking flavour into account

The different charged lepton enter in equilibrium when

$$\Gamma \sim H$$

for taus: T ~ 10^{12} GeV
for muons: T ~ 10^{9} GeV.

In this case, each lepton asymmetry needs to be evaluated separately:

$$\epsilon_\ell \propto \frac{1}{(Y_\nu Y_\nu^\dagger)_{11}} \sum_j \Im(Y_{1\ell}(Y_\nu Y_\nu^\dagger)_{1j} Y_{j\ell}^*) \frac{M_1}{M_j}$$

and then summed.