

# Low Energy CP-Violation in the Lepton Sector and Leptogenesis

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LAUNCH Workshop  
MPI, Heidelberg  
March 21, 2007

## Compelling Evidences for $\nu$ -Oscillations

$$\nu_{lL} = \sum_{j=1} U_{lj} \nu_{jL} \quad l = e, \mu, \tau.$$

B. Pontecorvo, 1957; 1958; 1967;  
Z. Maki, M. Nakagawa, S. Sakata, 1962;

# Three Neutrino Mixing

$$\nu_{lL} = \sum_{j=1}^3 U_{lj} \nu_{jL} .$$

$U$  is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

- $U$  -  $n \times n$  unitary:

	$n$	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6

CP-violating phases:

$\nu_j$ - Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
$\nu_j$ - Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$ : 1 Dirac and

2 additional CP-violating phases, Majorana phases

# PMNS Matrix: Standard Parametrization

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- $s_{ij} \equiv \sin \theta_{ij}$ ,  $c_{ij} \equiv \cos \theta_{ij}$ ,  $\theta_{ij} = [0, \frac{\pi}{2}]$ ,
- $\delta$  - Dirac CP-violation phase,  $\delta = [0, 2\pi]$ ,
- $\alpha_{21}$ ,  $\alpha_{31}$  - the two Majorana CP-violation phases.
- $\Delta m_{\odot}^2 \equiv \Delta m_{21}^2 \cong 8.0 \times 10^{-5} \text{ eV}^2 > 0$ ,  $\sin^2 \theta_{12} \cong 0.30$ ,  $\cos 2\theta_{12} \gtrsim 0.28$  ( $2\sigma$ ),
- $|\Delta m_{\text{atm}}^2| \equiv |\Delta m_{31}^2| \cong 2.5 \times 10^{-3} \text{ eV}^2$ ,  $\sin^2 2\theta_{23} \cong 1$ ,
- $\theta_{13}$  - the CHOOZ angle:  $\sin^2 \theta_{13} < 0.027$  (0.041)  $2\sigma$  ( $3\sigma$ ).

A.Bandyopadhyay, S.Choubey, S.Goswami, S.T.P., D.P.Roy, hep-ph/0406328 (updated)

T. Schwetz, hep-ph/0606060.

- $\sqrt{\Delta m_{\odot}^2} \sin^2 \theta_{12} \cong 3.0 \times 10^{-3} \text{ eV}$  ( $\pm$ )  $\sqrt{|\Delta m_{\text{atm}}^2|} \sin^2 \theta_{13} \lesssim 2.2 \times 10^{-3} \text{ eV}$ ;
- $\sqrt{|\Delta m_{\text{atm}}^2|} \cong 5 \times 10^{-2} \text{ eV}$ ;  $\sqrt{|\Delta m_{\text{atm}}^2|} \cos 2\theta_{12} \gtrsim 1.4 \times 10^{-2} \text{ eV}$  ( $\cos 2\theta_{12} \gtrsim 0.28$ )
- $m_0$ :  $m_0^2 \gg \Delta m_{\odot}^2, |\Delta m_{\text{atm}}^2|$ ,  $m_0 \gtrsim 0.1 \text{ eV}$
- $\text{sgn}(\Delta m_{\text{atm}}^2) = \text{sgn}(\Delta m_{31}^2)$  not determined

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 > 0, \text{ normal mass ordering}$$

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{32}^2 < 0, \text{ inverted mass ordering}$$

Convention:  $m_1 < m_2 < m_3$  - **NMO**,  $m_3 < m_1 < m_2$  - **IMO**

- **Majorana phases  $\alpha_{21}, \alpha_{31}$ :**

- $\nu_l \leftrightarrow \nu_l, \bar{\nu}_l \leftrightarrow \bar{\nu}_l$  not sensitive;

S.M. Bilenky, J. Hosek, S.T.P., 1980;  
P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

- $|\langle m \rangle|$  in  $(\beta\beta)_{0\nu}$ -decay depends on  $\alpha_{21}, \alpha_{31}$ ;

- $\Gamma(\mu \rightarrow e + \gamma)$  etc. in SUSY theories depend on  $\alpha_{21,31}$ ;

- BAU, leptogenesis scenario:  $\alpha_{21,31}$  !

## Future Progress

- Determination of the nature - Dirac or Majorana, of  $\nu_j$  .
- Determination of  $\text{sgn}(\Delta m_{\text{atm}}^2)$ , type of  $\nu$ - mass spectrum

$$m_1 \ll m_2 \ll m_3, \quad \text{NH,}$$

$$m_3 \ll m_1 < m_2, \quad \text{IH,}$$

$$m_1 \cong m_2 \cong m_3, \quad m_{1,2,3}^2 \gg \Delta m_{\text{atm}}^2, \quad \text{QD; } m_j \gtrsim 0.10 \text{ eV.}$$

- Determining, or obtaining significant constraints on, the absolute scale of  $\nu_j$ -masses, or  $\min(m_j)$ .
- Status of the CP-symmetry in the lepton sector: violated due to  $\delta$  (Dirac), and/or due to  $\alpha_{21}, \alpha_{31}$  (Majorana)?
- High precision determination of  $\Delta m_{\odot}^2, \theta_{\odot}, \Delta m_{\text{atm}}^2, \theta_{\text{atm}}$ .
- Measurement of, or improving by at least a factor of (5 - 10) the existing upper limit on,  $\sin^2 \theta_{13}$ .
- Searching for possible manifestations, other than  $\nu_l$ -oscillations, of the non-conservation of  $L_l, l = e, \mu, \tau$ , such as  $\mu \rightarrow e + \gamma, \tau \rightarrow \mu + \gamma$ , etc. decays.

- Understanding at fundamental level the mechanism giving rise to the  $\nu$ - masses and mixing and to the  $L_l$ -non-conservation. Includes understanding
  - the origin of the observed patterns of  $\nu$ -mixing and  $\nu$ -masses ;
  - the physical origin of  $CPV$  phases in  $U_{PMNS}$  ;
  - Are the observed patterns of  $\nu$ -mixing and of  $\Delta m_{21,31}^2$  related to the existence of a new symmetry?
  - Is there any relations between  $q$ -mixing and  $\nu$ - mixing? Is  $\theta_{12} + \theta_c = \pi/4$  ?
  - Is  $\theta_{23} = \pi/4$ , or  $\theta_{23} > \pi/4$  or else  $\theta_{23} < \pi/4$ ?
  - Is there any correlation between the values of  $CPV$  phases and of mixing angles in  $U_{PMNS}$ ?
- Progress in the theory of  $\nu$ -mixing might lead to a better understanding of the origin of the BAU.
  - Can the Majorana and/or Dirac CPVP in  $U_{PMNS}$  be the leptogenesis CPV parameters at the origin of BAU?

## Rephasing Invariants Associated with CPVP

Dirac phase  $\delta$ :

$$J_{CP} = \text{Im} \{ U_{e1} U_{\mu 2} U_{e2}^* U_{\mu 1}^* \} .$$

C. Jarlskog, 1985 (for quarks)

CP-, T- violation effects in neutrino oscillations

P. Krastev, S.T.P., 1988

Majorana phases  $\alpha_{21}, \alpha_{31}$ :

$$S_1 = \text{Im} \{ U_{e1} U_{e3}^* \}, \quad S_2 = \text{Im} \{ U_{e2} U_{e3}^* \} \quad (\text{not unique}); \quad \text{or}$$
$$S'_1 = \text{Im} \{ U_{\tau 1} U_{\tau 2}^* \}, \quad S'_2 = \text{Im} \{ U_{\tau 2} U_{\tau 3}^* \}$$

J.F. Nieves and P. Pal, 1987, 2001

G.C. Branco et al., 1986

J.A. Aguilar-Saavedra and G.C. Branco, 2000

**CP-violation:** both  $\text{Im} \{ U_{e1} U_{e3}^* \} \neq 0$  and  $\text{Re} \{ U_{e1} U_{e3}^* \} \neq 0$  .

$S_1, S_2$  appear in  $|\langle m \rangle|$  in  $(\beta\beta)_{0\nu}$ -decay.

In general,  $J_{CP}, S_1$  and  $S_2$  are independent.



# Dirac CP-Nonconservation: $\delta$ in $U_{\text{PMNS}}$

Observable manifestations in

$$\nu_l \leftrightarrow \nu_{l'} , \quad \bar{\nu}_l \leftrightarrow \bar{\nu}_{l'} , \quad l, l' = e, \mu, \tau$$

- not sensitive to Majorana CPVP  $\alpha_{21}, \alpha_{31}$

CP-invariance:

$$P(\nu_l \rightarrow \nu_{l'}) = P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) , \quad l \neq l' = e, \mu, \tau$$

N. Cabibbo, 1978  
S.M. Bilenky, J. Hosek, S.T.P., 1980;  
V. Barger et al., 1980.

CPT-invariance:

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

$$l = l' : \quad P(\nu_l \rightarrow \nu_l) = P(\bar{\nu}_l \rightarrow \bar{\nu}_l)$$

T-invariance:

$$P(\nu_l \rightarrow \nu_{l'}) = P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

$3\nu$ -mixing:

$$A_{\text{CP}}^{(l,l')} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) , \quad l \neq l' = e, \mu, \tau$$

$$A_{\text{T}}^{(l,l')} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

$$A_{\text{T}}^{(e,\mu)} = A_{\text{T}}^{(\mu,\tau)} = -A_{\text{T}}^{(e,\tau)}$$

In vacuum:

$$A_{\top}^{(e,\mu)} = J_{\text{CP}} F_{\text{osc}}^{\text{vac}}$$

$$J_{\text{CP}} = \text{Im} \{ U_{e1} U_{\mu 2} U_{e2}^* U_{\mu 1}^* \} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

$$F_{\text{osc}}^{\text{vac}} = \sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{32}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{13}^2 L}{2E}\right)$$

P.I. Krastev, S.T.P., 1988

In matter: Matter effects violate

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

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

P. Langacker et al., 1987

Can conserve the T-invariance (**Earth**)

$$P(\nu_l \rightarrow \nu_{l'}) = P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

In matter with constant density:  $A_{\top}^{(e,\mu)} = J_{\text{CP}}^{\text{mat}} F_{\text{osc}}^{\text{mat}}$

$$J_{\text{CP}}^{\text{mat}} = J_{\text{CP}}^{\text{vac}} R_{\text{CP}}$$

$R_{\text{CP}}$  does not depend on  $\theta_{23}$  and  $\delta$ ;  $|R_{\text{CP}}| \lesssim 2.5$

P.I. Krastev, S.T.P., 1988

## HOW?

- Reactor Experiments  $\sim 2$  km

$\sin 2\theta_{13}$

- Super Beams:  $\theta_{13}, \delta, \dots$

JHF (T2K), SK (HK)  $295$  km

NuMI (NO $\nu$ A)  $\sim 800$  km

SPL+ $\beta$ -beams, UNO (1 megaton):  
CERN-Frejus  $\sim 140$  km

$\nu$ -Factories  $\sim 3000, 7000$  km

If  $\nu_j$  – Majorana particles,  $U_{\text{PMNS}}$  contains (3- $\nu$  mixing)

$\delta$ -Dirac,  $\alpha_{21}$ ,  $\alpha_{31}$  - Majorana physical CPV phases

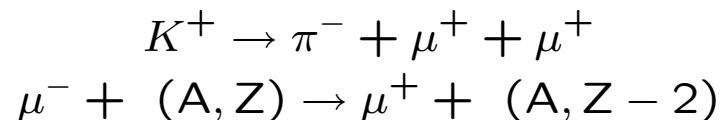
$\nu$ -oscillations  $\nu_l \leftrightarrow \nu_{l'}$ ,  $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ ,  $l, l' = e, \mu, \tau$ ,

- are not sensitive to the nature of  $\nu_j$ ,

S.M. Bilenky et al., 1980;  
P. Langacker et al., 1987

- provide information on  $\Delta m_{jk}^2 = m_j^2 - m_k^2$ , but not on the absolute values of  $\nu_j$  masses.

The Majorana nature of  $\nu_j$  can manifest itself in the existence of  $\Delta L = \pm 2$  processes:



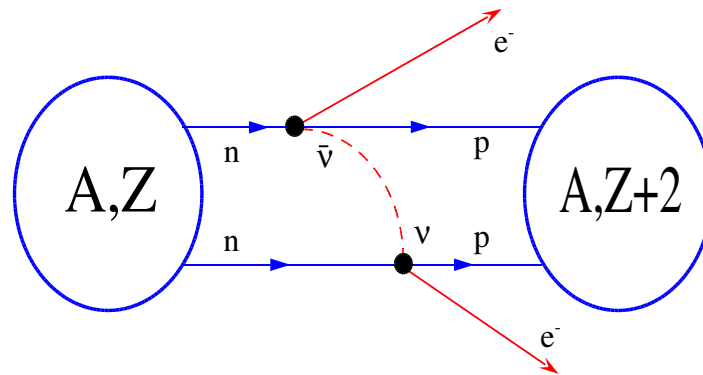
The process most sensitive to the possible Majorana nature of  $\nu_j$  -  $(\beta\beta)_{0\nu}$ -decay



of even-even nuclei,  $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$ .

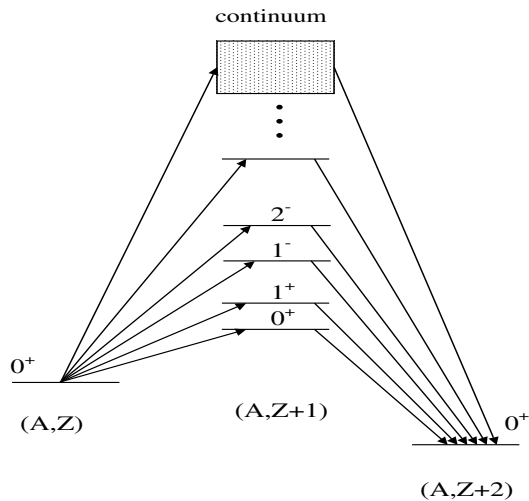
$2n$  from  $(A, Z)$  exchange a virtual Majorana  $\nu_j$  (via the CC weak interaction) and transform into  $2p$  of  $(A, Z+2)$  and two free  $e^-$ .

# Nuclear $0\nu\beta\beta$ -decay



strong in-medium modification of the basic process

$$dd \rightarrow uue^-e^-(\bar{\nu}_e\bar{\nu}_e)$$



virtual excitation  
of states of all multiplicities  
in  $(A, Z+1)$  nucleus

## $(\beta\beta)_{0\nu}$ –Decay Experiments:

- Majorana nature of  $\nu_j$
- Type of  $\nu$ –mass spectrum (NH, IH, QD)
- Absolute neutrino mass scale

${}^3\text{H}$   $\beta$ -decay , cosmology:  $m_{\nu}$  (QD, IH)

- CPV due to Majorana CPV phases

## $\nu_j$ – Dirac or Majorana particles, fundamental problem

$\nu_j$ –Dirac: **conserved lepton charge exists**,  $L = L_e + L_\mu + L_\tau$ ,  $\nu_j \neq \bar{\nu}_j$

$\nu_j$ –Majorana: **no lepton charge is exactly conserved**,  $\nu_j \equiv \bar{\nu}_j$

The observed patterns of  $\nu$ –mixing and of  $\Delta m_{\text{atm}}^2$  and  $\Delta m_{\odot}^2$  can be related to Majorana  $\nu_j$  and an **approximate** symmetry:

$$L' = L_e - L_\mu - L_\tau$$

S.T.P., 1982

See-saw mechanism:  $\nu_j$ – Majorana

**Establishing that  $\nu_j$  are Majorana particles would be as important as the discovery of  $\nu$ – oscillations.**

$$A(\beta\beta)_{0\nu} \sim \langle m \rangle M(A,Z), \quad M(A,Z) - \text{NME},$$

$$\begin{aligned} |\langle m \rangle| &= |m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}}| \\ &= |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i\alpha_{31}}|, \quad \theta_{12} \equiv \theta_{\odot}, \theta_{13} - \text{CHOOZ} \end{aligned}$$

$\alpha_{21}, \alpha_{31}$  - the two Majorana CPVP of the PMNS matrix.

**CP-invariance:**  $\alpha_{21} = 0, \pm\pi, \alpha_{31} = 0, \pm\pi;$

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

**relative CP-parities of  $\nu_1$  and  $\nu_2$ , and of  $\nu_1$  and  $\nu_3$  .**

L. Wolfenstein, 1981;

S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;

B. Kayser, 1984.

$$|\langle m \rangle| : m_j, \theta_\odot \equiv \theta_{12}, \theta_{13}, \alpha_{21,31}$$

$m_{1,2,3}$  - in terms of  $\min(m_j)$ ,  $\Delta m_{\text{atm}}^2$ ,  $\Delta m_\odot^2$

S.T.P., A.Yu. Smirnov, 1994

Convention:  $m_1 < m_2 < m_3$  - **NMO**,  $m_3 < m_1 < m_2$  - **IMO**

$$\Delta m_\odot^2 \equiv \Delta m_{21}^2, \quad m_2 = \sqrt{m_1^2 + \Delta m_\odot^2},$$

while either

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 > 0, \quad m_3 = \sqrt{m_1^2 + \Delta m_{\text{atm}}^2}, \quad \text{normal mass ordering, or}$$

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{32}^2 < 0, \quad m_1 = \sqrt{m_3^2 + |\Delta m_{\text{atm}}^2| - \Delta m_\odot^2}, \quad \text{inverted mass ordering}$$

The neutrino mass spectrum –

*Normal hierarchical (NH)* if  $m_1 \ll m_2 \ll m_3$ ,

*Inverted hierarchical (IH)* if  $m_3 \ll m_1 \cong m_2$ ,

*Quasi-degenerate (QD)* if  $m_1 \cong m_2 \cong m_3 = m$ ,  $m_j^2 \gg |\Delta m_{\text{atm}}^2|$ ;  $m_j \gtrsim 0.1$  eV

Given  $|\Delta m_{\text{atm}}^2|$ ,  $\Delta m_\odot^2$ ,  $\theta_\odot$ ,  $\theta_{13}$ ,

$$|\langle m \rangle| = |\langle m \rangle| (m_{\text{min}}, \alpha_{21}, \alpha_{31}; \mathbf{S}), \quad \mathbf{S} = \text{NO(NH)}, \text{IO(IH)}.$$



$$A(\beta\beta)_{0\nu} \sim \langle m \rangle M(A,Z), \quad M(A,Z) - \text{NME},$$

$$|\langle m \rangle| \cong \left| \sqrt{\Delta m_{\odot}^2} \sin^2 \theta_{12} e^{i\alpha} + \sqrt{\Delta m_{31}^2} \sin^2 \theta_{13} e^{i\beta_M} \right|, \quad m_1 \ll m_2 \ll m_3 \text{ (NH)},$$

$$|\langle m \rangle| \cong \sqrt{m_3^2 + \Delta m_{13}^2} |\cos^2 \theta_{12} + e^{i\alpha} \sin^2 \theta_{12}|, \quad m_3 < (\ll) m_1 < m_2 \text{ (IH)},$$

$$|\langle m \rangle| \cong m |\cos^2 \theta_{12} + e^{i\alpha} \sin^2 \theta_{12}|, \quad m_{1,2,3} \cong m \gtrsim 0.10 \text{ eV (QD)},$$

$$\theta_{12} \equiv \theta_{\odot}, \theta_{13}\text{-CHOOZ}; \quad \alpha \equiv \alpha_{21}, \beta_M \equiv \alpha_{31}.$$

$$\text{CP-invariance: } \alpha = 0, \pm\pi, \beta_M = 0, \pm\pi;$$

$$|\langle m \rangle| \lesssim 5 \times 10^{-3} \text{ eV, NH};$$

$$\sqrt{\Delta m_{13}^2} \cos 2\theta_{12} \cong 0.013 \text{ eV} \lesssim |\langle m \rangle| \lesssim \sqrt{\Delta m_{13}^2} \cong 0.055 \text{ eV, IH};$$

$$m \cos 2\theta_{12} \lesssim |\langle m \rangle| \lesssim m, \quad m \gtrsim 0.10 \text{ eV, QD}.$$

Best sensitivity: Heidelberg-Moscow  $^{76}\text{Ge}$  experiment.

Claim for a positive signal at  $> 3\sigma$ :

H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$|\langle m \rangle| = (0.1 - 0.9) \text{ eV}$  (99.73% C.L.).

IGEX  $^{76}\text{Ge}$ :  $|\langle m \rangle| < (0.33 - 1.35) \text{ eV}$  (90% C.L.).

Taking data - NEMO3 ( $^{100}\text{Mo}$ ), CUORICINO ( $^{130}\text{Te}$ ):

$|\langle m \rangle| < (0.7 - 1.2) \text{ eV}$ ,  $|\langle m \rangle| < (0.18 - 0.90) \text{ eV}$  (90% C.L.).

Large number of projects:  $|\langle m \rangle| \sim (0.01 - 0.05) \text{ eV}$

CUORE -  $^{130}\text{Te}$ ,

GERDA -  $^{76}\text{Ge}$ ,

SuperNEMO -  $^{82}\text{Se}$ ,

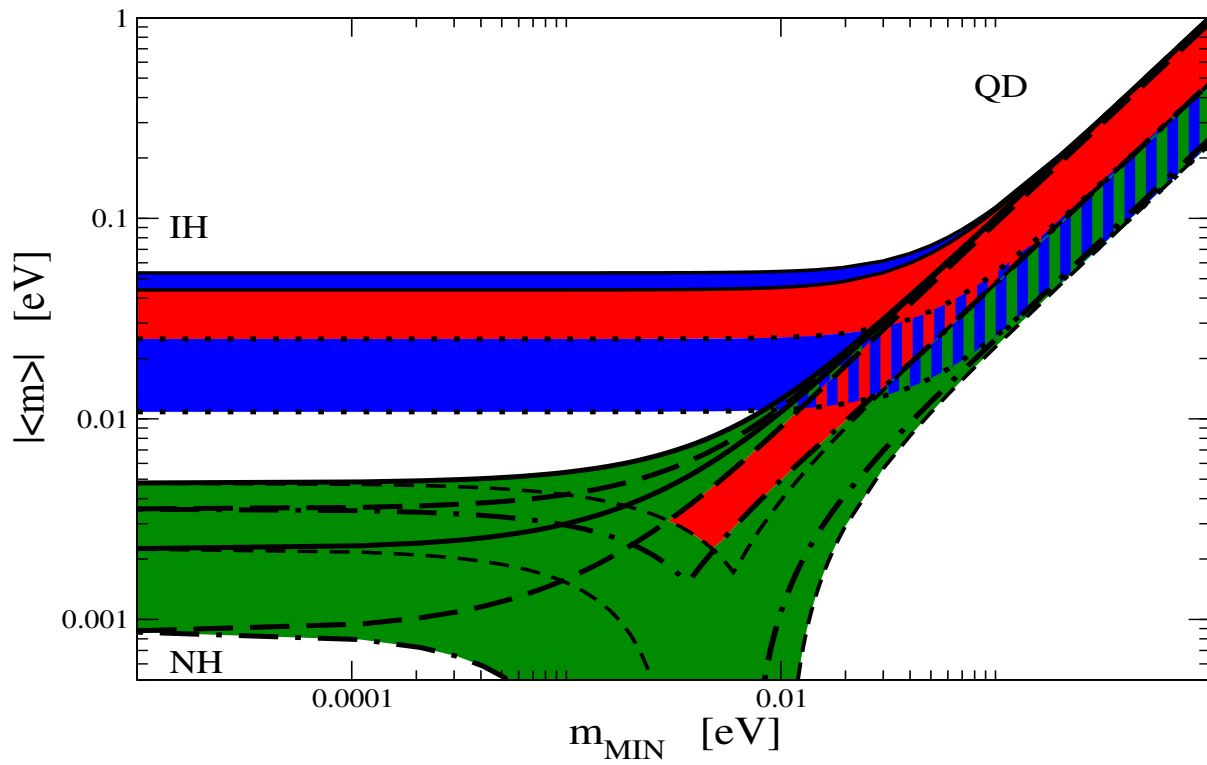
EXO -  $^{136}\text{Xe}$ ,

MAJORANA -  $^{76}\text{Ge}$ ,

MOON -  $^{100}\text{Mo}$ ,

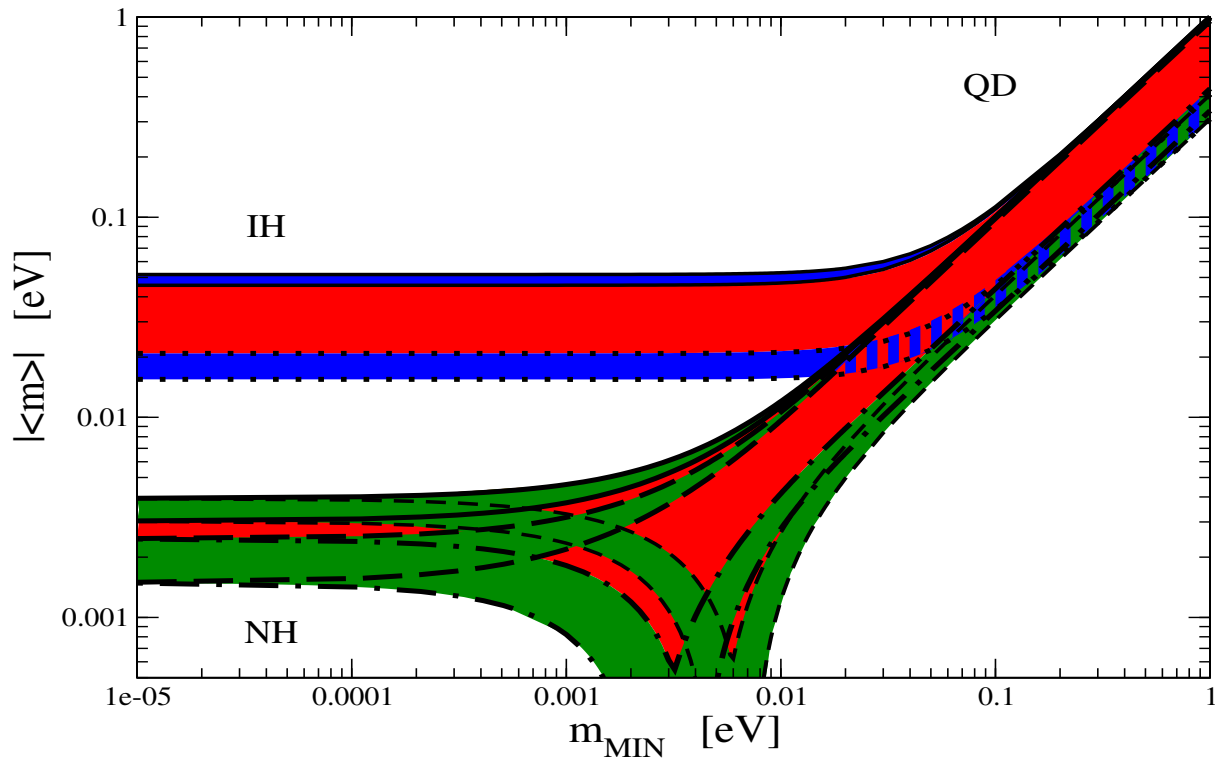
CANDLES -  $^{48}\text{Ca}$ ,

XMASS -  $^{136}\text{Xe}$ .



S. Pascoli, S.T.P., 2006

The current  $2\sigma$  ranges of values of the parameters used.



$\sin^2 \theta_{13} = 0.015 \pm 0.006$ ;  $1\sigma(\Delta m_{\odot}^2) = 4\%$ ,  $1\sigma(\sin^2 \theta_{\odot}) = 4\%$ ,  $1\sigma(|\Delta m_{\text{atm}}^2|) = 6\%$ ;

$2\sigma(|\langle m \rangle|)$  used.

## Majorana CPV Phases and $|\langle m \rangle|$

CPV can be established provided

- $|\langle m \rangle|$  measured with  $\Delta \lesssim 15\%$  ;
- $\Delta m_{\text{atm}}^2$  (IH) or  $m_0$  (QD) measured with  $\delta \lesssim 10\%$  ;
- $\xi \lesssim 1.5$  ;
- $\alpha_{21}$  (QD): in the interval  $\sim [\frac{\pi}{4} - \frac{3\pi}{4}]$ , or  $\sim [\frac{5\pi}{4} - \frac{3\pi}{2}]$  ;
- $\tan^2 \theta_{\odot} \gtrsim 0.40$  .

S. Pascoli, S.T.P., W. Rodejohann, 2002

S. Pascoli, S.T.P., L. Wolfenstein, 2002

S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

No “No-go for detecting CP-Violation via  $(\beta\beta)_{0\nu}$ -decay”

V. Barger *et al.*, 2002

# Absolute Neutrino Mass Measurements

The Troitzk and Mainz  ${}^3\text{H}$   $\beta$ -decay experiments

$$m_{\nu_e} < 2.3 \text{ eV} \quad (95\% \text{ C.L.})$$

There are prospects to reach sensitivity

$$\text{KATRIN :} \quad m_{\nu_e} \sim 0.2 \text{ eV}$$

Cosmological and astrophysical data: the WMAP result combined with data from large scale structure surveys (2dFGRS, SDSS)

$$\sum_j m_j \equiv \Sigma < (0.4 - 1.7) \text{ eV}$$

The WMAP and future PLANCK experiments can be sensitive to

$$\sum_j m_j \cong 0.4 \text{ eV}$$

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP and PLANCK experiments may allow to determine

$$\sum_j m_j : \quad \delta \cong 0.04 \text{ eV.}$$

# $M_\nu$ from the See-Saw Mechanism

P. Minkowski, 1977.

M. Gell-Mann, P. Ramond, R. Slansky, 1979;

T. Yanagida, 1979;

R. Mohapatra, G. Senjanovic, 1980.

- Explains the smallness of  $\nu$ -masses.
- Through **leptogenesis theory** links the  $\nu$ -mass generation to the generation of baryon asymmetry of the Universe  $Y_B$ .

S. Fukugita, T. Yanagida, 1986.

- In SUSY GUT's with see-saw mechanism of  $\nu$ -mass generation, the LFV decays

$$\mu \rightarrow e + \gamma, \quad \tau \rightarrow \mu + \gamma, \quad \tau \rightarrow e + \gamma, \quad \text{etc.}$$

are predicted to take place with rates within the reach of present and future experiments.

F. Borzumati, A. Masiero, 1986.

- The  $\nu_j$  are **Majorana particles**;  $(\beta\beta)_{0\nu}$ -decay is allowed.

**See-Saw:** Dirac  $\nu$ -mass  $m_D$  + Majorana mass  $M_R$  for  $N_R$

# The See-Saw Lagrangian

$$\mathcal{L}^{\text{lep}}(x) = \mathcal{L}_{\text{CC}}(x) + \mathcal{L}_Y(x) + \mathcal{L}_M^{\text{N}}(x),$$

$$\mathcal{L}_{\text{CC}} = -\frac{g}{\sqrt{2}} \bar{l}_L(x) \gamma_\alpha \nu_{lL}(x) W^{\alpha\dagger}(x) + h.c.,$$

$$\mathcal{L}_Y(x) = \lambda_{il} \bar{N}_{iR}(x) H^\dagger(x) \psi_{lL}(x) + Y_l H^c(x) \bar{l}_R(x) \psi_{lL}(x) + h.c.,$$

$$\mathcal{L}_M^{\text{N}}(x) = -\frac{1}{2} M_i \bar{N}_i(x) N_i(x).$$

$\psi_{lL}$  - LH doublet,  $\psi_{lL}^T = (\nu_{lL} \ l_L)$ ,  $l_R$  - RH singlet,  $H$  - Higgs doublet.

Basis:  $M_R = (M_1, M_2, M_3)$ ;  $D_N \equiv \text{diag}(M_1, M_2, M_3)$ ,  $D_\nu \equiv \text{diag}(m_1, m_2, m_3)$ .

$m_D$  generated by the Yukawa interaction:

$$-\mathcal{L}_Y^\nu = \lambda_{il} \bar{N}_{iR} H^\dagger(x) \psi_{lL}(x), \quad v = 174 \text{ GeV}, \quad v \lambda = m_D - \text{complex}$$

For  $M_R$  - sufficiently large,

$$m_\nu \simeq v^2 \lambda^T M_R^{-1} \lambda = U_{\text{PMNS}}^* m_\nu^{\text{diag}} U_{\text{PMNS}}^\dagger.$$

$Y_\nu \equiv \lambda = \sqrt{D_N} R \sqrt{D_\nu} (U_{\text{PMNS}})^\dagger / v_u$ , all at  $M_R$ ;  $R$ -complex,  $R^T R = \mathbf{1}$ .

J.A. Casas and A. Ibarra, 2001

In GUTs,  $M_R < M_X$ ,  $M_X \sim 10^{16}$  GeV;

in GUTs, e.g.,  $M_R = (10^9, 10^{12}, 10^{15})$  GeV,  $m_D \sim 1$  GeV.



## The CP-Invariance Constraints

Assume:  $C(\bar{\nu}_j)^T = \nu_j$ ,  $C(\bar{N}_k)^T = N_k$ ,  $j, k = 1, 2, 3$ .

The CP-symmetry transformation:

$$\begin{aligned} U_{\text{CP}} N_j(x) U_{\text{CP}}^\dagger &= \eta_j^{\text{NCP}} \gamma_0 N_j(x'), \quad \eta_j^{\text{NCP}} = i\rho_j^N = \pm i, \\ U_{\text{CP}} \nu_k(x) U_{\text{CP}}^\dagger &= \eta_k^{\nu\text{CP}} \gamma_0 \nu_k(x'), \quad \eta_k^{\nu\text{CP}} = i\rho_k^\nu = \pm i. \end{aligned}$$

CP-invariance:

$$\lambda_{jl}^* = \lambda_{jl} (\eta_j^{\text{NCP}})^* \eta^l \eta^{H*}, \quad j = 1, 2, 3, \quad l = e, \mu, \tau,$$

Convenient choice:  $\eta^l = i$ ,  $\eta^H = 1$  ( $\eta^W = 1$ ):

$$\lambda_{jl}^* = \lambda_{jl} \rho_j^N, \quad \rho_j^N = \pm 1,$$

$$U_{lj}^* = U_{lj} \rho_j^\nu, \quad \rho_j^\nu = \pm 1,$$

$$R_{jk}^* = R_{jk} \rho_j^N \rho_k^\nu, \quad j, k = 1, 2, 3, \quad l = e, \mu, \tau,$$

$\lambda_{jl}$ ,  $U_{lj}$ ,  $R_{jk}$  - either real or purely imaginary.

Relevant quantity:

$$P_{jkml} \equiv R_{jk} R_{jm} U_{lk}^* U_{lm}, \quad k \neq m,$$

$$\text{CP: } P_{jkml}^* = P_{jkml} (\rho_j^N)^2 (\rho_k^\nu)^2 (\rho_m^\nu)^2 = P_{jkml}, \quad \text{Im}(P_{jkml}) = 0.$$

$$P_{jkml} \equiv R_{jk} R_{jm} U_{lk}^* U_{lm}, \quad k \neq m,$$

$$CP: \quad P_{jkml}^* = P_{jkml} (\rho_j^N)^2 (\rho_k^\nu)^2 (\rho_m^\nu)^2 = P_{jkml}, \quad \text{Im}(P_{jkml}) = 0.$$

Consider NH  $N_j$ , NH  $\nu_k$ :  $P_{123\tau} = R_{12} R_{13} U_{\tau 2}^* U_{\tau 3}$

Suppose, CP-invariance holds at low  $E$ :  $\delta = 0$ ,  $\alpha_{21} = \pi$ ,  $\alpha_{31} = 0$ .

Thus,  $U_{\tau 2}^* U_{\tau 3}$  - purely imaginary.

Then real  $R_{12} R_{13}$  corresponds to CP-violation at "high"  $E$ .

# Leptogenesis

$$Y_B = \frac{n_B - n_{\bar{B}}}{S} \sim 8.6 \times 10^{-11} \quad (n_\gamma: \sim 6.3 \times 10^{-10})$$

$$Y_B \cong -10^{-2} \quad \varepsilon \kappa$$

W. Buchmüller, M. Plümacher, 1998;

W. Buchmüller, P. Di Bari, M. Plümacher, 2004

$\kappa$ - efficiency factor;  $\kappa \sim 10^{-1} - 10^{-3}$ :  $\varepsilon \gtrsim 10^{-7}$ .

$\varepsilon$ :  $CP$ -,  $L$ - violating asymmetry generated in out of equilibrium  $N_{Rj}$ -decays in the early Universe,

$$\varepsilon_1 = \frac{\Gamma(N_1 \rightarrow \Phi^- \ell^+) - \Gamma(N_1 \rightarrow \Phi^+ \ell^-)}{\Gamma(N_1 \rightarrow \Phi^- \ell^+) + \Gamma(N_1 \rightarrow \Phi^+ \ell^-)}$$

M.A. Luty, 1992;

L. Covi, E. Roulet and F. Vissani, 1996;

M. Flanz *et al.*, 1996;

M. Plümacher, 1997;

A. Pilaftsis, 1997.

$\kappa = \kappa(\tilde{m})$ ,  $\tilde{m}$  - determines the rate of wash-out processes:

$\Phi^+ + \ell^- \rightarrow N_1$ ,  $\ell^- + \Phi^+ \rightarrow \Phi^- + \ell^+$ , etc.

W. Buchmüller, P. Di Bari and M. Plümacher, 2002;

G. F. Giudice *et al.*, 2004

# Low Energy Leptonic CPV and Leptogenesis

Assume:  $M_1 \ll M_2 \ll M_3$ ,  $M_1 \gtrsim 10^{12}$  GeV

Individual asymmetries:

$$\varepsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left( \sum_{j,k} m_j^{1/2} m_k^{3/2} U_{lj}^* U_{lk} R_{1j} R_{1k} \right)}{\sum_j m_j |R_{1j}|^2}, \quad v = 174 \text{ GeV}$$

$$\widetilde{m}_l \equiv \frac{|\lambda_{1l}|^2 v^2}{M_1} = \left| \sum_k R_{1k} m_k^{1/2} U_{lk}^* \right|^2, \quad l = e, \mu, \tau.$$

The “one-flavor” approximation -  $\mathbf{Y}_{e,\mu,\tau}$  - “small”:

Boltzmann eqn. for  $n(N_1)$  and  $\Delta L = \Delta(L_e + L_\mu + L_\tau)$ .

$Y_l H^c(x) \bar{l}_R(x) \psi_{lL}$ - out of equilibrium at  $T \sim M_1$ .

One-flavor approximation:  $M_1 \sim T > 10^{12}$  GeV

$$\varepsilon_1 = \sum_l \varepsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left( \sum_{j,k} m_j^2 R_{1j}^2 \right)}{\sum_k m_k |R_{1k}|^2},$$

$$\widetilde{m}_1 = \sum_l \widetilde{m}_l = \sum_k m_k |R_{1k}|^2.$$

At  $M_1 \sim 10^{12}$  GeV:  $Y_\tau$  - in equilibrium,  $Y_{e,\mu}$  - not; dynamics changes:  $\tau_R^-, \tau_L^+$

$\tau_R^- + N_1 \rightarrow \nu_L + \tau_R^-$ ,  $N_1 + \nu_L \rightarrow \tau_R^- + \tau_L^+$ , etc.

At  $M_1 \sim 10^9$  GeV:  $Y_\tau, Y_\mu$  - in equilibrium,  $Y_e$  - not.

Thus, at  $M_1 \sim 10^9 - 10^{12}$  GeV:  $L_\tau, \Delta L_\tau$  - distinguishable;

$L_e, L_\mu, \Delta L_e, \Delta L_\mu$  - individually not distinguishable;

$L_e + L_\mu, \Delta(L_e + L_\mu)$

A. Abada et al., 2006; E. Nardi et al., 2006

A. Abada et al., 2006

## Individual asymmetries:

Assume:  $M_1 \ll M_2 \ll M_3$ ,  $10^9 \lesssim M_1 \lesssim 10^{12}$  GeV,

$$\epsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left( \sum_{j,k} m_j^{1/2} m_k^{3/2} U_{lj}^* U_{lk} R_{1j} R_{1k} \right)}{\sum_j m_j |R_{1j}|^2}$$

$$\widetilde{m}_l \equiv \frac{|\lambda_{1l}|^2 v^2}{M_1} = \left| \sum_k R_{1k} m_k^{1/2} U_{lk}^* \right|^2, \quad l = e, \mu, \tau.$$

The baryon asymmetry is

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

$$\eta(\widetilde{m}_l) \simeq \left( \left( \frac{\widetilde{m}_l}{8.25 \times 10^{-3} \text{ eV}} \right)^{-1} + \left( \frac{0.2 \times 10^{-3} \text{ eV}}{\widetilde{m}_l} \right)^{-1.16} \right)^{-1}.$$

$$Y_B = -(12/37) (Y_2 + Y_\tau),$$

$$Y_2 = Y_{e+\mu}, \quad \epsilon_2 = \epsilon_{1e} + \epsilon_{1\mu}, \quad \widetilde{m}_2 = \widetilde{m}_{1e} + \widetilde{m}_{1\mu}$$

A. Abada et al., 2006; E. Nardi et al., 2006

A. Abada et al., 2006

Real (Purely Imaginary)  $R$ :  $\varepsilon_{1l} \neq 0$ , CPV from  $U$

$$\varepsilon_{1e} + \varepsilon_{1\mu} + \varepsilon_{1\tau} = \varepsilon_2 + \varepsilon_{1\tau} = 0,$$

$$\begin{aligned} \varepsilon_{1\tau} &= -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left( \sum_{j,k} m_j^{1/2} m_k^{3/2} U_{\tau j}^* U_{\tau k} R_{1j} R_{1k} \right)}{\sum_j m_j |R_{1j}|^2} \\ &= -\frac{3M_1}{16\pi v^2} \frac{\sum_{j,k>j} m_j^{1/2} m_k^{1/2} (m_k - m_j) R_{1j} R_{1k} \text{Im} (U_{\tau j}^* U_{\tau k})}{\sum_j m_j |R_{1j}|^2}, R_{1j} R_{1k} = \pm |R_{1j} R_{1k}|, \\ &= \mp \frac{3M_1}{16\pi v^2} \frac{\sum_{j,k>j} m_j^{1/2} m_k^{1/2} (m_k + m_j) |R_{1j} R_{1k}| \text{Re} (U_{\tau j}^* U_{\tau k})}{\sum_j m_j |R_{1j}|^2}, R_{1j} R_{1k} = \pm i |R_{1j} R_{1k}| \end{aligned}$$

S. Pascoli, S.T.P., A. Riotto, 2006.

CP-Violation:  $\text{Im} (U_{\tau j}^* U_{\tau k}) \neq 0$ ,  $\text{Re} (U_{\tau j}^* U_{\tau k}) \neq 0$ ;

$$Y_B = -\frac{12}{37} \frac{\varepsilon_{1\tau}}{g_*} \left( \eta \left( \frac{390}{589} \widetilde{m}_\tau \right) - \eta \left( \frac{417}{589} \widetilde{m}_2 \right) \right)$$

$m_1 \ll m_2 \ll m_3, M_1 \ll M_{2,3}; R_{12}R_{13} - \text{real}; m_1 \cong 0, R_{11} \cong 0 (N_3 \text{ decoupling})$

$$\varepsilon_{1\tau} = - \frac{3M_1 \sqrt{\Delta m_{31}^2}}{16\pi v^2} \left( \frac{\Delta m_{\odot}^2}{\Delta m_{31}^2} \right)^{\frac{1}{4}} \frac{|R_{12}R_{13}|}{\left( \frac{\Delta m_{\odot}^2}{\Delta m_{31}^2} \right)^{\frac{1}{2}} |R_{12}|^2 + |R_{13}|^2} \\ \times \left( 1 - \frac{\sqrt{\Delta m_{\odot}^2}}{\sqrt{\Delta m_{31}^2}} \right) \text{Im} (U_{\tau 2}^* U_{\tau 3})$$

$$\text{Im} (U_{\tau 2}^* U_{\tau 3}) = -c_{13} \left[ c_{23}s_{23}c_{12} \sin \left( \frac{\alpha_{32}}{2} \right) - c_{23}^2 s_{12}s_{13} \sin \left( \delta - \frac{\alpha_{32}}{2} \right) \right]$$

$\alpha_{32} = \pi, \delta = 0: \text{Re}(U_{\tau 2}^* U_{\tau 3}) = 0, \text{CPV due to } R$

S. Pascoli, S.T.P., A. Riotto, 2006.



$$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3 \text{ (NH)}$$

Dirac CP-violation

$$\alpha_{32} = 0 \text{ (} 2\pi \text{)}, \beta_{23} = \pi \text{ (} 0 \text{)}; \quad \beta_{23} \equiv \beta_{12} + \beta_{13} \equiv \arg(R_{12}R_{13}).$$

$$|R_{12}|^2 \cong 0.85, |R_{13}|^2 = 1 - |R_{12}|^2 \cong 0.15 - \text{maximise } |\epsilon_\tau| \text{ and } |Y_B|:$$

$$|Y_B| \cong 2.8 \times 10^{-13} |\sin \delta| \left( \frac{s_{13}}{0.2} \right) \left( \frac{M_1}{10^9 \text{ GeV}} \right).$$

$$|Y_B| \gtrsim 8 \times 10^{-11}, \quad M_1 \lesssim 5 \times 10^{11} \text{ GeV imply}$$

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

The lower limit corresponds to

$$|J_{\text{CP}}| \gtrsim 2.4 \times 10^{-2}$$

FOR  $\alpha_{32} = 0 \text{ (} 2\pi \text{)}, \beta_{23} = 0 \text{ (} \pi \text{)}$ :

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.09, \quad \sin \theta_{13} \gtrsim 0.09; \quad |J_{\text{CP}}| \gtrsim 2.0 \times 10^{-2}$$

$$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3 \text{ (NH)}$$

Majorana CP-violation

$$\delta = 0, \text{ real } R_{12}, R_{13} (\beta_{23} = \pi (0));$$

$$\alpha_{32} \cong \pi/2, \quad |R_{12}|^2 \cong 0.85, \quad |R_{13}|^2 = 1 - |R_{12}|^2 \cong 0.15 - \text{maximise } |\epsilon_\tau| \text{ and } |Y_B|:$$

$$|Y_B| \cong 2 \times 10^{-12} \left( \frac{\sqrt{\Delta m_{31}^2}}{0.05 \text{ eV}} \right) \left( \frac{M_1}{10^9 \text{ GeV}} \right).$$

We get  $|Y_B| \gtrsim 8 \times 10^{-11}$ , for  $M_1 \gtrsim 3.6 \times 10^{10} \text{ GeV}$

$$M_1 \ll M_2 \ll M_3, m_3 \ll m_1 < m_2 \text{ (IH)}$$

Dirac CP-violation

$$m_3 \cong 0, R_{13} \cong 0 \text{ (} N_3 \text{ decoupling)}$$

$$\alpha_{21} = \pi; R_{11}R_{12} = i\kappa|R_{11}R_{12}|, \kappa = 1;$$

$$|R_{11}| \cong 1.07, |R_{12}|^2 = |R_{11}|^2 - 1, |R_{12}| \cong 0.38 - \text{maximise } |\epsilon_\tau| \text{ and } |Y_B|:$$

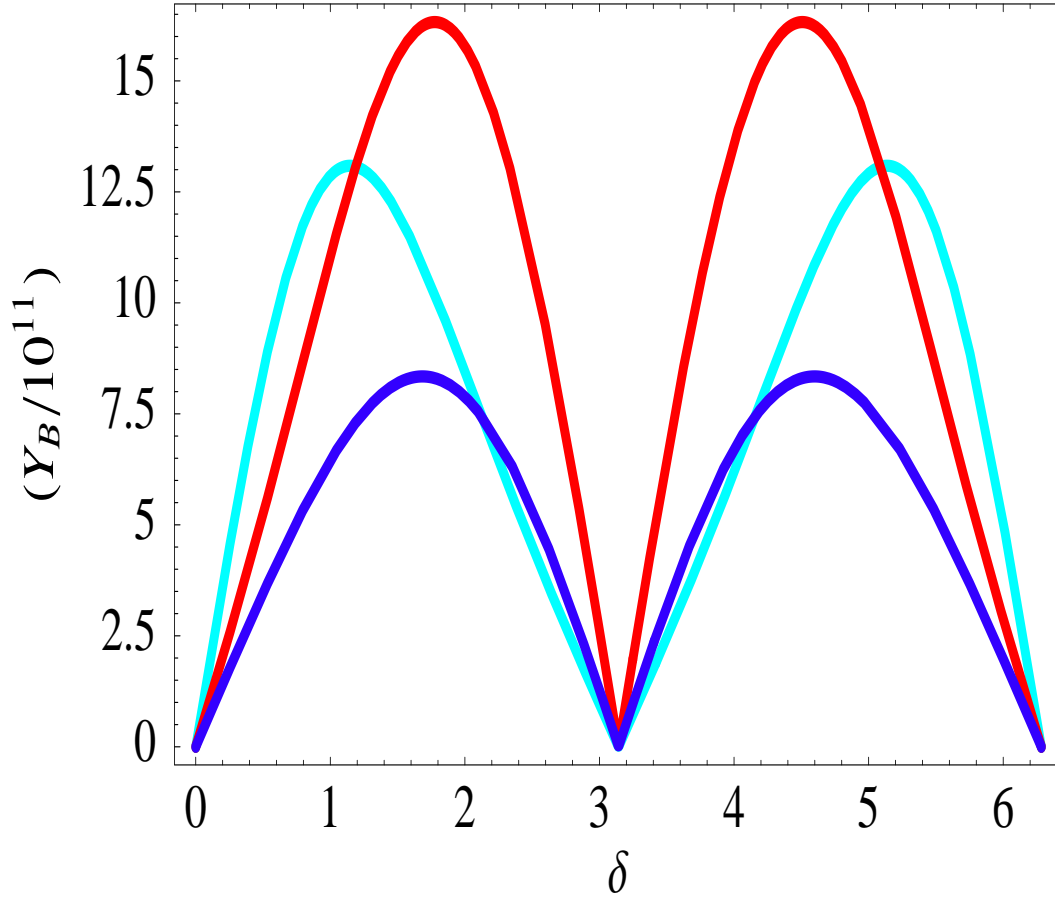
$$|Y_B| \cong 8.1 \times 10^{-12} |s_{13} \sin \delta| \left( \frac{M_1}{10^9 \text{ GeV}} \right).$$

$$|Y_B| \gtrsim 8 \times 10^{-11}, M_1 \lesssim 5 \times 10^{11} \text{ GeV imply}$$

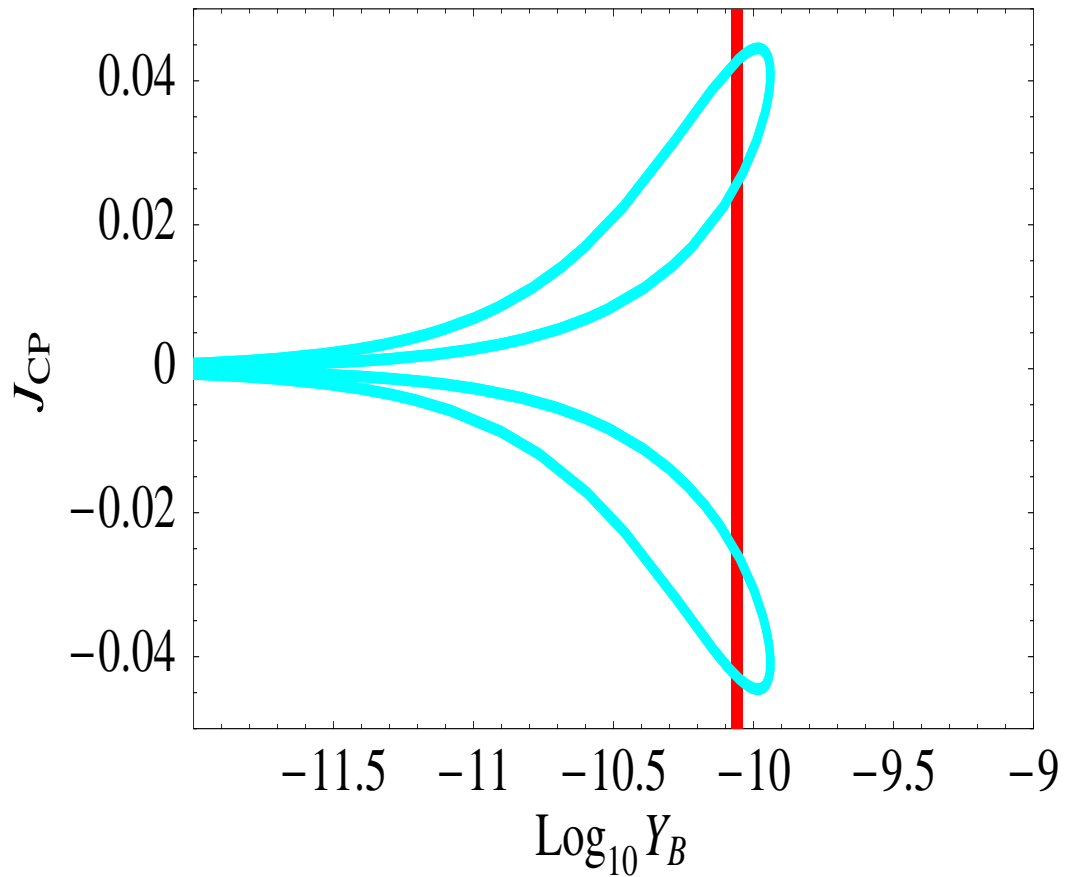
$$|\sin \theta_{13} \sin \delta| \gtrsim 0.02, \quad \sin \theta_{13} \gtrsim 0.02.$$

The lower limit corresponds to

$$|J_{\text{CP}}| \gtrsim 4.6 \times 10^{-3}$$

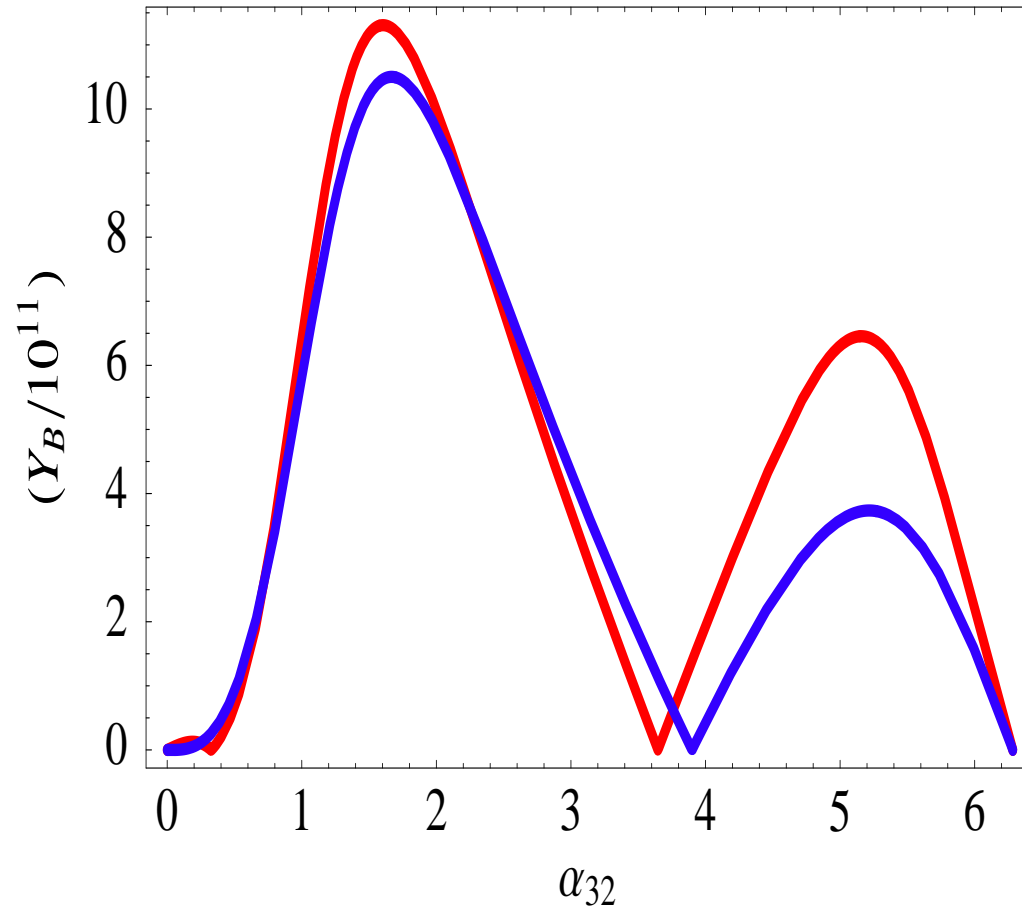


$M_1 \ll M_2 \ll M_3$ ,  $m_1 \ll m_2 \ll m_3$ ; Dirac CP-violation,  $\alpha_{32} = 0$ ;  $2\pi$ ;  
 real  $R_{12}$ ,  $R_{13}$ ,  $|R_{12}|^2 + |R_{13}|^2 = 1$ ,  $|R_{12}| = 0.86$ ,  $|R_{13}| = 0.51$ ,  $\text{sign}(R_{12}R_{13}) = +1$ ;  
 i)  $\alpha_{32} = 0$  ( $\kappa' = +1$ ),  $s_{13} = 0.2$  (red line) and  $s_{13} = 0.1$  (dark blue line);  
 ii)  $\alpha_{32} = 2\pi$  ( $\kappa' = -1$ ),  $s_{13} = 0.2$  (light blue line);  
 $M_1 = 5 \times 10^{11}$  GeV.



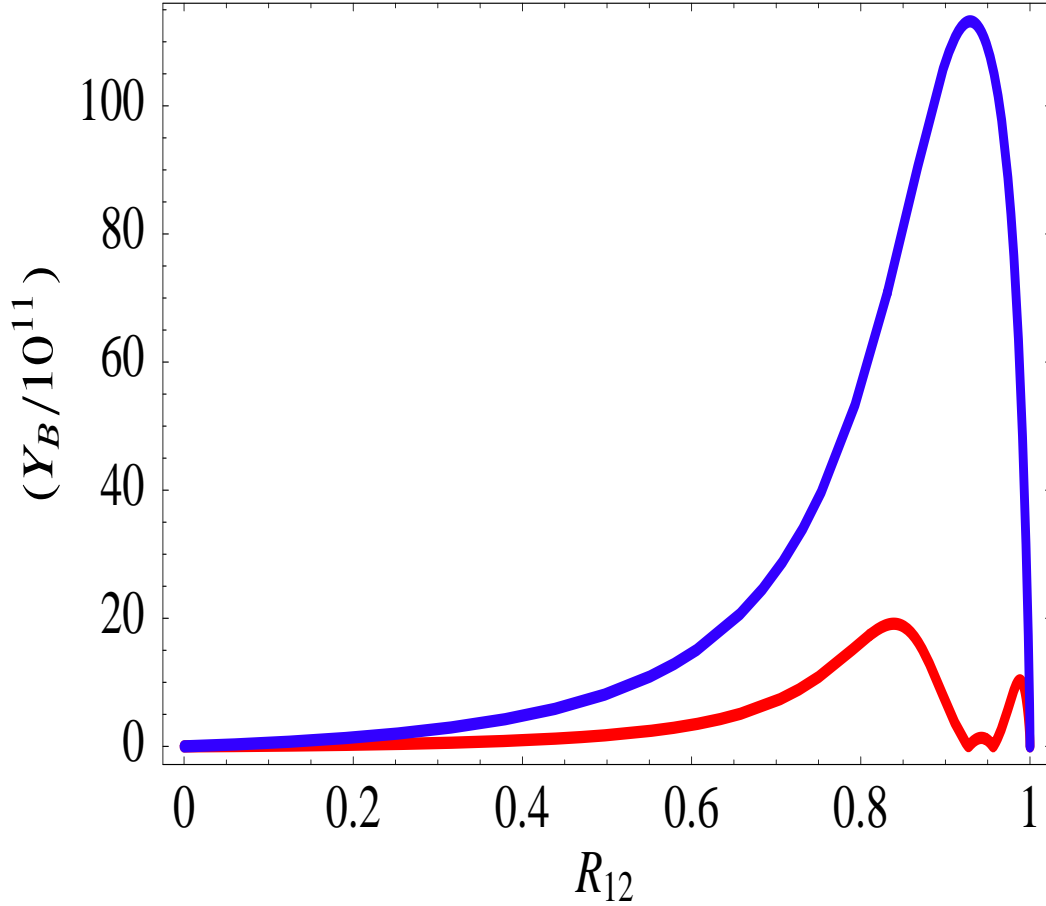
$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3; M_1 = 5 \times 10^{11} \text{ GeV};$   
 Dirac CP-violation,  $\alpha_{32} = 0 \text{ (} 2\pi \text{)}$ ;  
 $|R_{12}| = 0.86, |R_{13}| = 0.51, \text{sign}(R_{12}R_{13}) = +1 \text{ (-1)} \text{ (}\beta_{23} = 0 \text{ (}\pi\text{), } \kappa' = +1\text{)}$ ;  
 The red region denotes the  $2\sigma$  allowed range of  $Y_B$ .

S. Pascoli, S.T.P., A. Riotto, 2006.

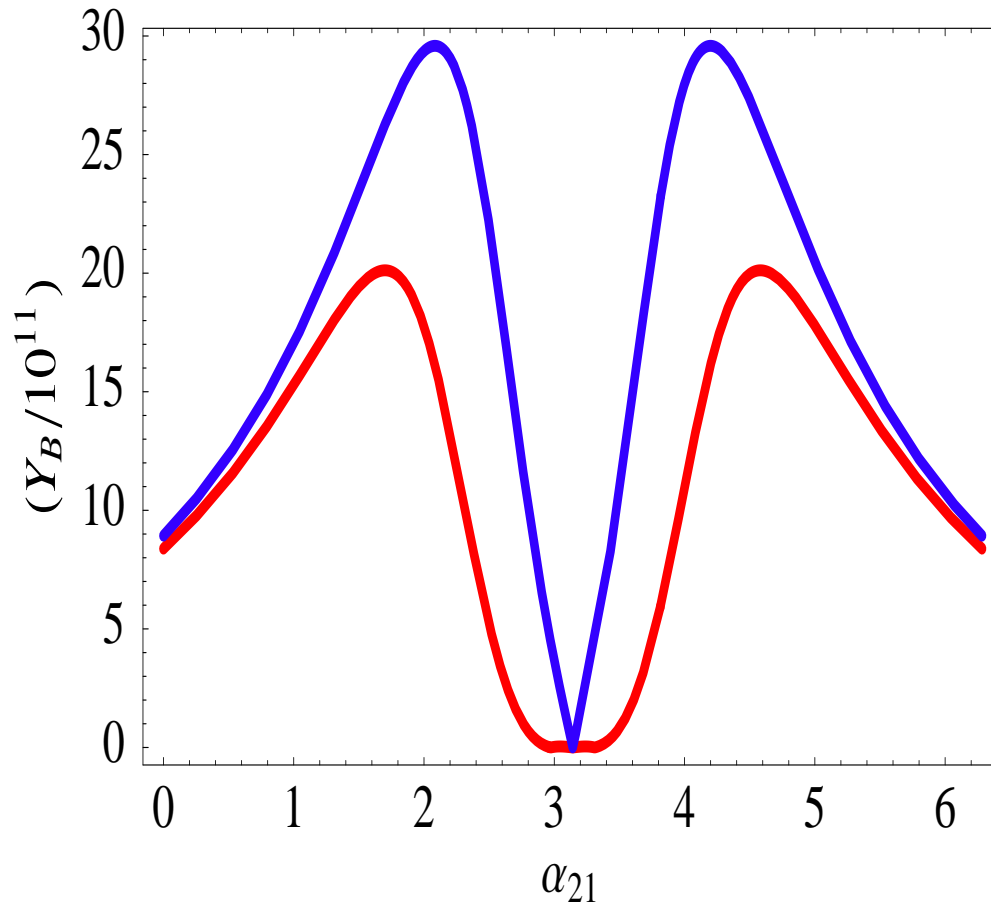


$M_1 \ll M_2 \ll M_3$ ,  $m_1 \ll m_2 \ll m_3$ ; Majorana CP-violation,  $\delta = 0$ ;  
 real  $R_{12}$ ,  $R_{13}$ ,  $|R_{12}| = 0.92$ ,  $|R_{13}| = 0.39$ ,  $\text{sgn}(R_{12}R_{13}) = +1$  ( $\beta_{23} = 0$ ,  $\kappa = +1$ );  
 $M_1 = 5 \times 10^{10}$  GeV,  $s_{13} = 0$  (blue line) and 0.2 (red line).

S. Pascoli, S.T.P., A. Riotto, 2006.

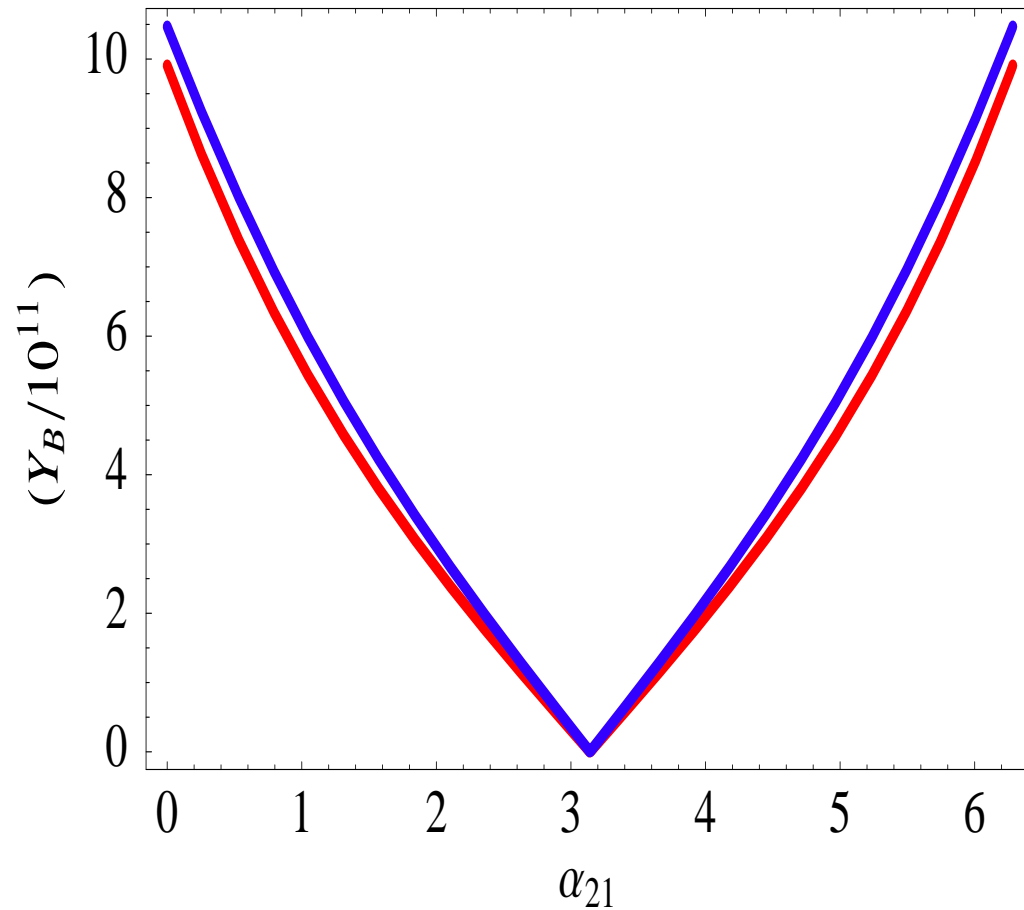


$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3; M_1 = 5 \times 10^{11} \text{ GeV};$   
 real  $R_{12}, R_{13}, \text{sign}(R_{12}R_{13}) = +1, R_{12}^2 + R_{13}^2 = 1, s_{13} = 0.20;$   
 a) Majorana CP-violation (blue line),  $\delta = 0$  and  $\alpha_{32} = \pi/2$  ( $\kappa = +1$ );  
 b) Dirac CP-violation (red line),  $\delta = \pi/2$  and  $\alpha_{32} = 0$  ( $\kappa' = +1$ );  
 $\Delta m_{\odot}^2, \sin^2 \theta_{12}, \Delta m_{31}^2, \sin^2 2\theta_{23}$  - fixed at their best fit values.

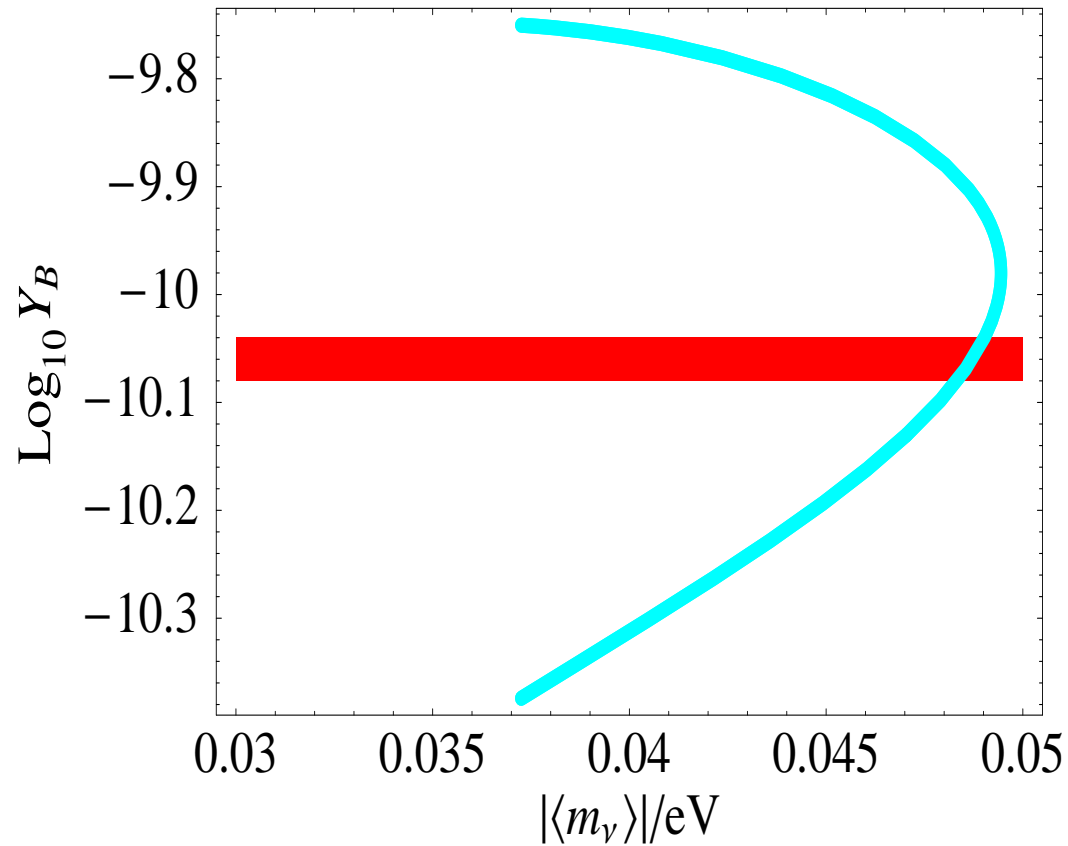


$M_1 \ll M_2 \ll M_3$ ,  $m_3 \ll m_1 < m_2$ ;  $M_1 = 2 \times 10^{11}$  GeV;  
 Majorana CP-violation,  $\delta = 0$ ;  
 purely imaginary  $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$ ,  $\kappa = -1$ ,  $|R_{11}|^2 - |R_{12}|^2 = 1$ ,  $|R_{11}| = 1.2$ ;  
 $s_{13} = 0$  (blue line) and 0.2 (red line).





$M_1 \ll M_2 \ll M_3, m_3 \ll m_1 < m_2; M_1 = 2 \times 10^{11}$  GeV;  
 Majorana CP-violation,  $\delta = 0$ ;  
 purely imaginary  $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$ ,  $\kappa = +1$ ,  $|R_{11}|^2 - |R_{12}|^2 = 1$ ,  $|R_{11}| = 1.05$ ;  
 $s_{13} = 0$  (blue line) and 0.2 (red line).



$M_1 \ll M_2 \ll M_3$ ,  $m_3 \ll m_1 < m_2$ ;  $M_1 = 2 \times 10^{11}$  GeV;  
 Majorana CP-violation,  $\delta = 0$ ,  $s_{13} = 0$ ;  
 purely imaginary  $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$ ,  $\kappa = +1$   $|R_{11}|^2 - |R_{12}|^2 = 1$ ,  $|R_{11}| = 1.05$ .  
 The Majorana phase  $\alpha_{21}$  is varied in the interval  $[-\pi/2, \pi/2]$ .

S. Pascoli, S.T.P., A. Riotto, 2006.

# Low Energy Leptonic CPV and Leptogenesis: Summary

Leptogenesis: see-saw mechanism;  $N_j$  - heavy RH  $\nu$ 's;

$N_j, \nu_k$  - Majorana particles

$$N_j: M_1 \ll M_2 \ll M_3$$

The observed value of the baryon asymmetry of the Universe can be generated

A. CP-violation due to the Dirac phase  $\delta$  in  $U_{\text{PMNS}}$ , no other sources of CPV (Majorana phases in  $U_{\text{PMNS}}$  equal to 0, etc.)

$m_1 \ll m_2 \ll m_3$  (NH):

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.09, \quad \sin \theta_{13} \gtrsim 0.09; \quad |J_{\text{CP}}| \gtrsim 2.0 \times 10^{-2}$$

$m_3 \ll m_1 < m_2$  (IH):

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.02, \quad \sin \theta_{13} \gtrsim 0.02; \quad |J_{\text{CP}}| \gtrsim 4.6 \times 10^{-3}$$

B. CP-violation due to the Majorana phases in  $U_{\text{PMNS}}$ , no other sources of CPV (Dirac phase in  $U_{\text{PMNS}}$  equal to 0, etc.)

C. CP-violation due to both Dirac and Majorana phases in  $U_{\text{PMNS}}$ , no other source of CPV.

## Conclusions

The see-saw mechanism provides a link between  $\nu$ -mass generation and BAU.

Determining the nature - Dirac or Majorana, of massive neutrinos is of fundamental importance for understanding the origin of neutrino masses.

CPV phases in  $U_{\text{PMNS}}$  can be the leptogenesis CPV parameters.

Low energy leptonic CPV can be directly related to the existence of BAU.

Understanding the status of the CP-symmetry in the lepton sector is of fundamental importance.

These results underline further the importance of the experiments aiming to measure the CHOOZ angle  $\theta_{13}$  and of the experimental searches for Dirac and/or Majorana leptonic CP-violation at low energies.