Neutrino Mixing, Dirac and Majorana Leptonic CP-Violation and Leptogenesis

S. T. Petcov

SISSA/INFN, Trieste, Italy,
Kavli IPMU, University of Tokyo, Tokyo, Japan

NOW 2012
Conca Specchiulla
September 10, 2012

There were spectacular developments regarding the "CHOOZ" angle θ_{13} in the last year or so.

Started in 2008 with weak indications for $\theta_{13} \sim 0.1$:

$$\sin^2\theta_{13} = 0.016 \pm 0.010, \; \sin\theta_{13} = (0.077 - 0.161)\,, \quad 1\sigma$$

E. Lisi *et al.*, arXiv:0806.2649

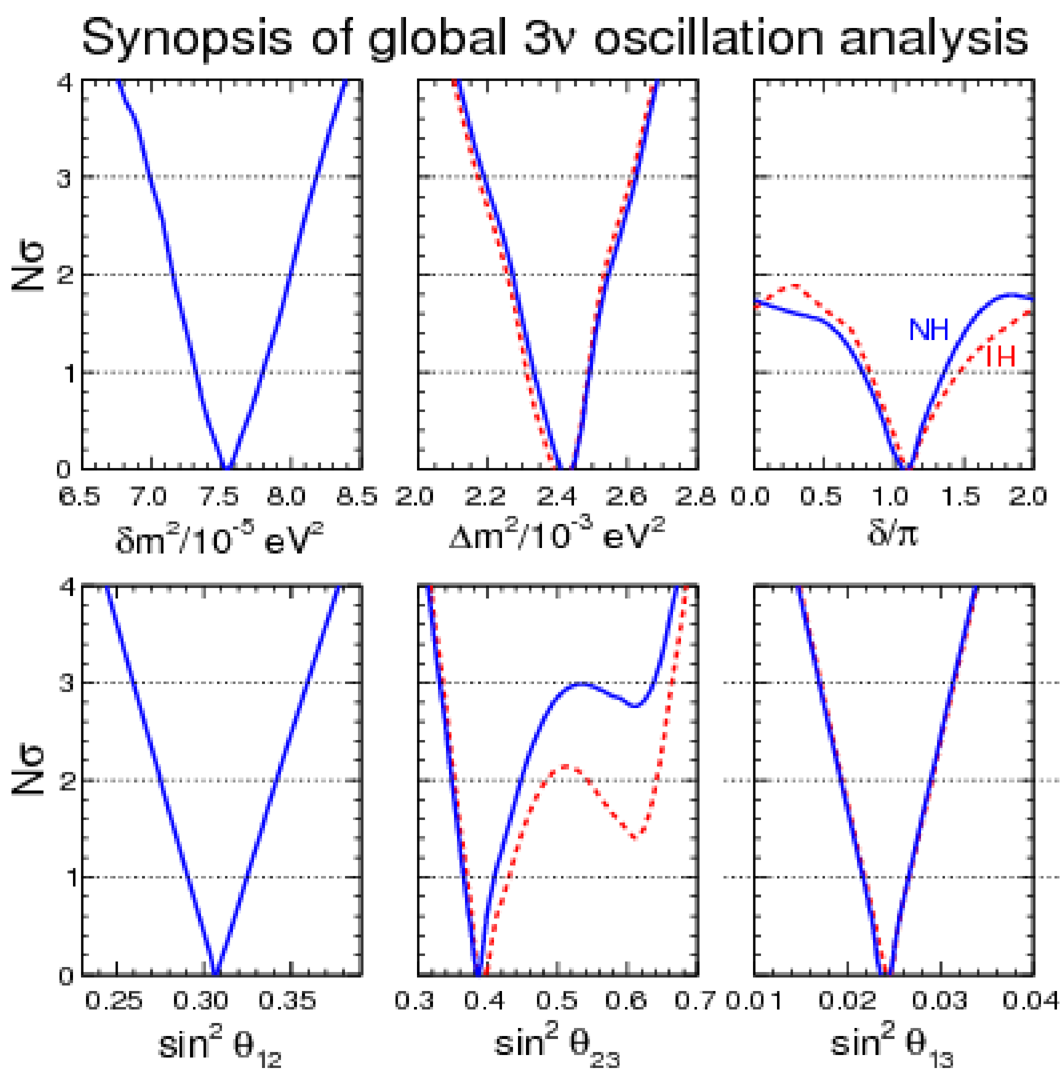
A.B. Balantekin, D. Yilmaz, arXiv:0804.3345;

Atmospheric ν data: $\cos\delta = -1$ favored over $\cos\delta = +1$

J. Escamilla *et al.*, arXiv:0805.2924


Sendai
Super Kamiokande
295km
JAERI
(Tokai)
Japan
KEK
Tokyo
Gifu
Nagoya
Kawasaki
Kyoto
Yokohama
Osaka
(c) 2000 ESRI
~ 420.0 mi / 675.8 km across

- June 14, 2011, T2K: 2.5σ evidence for $\theta_{13} \neq 0$.
- June 24, 2011, MINOS: 1.7σ evidence for $\theta_{13} \neq 0$.
- June 28, 2011, Fogli et al.: from global analysis more than 3σ evidence for $\theta_{13} \neq 0$; b.f.v.: $\sin^2\theta_{13} = 0.025$ (0.023).
- November 9, 2011, Double Chooz: $\theta_{13} \neq 0$ at 1.5σ.
- March 8, 2012, Daya Bay: 5.2σ evidence for $\theta_{13} \neq 0$, $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$.
- April 4, 2012, RENO: 4.9σ evidence for $\theta_{13} \neq 0$, $\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.019$.
- Nu'2012 (June 4-9, 2012), T2K, Double Chooz: 3.2σ and 3.1σ evidence for $\theta_{13} \neq 0$.
- Nu'2012 (June 4-9, 2012), Daya Bay: $\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$.
- June , 2012, Fogli et al., global analysis, b.f.v.: $\sin^2\theta_{13} = 0.0241$ (0.0244), NH (IH).



Global data: $\cos\delta = -1$ favored over $\cos\delta = +1$;

best fit: $\sin\theta_{13}\cos\delta \cong -0.15$.

Fogli *et al.*, arXiv:1205.5254v3

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.54 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.307$, $\cos 2\theta_{12} \gtrsim 0.28$ (3σ),
- $|\Delta m^2_{31(32)}| \cong 2.47$ $(2.46) \times 10^{-3}$ eV^2, $\sin^2\theta_{23} \cong 0.386$ (0.392), NH (IH),
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0241$ (0.0244), NH (IH).

Fogli *et al.*, arXiv:1205.5254v3

Large $\sin^2\theta_{13} \cong (0.01 - 0.02)$ - far-reaching implications for the program of reserach in neutrino physics:

- For the searches for CP violation in ν-oscillations;
- For the determination of the type of $\nu-$ mass spectrum (or of $\text{sgn}(\Delta m^2_{\text{atm}})$) in neutrino oscillation experiments.
- For understanding the patern of the neutrino mixing and its origins (symmetry, etc.?).
- For the predictions for the $(\beta\beta)_{0\nu}$-decay effective Majorana mass in the case of NH light ν mass spectrum (possibility of a strong suppression).
- Important implications also for the "flavoured" leptogenesis scenario of generation of the baryon asymmetry of the Universe.

One of the next most important steps - determine the status of the CP symmetry in the lepton sector.

The reference scheme: 3-ν mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}} \qquad l = e, \mu, \tau.$$

PMNS Matrix: Standard Parametrization

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

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

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21}, α_{31} - the two Majorana CP-violation phases.

S.M. Bilenky, J. Hosek, S.T.P., 1980

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.54 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.307$, $\cos 2\theta_{12} \gtrsim 0.28$ (3σ),
- $|\Delta m^2_{31(32)}| \cong 2.47$ $(2.46) \times 10^{-3}$ eV^2, $\sin^2\theta_{23} \cong 0.386$ (0.392), NH (IH),
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0241$ (0.0244), NH (IH).

Fogli *et al.*, arXiv:1205.5254v3

- Dirac phase δ: $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l \neq l'$; $A^{(l,l')}_{\rm CP} \propto J_{\rm CP} \propto \sin\theta_{13} \sin\delta$:

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

$$J_{CP} = \mathrm{Im}\left\{U_{e1}\, U_{\mu 2}\, U^*_{e2}\, U^*_{\mu 1}\right\} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Current data: $|J_{CP}| \lesssim 0.045$ (can be realtively large!)

- Majorana phases α_{21}, α_{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

  - $\left|<m>\right|$ in $(\beta\beta)_{0\nu}$−decay depends on α_{21}, α_{31};
  - $\Gamma(\mu \to e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\delta, \alpha_{21,31}$!

- $\mathrm{sgn}(\Delta m^2_{\rm atm}) = \mathrm{sgn}(\Delta m^2_{31})$ not determined

$\Delta m^2_{\rm atm} \equiv \Delta m^2_{31} > 0$, normal mass ordering
$\Delta m^2_{\rm atm} \equiv \Delta m^2_{32} < 0$, inverted mass ordering

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

$m_1 \ll m_2 < m_3$, NH,
$m_3 \ll m_1 < m_2$, IH,
$m_1 \cong m_2 \cong m_3$, $m^2_{1,2,3} >> \Delta m^2_{\rm atm}$, QD; $m_j \gtrsim 0.10$ eV.

Dirac CP-Nonconservation: δ in U_{PMNS}

Observable manifestations in

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

- not sensitive to Majorana CPVP α_{21}, α_{31}

CP-invariance:

N. Cabibbo, 1978

S.M. Bilenky, J. Hosek, S.T.P.,1980;

V. Barger, S. Pakvasa et al.,1980.

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

CPT-invariance:

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

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

T-invariance:

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

3ν —mixing:

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

$$A_{\mathrm{T}}^{(l,l')} \equiv P(\nu_l \to \nu_{l'}) - P(\nu_{l'} \to \nu_l),\ l \neq l'$$

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

P.I. Krastev, S.T.P., 1988; V. Barger, S. Pakvasa *et al.*, 1980

In vacuum: $A^{(e,\mu)}_{\mathrm{CP(T)}} = J_{\mathrm{CP}} F^{vac}_{osc}$

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

$$F^{vac}_{osc} = \sin\left(\frac{\Delta m^2_{21}}{2E} L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E} L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E} L\right)$$

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

In matter: Matter effects violate

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

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

P. Langacker et al., 1987

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

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

In matter with constant density: $\mathrm{A}^{(e,\mu)}_{\mathrm{T}} = \mathrm{J}^{\mathrm{mat}}_{\mathrm{CP}} \mathrm{F}^{\mathrm{mat}}_{\mathrm{osc}}$

$$\mathrm{J}^{\mathrm{mat}}_{\mathrm{CP}} = \mathrm{J}^{\mathrm{vac}}_{\mathrm{CP}}\ \mathrm{R}_{\mathrm{CP}}$$

R_{CP} does not depend on θ_{23} and δ; $|R_{CP}| \lesssim 2.5$

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

P. Harrison, S. Scott, 2000

Rephasing Invariants Associated with CPVP

Dirac phase δ:

$$J_{CP} = \mathrm{Im}\left\{U_{e1}\, U_{\mu 2}\, U^*_{e2}\, U^*_{\mu 1}\right\} \ .$$

C. Jarlskog, 1985 (for quarks)

CP-, T- violation effects in neutrino oscillations

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

Majorana phases α_{21}, α_{31}:

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

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 $\mathrm{Im}\left\{U_{e1} U^*_{e3}\right\} \neq 0$ and $\mathrm{Re}\left\{U_{e1} U^*_{e3}\right\} \neq 0$.

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

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

Absolute Neutrino Mass Measurements

The Troitzk and Mainz ^{3}H β-decay experiments

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

It is expected that the following sensitivity will be reached:

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

Cosmological and astrophysical data, the CMB data of the WMAP experiment, combined with supernovae data and data on galaxy clustering imply (depending on the model complexity and the input data used):

$$\sum_j m_j \leq (0.3 - 1.3) \text{ eV} \quad (95\% \text{ C.L.})$$

K.N. Abazajian *et al.*, arXiv:1103.5083

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

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

M_ν 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; GUT's: M. Yoshimura, 1978.

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

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

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

F. Borzumati, A. Masiero, 1986.

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

See-Saw: Dirac ν-mass m_D + Majorana mass M_R for N_R

The See-Saw Lagrangian

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

$$\begin{aligned}
\mathcal{L}_{\text{CC}} &= -\frac{g}{\sqrt{2}}\overline{l_L}(x)\,\gamma_\alpha\,\nu_{lL}(x)\,W^{\alpha\dagger}(x) + h.c.\,,\\
\mathcal{L}_{\text{Y}}(x) &= \lambda_{il}\,\overline{N_{iR}}(x)\,H^\dagger(x)\,\psi_{lL}(x) + Y_l\,H^c(x)\,\overline{l_R}(x)\,\psi_{lL}(x) + \text{h.c.}\,,\\
\mathcal{L}_{\text{M}}^{\text{N}}(x) &= -\frac{1}{2}M_i\,\overline{N_i}(x)\,N_i(x)\,.
\end{aligned}$$

ψ_{lL} - LH doublet, $\psi_{lL}^{\text{T}} = (\nu_{lL}\ \ l_L)$, 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:

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

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, $R^T R = 1$.

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.

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

$$R\text{-complex},\ \ R^T R = 1.$$

J.A. Casas and A. Ibarra, 2001

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

Models: R - CP conserving ($SU(5) \times T'$); CPV parameters in R determined by the CPV phases in U (class of A_4 models).
Texture zeros in Y_ν: CPV parameters in R and U - related.

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-Invarinace Constraints

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

The CP-symmetry transformation:

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

CP-invariance:

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

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

$$\begin{aligned} \lambda_{jl}^* &= \lambda_{jl}\, \rho_j^N\,, \;\; \rho_j^N = \pm 1\,, \\ U_{lj}^* &= U_{lj}\, \rho_j^{\nu}\,, \;\; \rho_j^{\nu} = \pm 1\,, \\ R_{jk}^* &= R_{jk}\, \rho_j^N\, \rho_k^{\nu}, \quad j,k = 1,2,3,\;\; l = e,\mu,\tau, \end{aligned}$$

λ_{jl}, U_{lj}, R_{jk} - either real or purely imaginary.

Relevant quantity:

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

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

$$
\begin{aligned}
P_{jkml} &\equiv R_{jk}\,R_{jm}\,U^*_{lk}\,U_{lm}\,,\ k \neq m\,, \\
CP: \quad P^*_{jkml} &= P_{jkml}\,(\rho^N_j)^2\,(\rho^\nu_k)^2\,(\rho^\nu_m)^2 = P_{jkml}\,, \quad \mathrm{Im}(P_{jkml}) = 0\,.
\end{aligned}
$$

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

Suppose, CP-invrainace 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.

Baryon Asymmetry

$$Y_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}, \quad \text{CMB}$$

Sakharov conditions for a dynamical generation of $Y_B \neq 0$ in the Early Universe

- **B number non-conservation.**
- **Violation of C and CP symmetries.**
- **Deviation from thermal equilibrium.**

Leptogenesis

- The heavy Majorana neutrinos N_i are in equilibrium in the Early Universe as far as the processes which produce and destroy them are efficient.

- When $T < M_1$, N_1 drops out of equilibrium as it cannot be produced efficiently anymore.

- If $\Gamma(N_1 \to \Phi^- \ell^+) \neq \Gamma(N_1 \to \Phi^+ \ell^-)$, a lepton asymmetry will be generated.

- Wash-out processes, like $\Phi^+ + \ell^- \to N_1$, $\ell^- + \Phi^+ \to \Phi^- + \ell^+$, etc. tend to erase the asymmetry. Under the condition of non-equilibrium, they are less efficient than the direct processes in which the lepton asymmetry is created. The final resullt is a net (non-zero) lepton asymmetry.

- This lepton asymmetry is then converted into a baryon asymmetry by $(B+L)$ violating but $(B-L)$ conserving sphaleron processes which exist within the SM (at $T \gtrsim M_{\mathrm{EWSB}}$).

S. Fukugita, T. Yanagida, 1986.

In order to compute Y_B:

1. calculate the CP-asymmetry:

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

2. solve the Boltzmann equation to account for the wash-out of the asymmetry:

$$Y_\mathrm{L} = \kappa\,\varepsilon$$

where $\kappa = \kappa(\tilde{m})$ is the "efficiency factor", $\tilde{m}$ is the "the wash-out mass parameter" - determines the rate of wash-out processes;

3. the lepton asymmetry is converted into a baryon asymmetry:

$$Y_\mathrm{B} = \frac{c_S}{g_*}\kappa\varepsilon$$

Baryon number violation in the SM

Sphaleron processes

SU(2) instantons lead to effective 12 fermion interactions:

$O(B+L) = \Pi_i q_{Li} q_{Li} q_{Li} l_{Li}$

These would induce $\Delta B = \Delta L = 3$ processes:

$$u_L + d_L + c_L + s_L + t_L + b_L + \nu_{eL} + \nu_{\mu L} + \nu_{\tau L} \rightarrow \bar{d}_R + \bar{b}_R + \bar{s}_R$$

However, at T = 0 the probability of such processes is $\Gamma \sim e^{-4\pi/\alpha} \sim 10^{-165}$.

At finite T, the transitions proceed via thermal fluctuations with an un-suppressed probability: $\Gamma \sim \alpha T^4$.

Sphaleron processes are efficient for

$$T_{\mathrm{EW}} \sim 100 \text{ GeV} < T < 10^{12} \text{ GeV}$$

V. Kuzmin, V. Rubakov, M. Shaposhnikov, 1985

Leptogenesis

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

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

W. Buchmüller, M. Plümacher, 1998;
W. Buchmüller, P. Di Bari, M. Plümacher, 2004

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

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

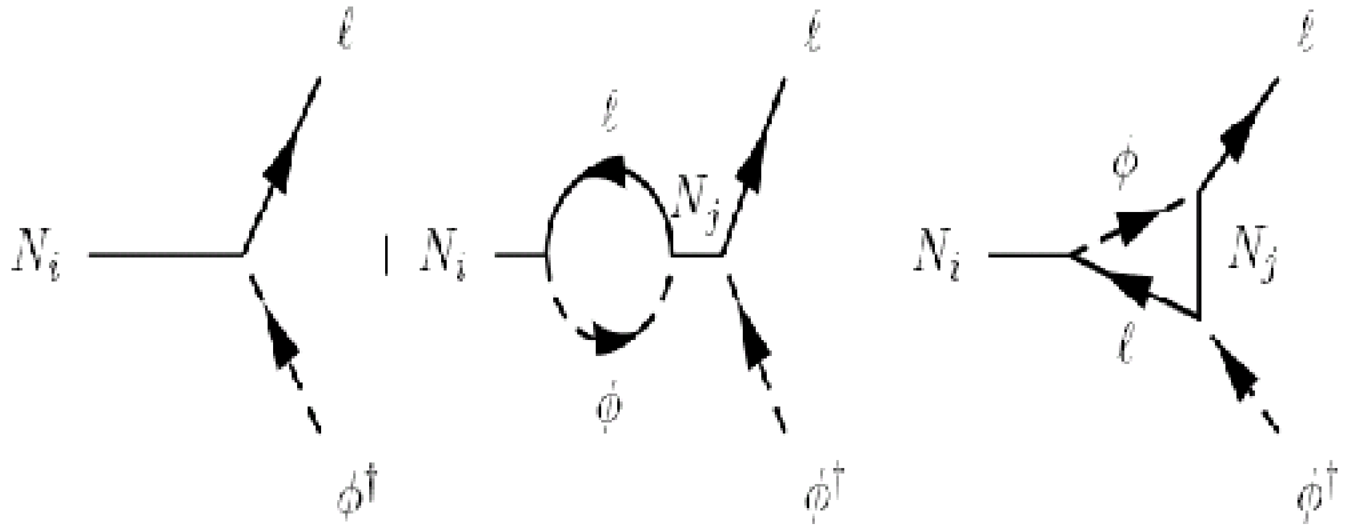
$$\varepsilon_1 = \frac{\Gamma(N_1 \to \Phi^- \ell^+) - \Gamma(N_1 \to \Phi^+ \ell^-)}{\Gamma(N_1 \to \Phi^- \ell^+) + \Gamma(N_1 \to \Phi^+ \ell^-)}$$

M.A. Luty, 1992;
L. Covi, E. Roulet and F. Vissani, 1996;
M. Flanz *et al.*, 1996;
M. Plümacher, 1997;
A. Pilaftsis, 1997.

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

$\Phi^+ + \ell^- \to N_1$, $\quad \ell^- + \Phi^+ \to \Phi^- + \ell^+$, etc.

W. Buchmuller, P. Di Bari and M. Plumacher, 2002;
G. F. Giudice *et al.*, 2004



N_i
ℓ
$\phi^\dagger$
N_i
ℓ
ϕ
N_j
ℓ
$\phi^\dagger$
N_i
ϕ
ℓ
N_j
ℓ
$\phi^\dagger$

Low Energy Leptonic CPV and Leptogenesis

Assume: $M_1 \ll M_2 \ll M_3$

Individual asymmetries:

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

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

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

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

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

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

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

$$\widetilde{m_1} = \sum_l \widetilde{m_l} = \sum_k m_k\,|R_{1k}|^2\,.$$

Two-Flavour Regime

At $M_1 \sim T \sim 10^{12}$ GeV: Y_τ - in equilibrium, $Y_{e,\mu}$ - not;

wash-out dynamics changes: τ_R^-, τ_L^+

$N_1 \to (\lambda_{1e} e_L^- + \lambda_{1\mu} \mu_L^- + \lambda_{1\tau} \tau_L^-) + \Phi^+$; $(\lambda_{1e} e_L^- + \lambda_{1\mu} \mu_L^- + \lambda_{1\tau} \tau_L^-) + \Phi^+ \to N_1$;

$\tau_L^- + \Phi^0 \to \tau_R^-$, $\tau_L^- + \tau_L^+ \to N_1 + \nu_L$, etc.

$\varepsilon_{1\tau}$ and $(\varepsilon_{1e} + \varepsilon_{1\mu}) \equiv \varepsilon_2$ evolve independently.

Three-Flavour Regime

At $M_1 \sim T \sim 10^9$ GeV: Y_τ, Y_μ - in equilibrium, Y_e - not.

$\varepsilon_{1\tau}$, ε_{1e} and $\varepsilon_{1\mu}$ evolve independently.

Thus, at $M_1 \sim 10^9 - 10^{12}$ GeV: L_τ, ΔL_τ - distinguishable;

L_e, L_μ, ΔL_e, ΔL_μ - 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: $M_1 \ll M_2 \ll M_3$, $\quad 10^9 \lesssim M_1\ (\sim T) \lesssim 10^{12}$ GeV,

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

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

The baryon asymmetry is

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

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

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

$Y_2 = Y_{e+\mu}$, $\quad \varepsilon_2 = \varepsilon_{1e} + \varepsilon_{1\mu}$, $\quad \widetilde{m_2} = \widetilde{m_{1e}} + \widetilde{m_{1\mu}}$

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

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

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

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

CP-Violation: $\mathrm{Im}\left(U^*_{\tau j} U_{\tau k}\right) \neq 0$, $\mathrm{Re}\left(U^*_{\tau j} U_{\tau k}\right) \neq 0$;

$$Y_B = -\frac{12}{37} \frac{\varepsilon_{1\tau}}{g_*} \left(\eta\left(\frac{390}{589} \widetilde{m_\tau}\right) - \eta\left(\frac{417}{589} \widetilde{m_2}\right) \right)$$

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

$$\varepsilon_{1\tau} = -\frac{3M_1\sqrt{\Delta m^2_{31}}}{16\pi v^2}\left(\frac{\Delta m^2_{\odot}}{\Delta m^2_{31}}\right)^{\frac{1}{4}} \frac{|R_{12}R_{13}|}{\left(\frac{\Delta m^2_{\odot}}{\Delta m^2_{31}}\right)^{\frac{1}{2}}|R_{12}|^2 + |R_{13}|^2}$$

$$\times \left(1 - \frac{\sqrt{\Delta m^2_{\odot}}}{\sqrt{\Delta m^2_{31}}}\right) \mathrm{Im}\,(U^*_{\tau 2}U_{\tau 3})$$

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

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

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

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

Dirac CP-violation

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

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

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

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

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

The lower limit corresponds to

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

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

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

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

Majorana CP-violation

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

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

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

We get $|Y_B| \gtrsim 8 \times 10^{-11}$, for $M_1 \gtrsim 3.6 \times 10^{10}$ GeV, or $|\sin \alpha_{32}/2| \gtrsim 0.15$

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

$m_3 \cong 0$, $R_{13} \cong 0$ (N_3 decoupling): impossible to reproduce Y_B^{obs} for real $R_{11} R_{12}$;

$|Y_B|$ suppressed by the additional factor $\Delta m^2_\odot / |\Delta m^2_{\rm A}| \cong 0.03$.

Purely imaginary $R_{11} R_{12}$: no (additional) suppression

Dirac CP-violation

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

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

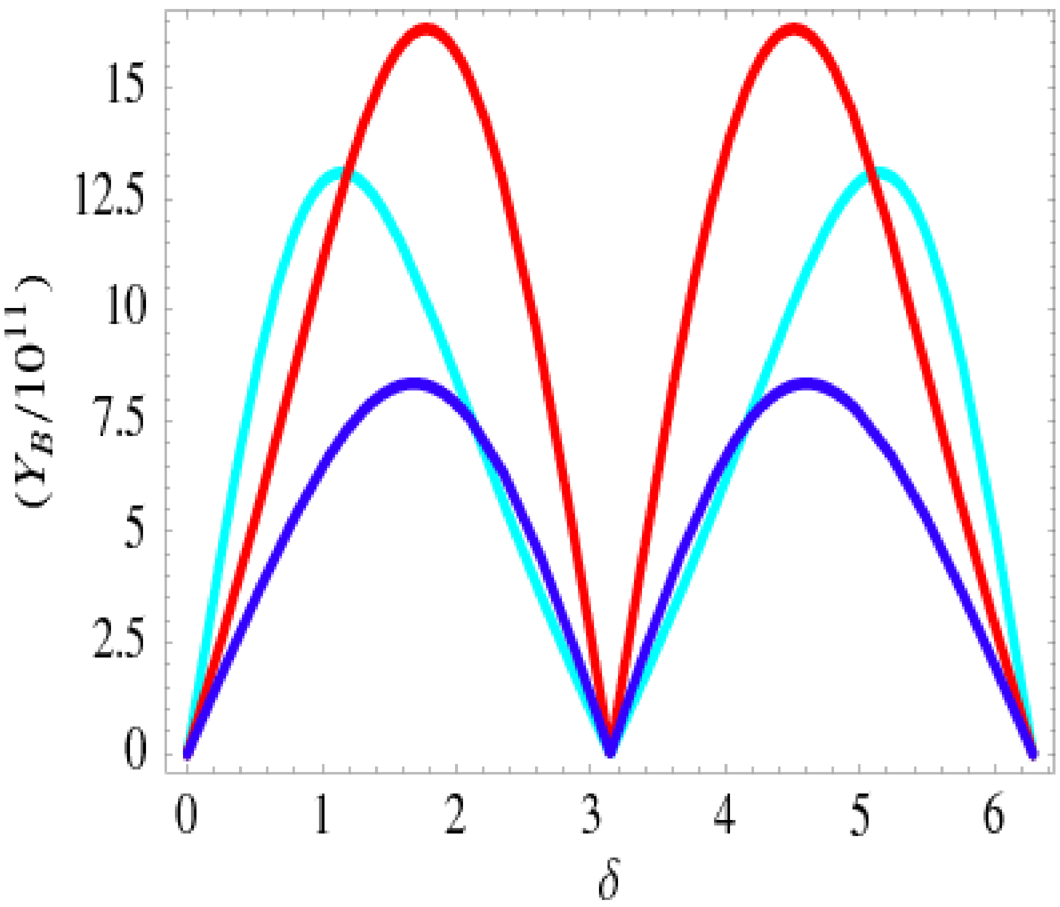
$$|Y_B| \cong 8.1 \times 10^{-12} |s_{13} \sin\delta| \left(\frac{M_1}{10^9 \text{ GeV}} \right).$$

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

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

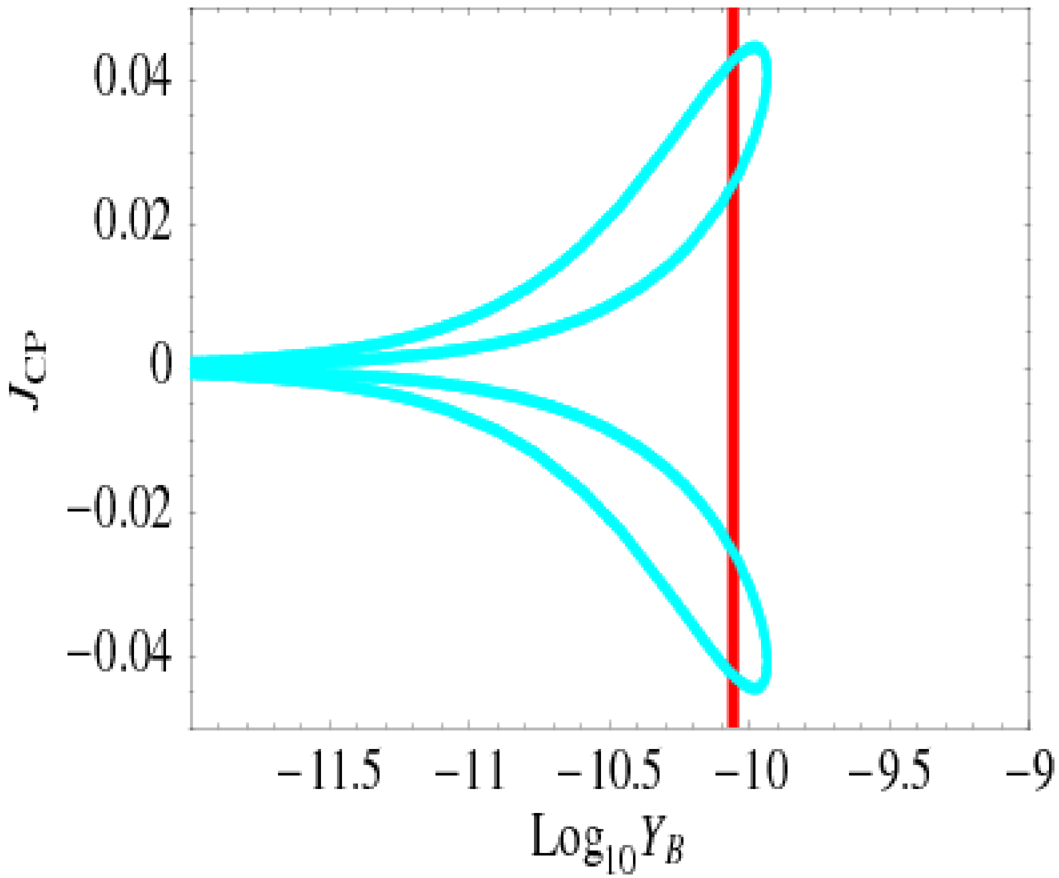
The lower limit corresponds to

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



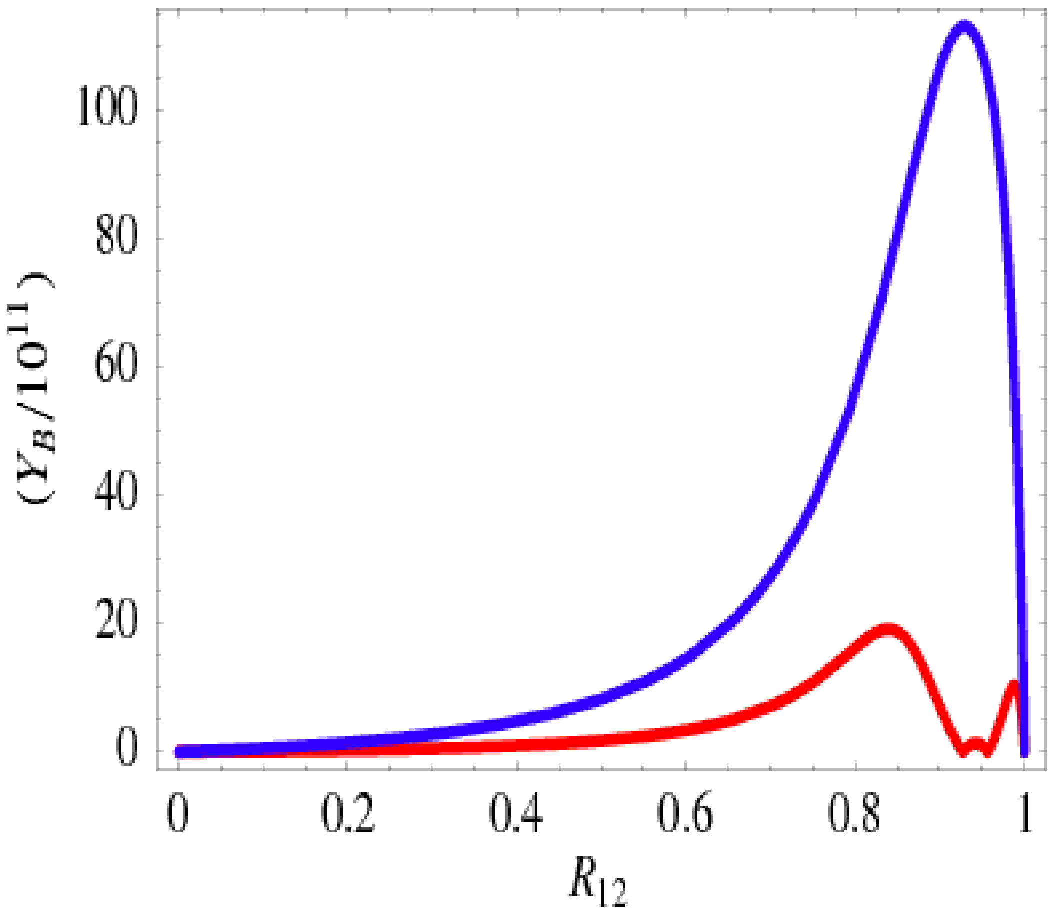
$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; Dirac CP-violation, $\alpha_{32} = 0;\ 2\pi$;
real R_{12}, R_{13}, $|R_{12}|^2 + |R_{13}|^2 = 1$, $|R_{12}| = 0.86$, $|R_{13}| = 0.51$, sign$(R_{12}R_{13}) = +1$;
i) $\alpha_{32} = 0$ ($\kappa' = +1$), $s_{13} = 0.2$ (red line) and $s_{13} = 0.1$ (dark blue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

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

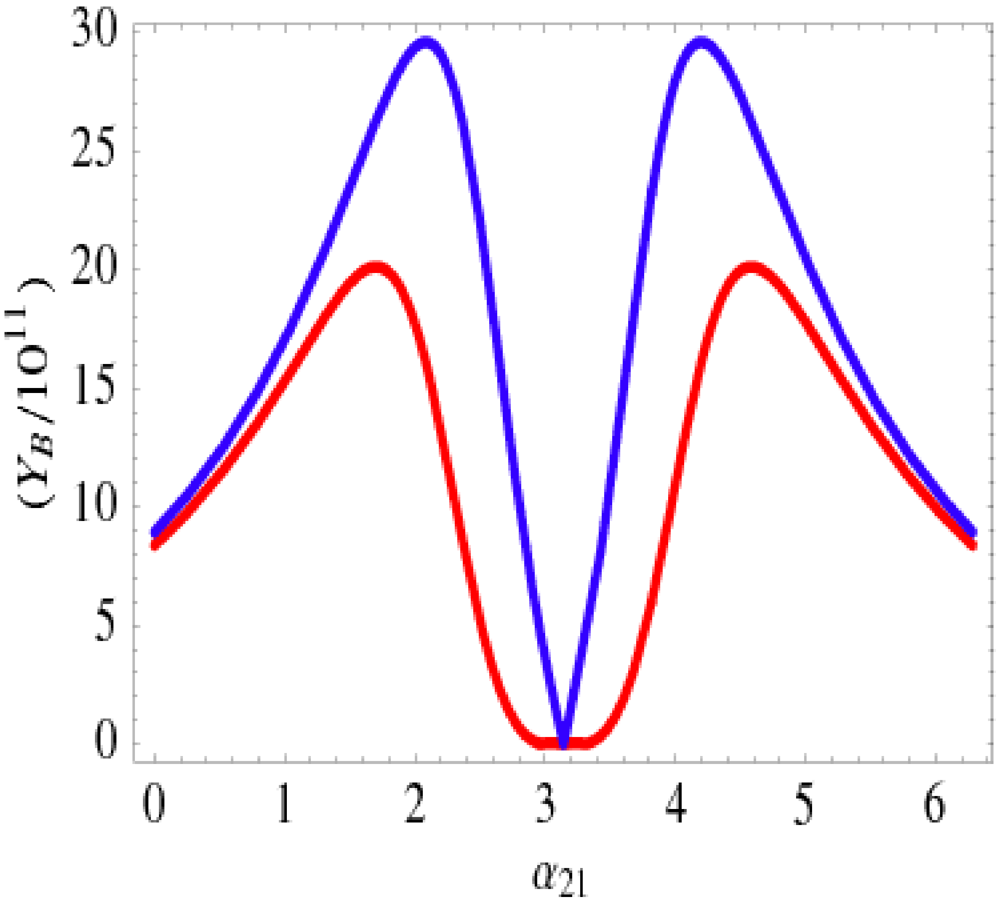


$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; $M_1 = 5 \times 10^{11}$ GeV;
Dirac CP-violation, $\alpha_{32} = 0$ (2π);
$|R_{12}| = 0.86$, $|R_{13}| = 0.51$, sign $(R_{12}R_{13}) = +1$ (-1) $(\beta_{23} = 0$ (π), $\kappa' = +1)$;
The red region denotes the 2σ allowed range of Y_B.

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

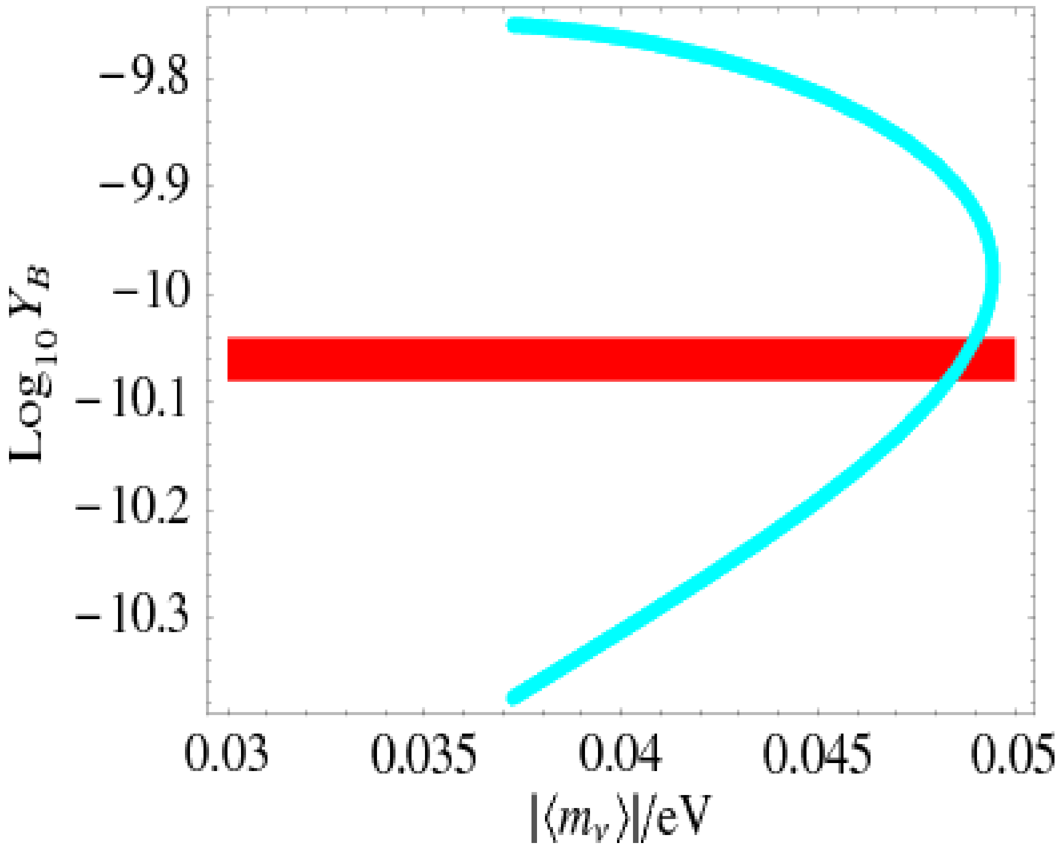


$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; $M_1 = 5 \times 10^{11}$ GeV;
real R_{12}, R_{13}, sign$(R_{12}R_{13}) = +1$, $R_{12}^2 + R_{13}^2 = 1$, $s_{13} = 0.20$;
a) Majorana CP-violation (blue line), $\delta = 0$ and $\alpha_{32} = \pi/2$ ($\kappa = +1$);
b) Dirac CP-violation (red line), $\delta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

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



$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$; $M_1 = 2 \times 10^{11}$ 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 α_{21} is varied in the interval $[-\pi/2, \pi/2]$.

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

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

Majorana or Dirac CP-violation

$m_3 \neq 0$, $R_{13} \neq 0$, $R_{11}(R_{12}) = 0$: possible to reproduce Y_B^{obs} for real $R_{12(11)}R_{13} \neq 0$

Requires $m_3 \cong (10^{-5} - 10^{-2})$ eV; non-trivial dependence of $|Y_B|$ on m_3

Majorana CPV, $\delta = 0$ (π): requires $M_1 \gtrsim 3.5 \times 10^{10}$ GeV

Dirac CPV, $\alpha_{32(31)} = 0$: typically requires $M_1 \gtrsim 10^{11}$ GeV

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

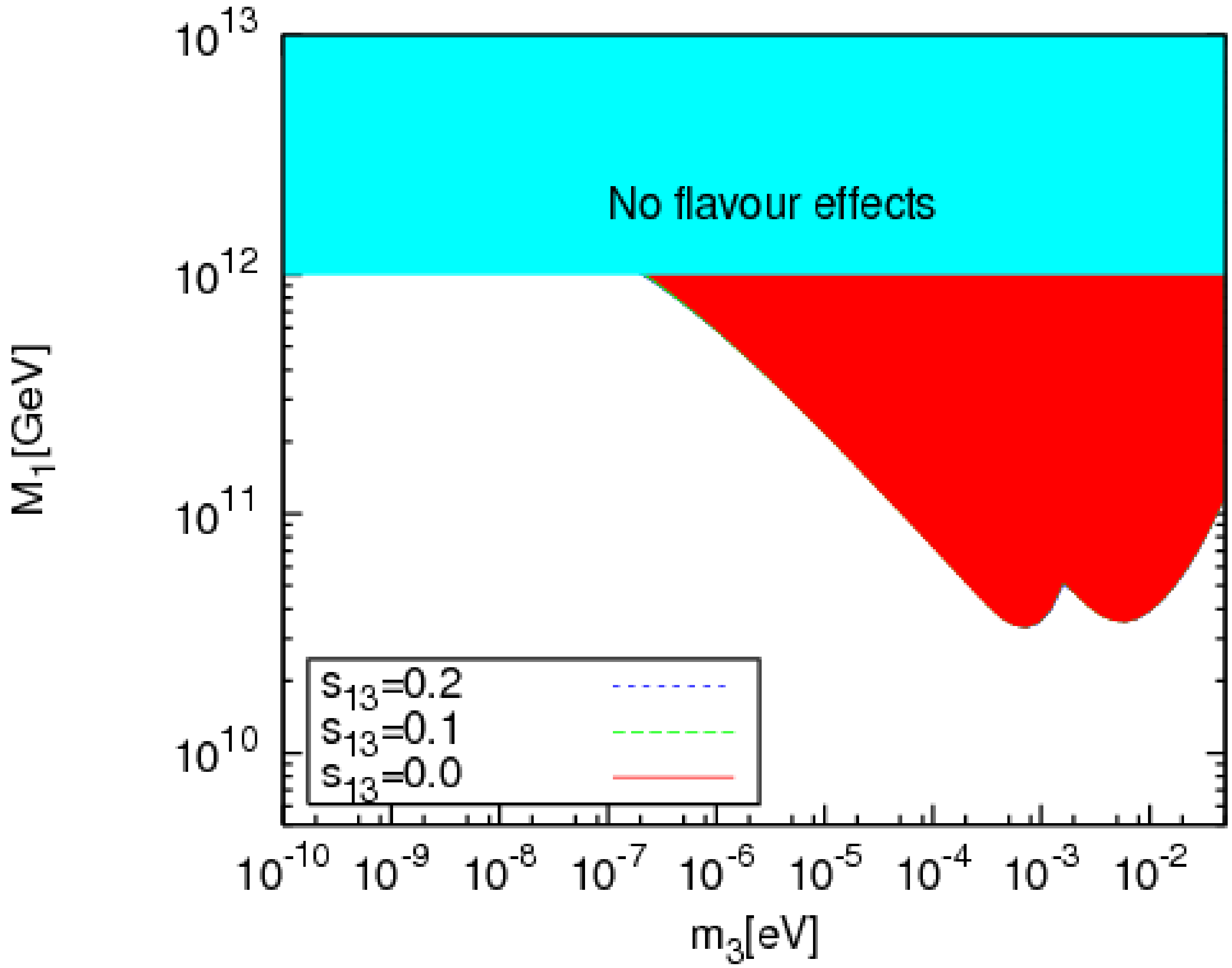
$$|\sin\theta_{13} \sin\delta|,\ \ \sin\theta_{13} \gtrsim (0.04 - 0.09)\,.$$

The lower limit corresponds to

$$|J_{\text{CP}}| \gtrsim (0.009 - 0.02)$$

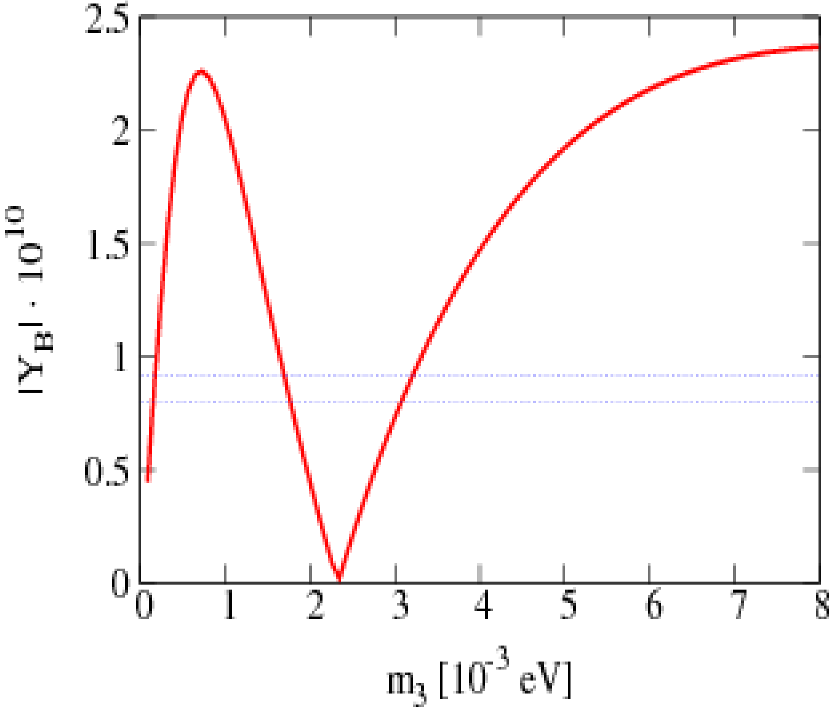
NO (NH) spectrum, $m_1 <\ (\ll)\ m_2 < m_3$: similar dependence of $|Y_B|$ on m_1 if $R_{12} = 0$, $R_{11}R_{13} \neq 0$; non-trivial effects for $m_1 \cong (10^{-4} - 5 \times 10^{-2})$ eV.

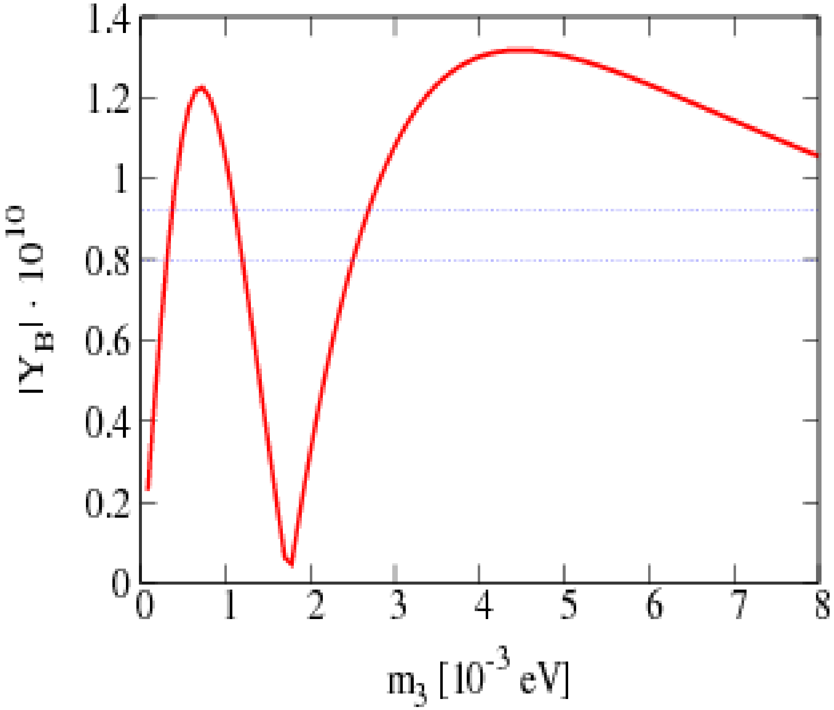
E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007



$m_3 < m_1 < m_2$, $M_1 \ll M_2 \ll M_3$, real R_{1j}; $M_1 = (10^9 - 10^{12})$ GeV, $s_{13} = 0.2; 0.1; 0$;
R_{1j} varied within $|R_{13}|^2 + |R_{12}|^2 + |R_{13}|^2 = 1$; $\alpha_{21}, \alpha_{31}, \delta$ varied in [0,2π];
min(M_1) for given m_3: $|Y_B| = 8.6 \times 10^{-11}$; absolute minima of M_1:
$m_3 \cong 5.5 \times 10^{-4}$; 5.9×10^{-3} eV, $\alpha_{32} \cong \pi/2$, $M_1 = 3.4\ (3.5) \times 10^{10}$ GeV.

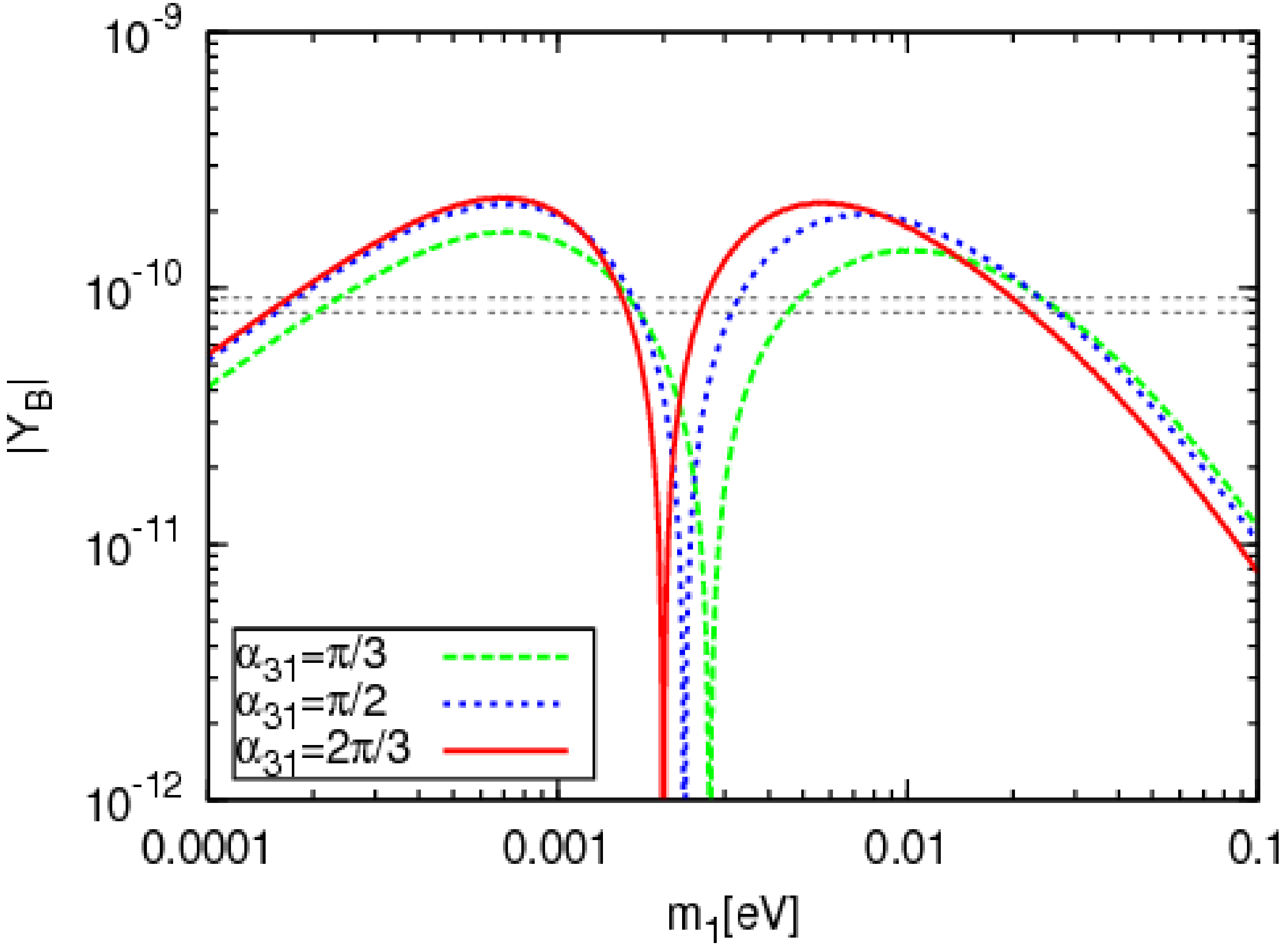
E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007





$m_3 \ll m_1 \ll m_2$ (IH), $R_{11} = 0$, real $R_{12}R_{13}$, Majorana CPV;
$\alpha_{32} = \pi/2$, $s_{13} = 0$, $M_1 = 10^{11}$ GeV; $R_{12}^2/R_{13}^2 = m_3/m_2$: maximises $|\epsilon_\tau|$;
i) $\mathrm{sgn}(R_{12}R_{13}) = +1$; ii) $\mathrm{sgn}(R_{12}R_{13}) = -1$.

E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007



$m_1 < m_2 < m_3$ (NO(NH)), $R_{12} = 0$, real $R_{11}R_{13}$, Majorana CPV, $s_{13} = 0$;
$\mathrm{sgn}(R_{11}R_{13}) = -1$, $\sin^2\theta_{23} = 0.50$, $M_1 = 1.5 \times \times 10^{11}$ GeV;
$\alpha_{32} = 2\pi/3; \pi/2; \pi/3$ (red, blue, green lines).

E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007

Low Energy Leptonic CPV and Leptogenesis: Summary

Leptogenesis: see-saw mechanism; N_j - heavy RH ν's;
N_j, ν_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 δ in $U_{\rm PMNS}$, no other sources of CPV (Majorana phases in $U_{\rm PMNS}$ equal to 0, etc.); requires $M_1 \gtrsim 10^{11}$ GeV.

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

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

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

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

B. CP-violation due to the Majorana phases in $U_{\rm PMNS}$, no other sources of CPV (Dirac phase in $U_{\rm PMNS}$ equal to 0, etc.); requires $M_1 \gtrsim 3.5 \times 10^{10}$ GeV.

C. CP-violation due to both Dirac and Majorana phases in $U_{\rm PMNS}$.

D. Y_B can depend non-trivially on $\min(m_j) \sim (10^{-5} - 10^{-2})$ eV.

S. Pascoli, S.T.P., A. Riotto, 2006 (A-C);
E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007 (D).

Complex R: $\varepsilon_{1l} \neq 0$, CPV from U and R

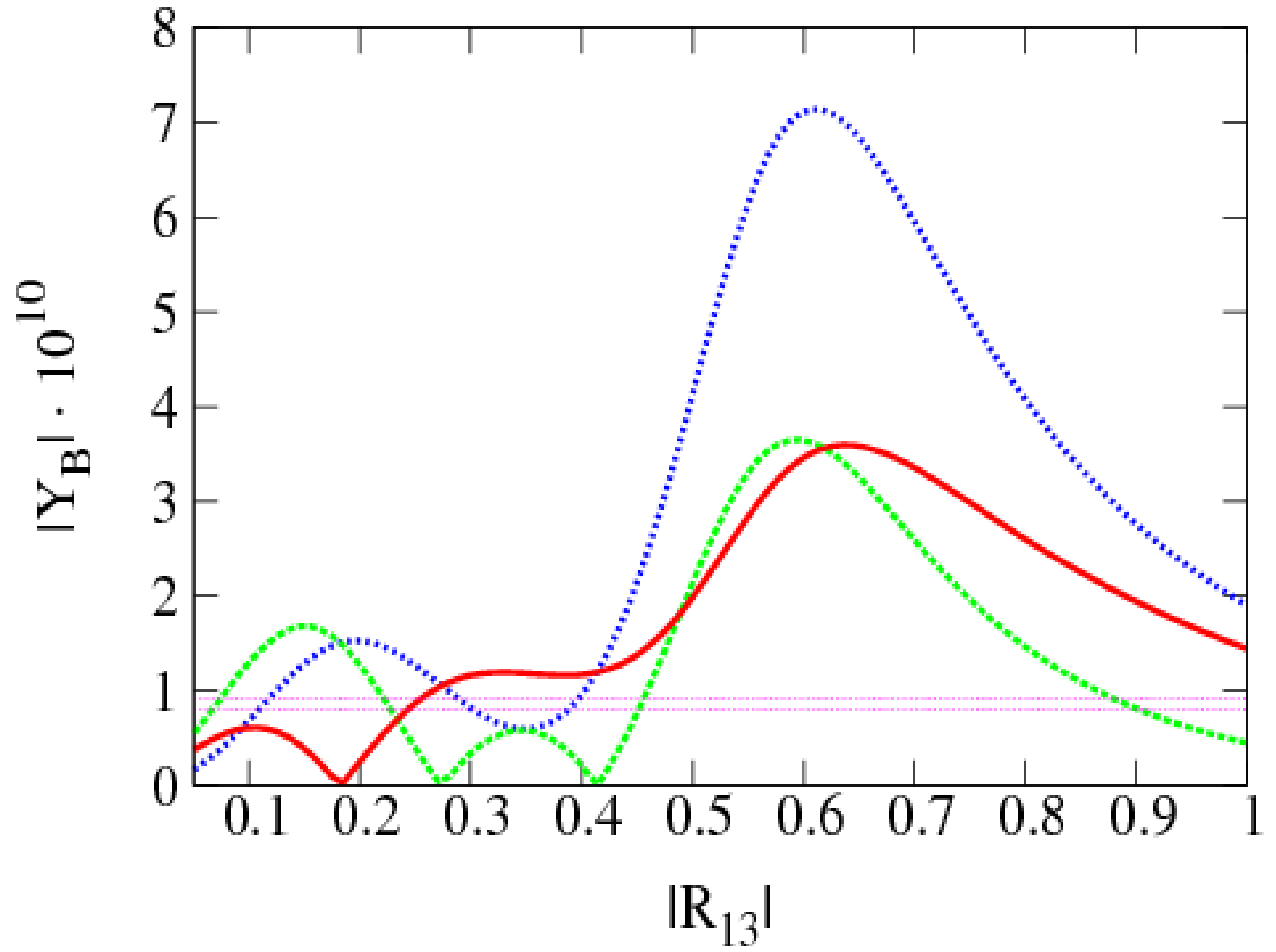
$m_1 \ll m_2 < m_3$ (NH), $M_1 \ll M_{2,3}$; $m_1 \cong 0$, $R_{11} \cong 0$ (N_3 decoupling)

$$R_{12}^2 + R_{13}^2 = |R_{12}|^2 e^{i2\varphi_{12}} + |R_{13}|^2 e^{i2\varphi_{13}} = 1\,,$$

$$|R_{12}|^2 \sin 2\varphi_{12} + |R_{13}|^2 \sin 2\varphi_{13} = 0: \ \text{sgn}(\sin 2\varphi_{12}) = -\text{sgn}(\sin 2\varphi_{13})\,.$$

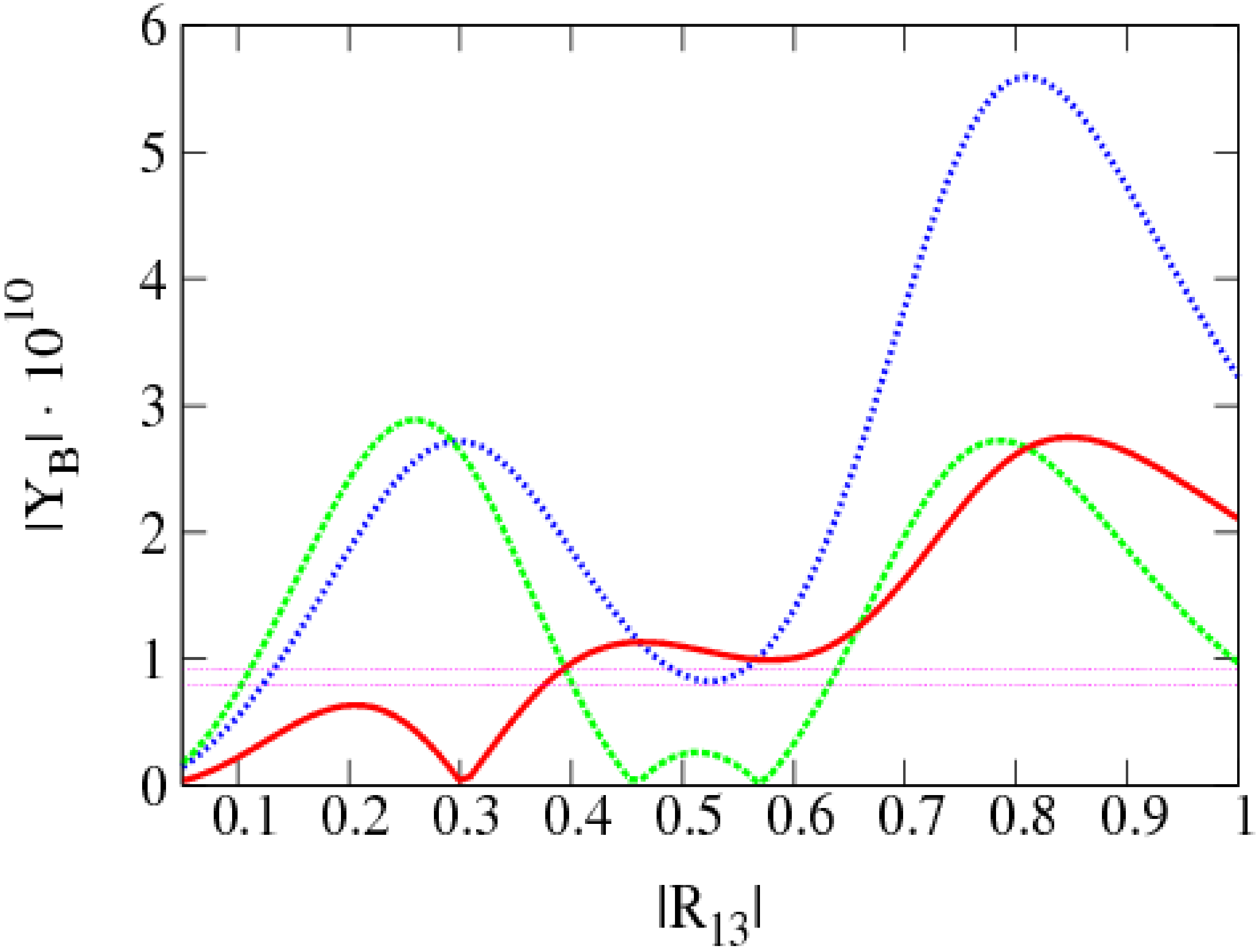
$$\cos 2\varphi_{12} = \frac{1+|R_{12}|^4-|R_{13}|^4}{2|R_{12}|^2}\,, \quad \sin 2\varphi_{12} = \pm\sqrt{1-\cos^2 2\varphi_{12}}\,,$$

$$\cos 2\varphi_{13} = \frac{1-|R_{12}|^4+|R_{13}|^4}{2|R_{13}|^2}\,, \quad \sin 2\varphi_{13} = \mp\sqrt{1-\cos^2 2\varphi_{13}}\,.$$



$m_1 < m_2 < m_3$ (NO(NH)), $R_{11} = 0$, CPV due to R and U,
$\alpha_{32} = \pi/2$, $s_{13} = 0$, $\sin^2\theta_{23} = 0.50$, $|R_{12}| \cong 1$, $M_1 = 10^{11}$ GeV;
$|Y_B^0 A_{\mathrm{HE}}|$ (R CPV, blue), $|Y_B^0 A_{\mathrm{MIX}}|$ (U CPV, green), total $|Y_B|$ (red line)

E. Molinaro, S.T.P., 2008



$m_1 < m_2 < m_3$ (NO(NH)), $R_{11} = 0$, CPV due to R and U,
$\alpha_{32} = \pi/2$, $s_{13} = 0$, $\sin^2\theta_{23} = 0.64$, $|R_{12}| \cong 1$, $M_1 = 10^{11}$ GeV;
$|Y_B^0 A_{\rm HE}|$ (R CPV, blue), $|Y_B^0 A_{\rm MIX}|$ (U CPV, green), total $|Y_B|$ (red line)

E. Molinaro, S.T.P., 2008

Low Energy Leptonic CPV and Leptogenesis (contd.)

E. Interesting case: CPV due to the Majorana phases in U_{PMNS} and the R-phases

$m_3 \ll m_1 < m_2$ (IH), $M_1 \ll M_{2,3}$; $m_3 \cong 0$, $\text{Im}(R_{13}^2) = 0$.

$R_{11}^2 + R_{12}^2 + R_{13}^2 = 1$:

$|R_{11}|^2 e^{i2\varphi_{11}} + R_{12}^2 e^{i2\varphi_{12}} + R_{13}^2 = 1$,

$|R_{11}|^2 \sin 2\varphi_{11} + |R_{12}|^2 \sin 2\varphi_{12} = 0$.

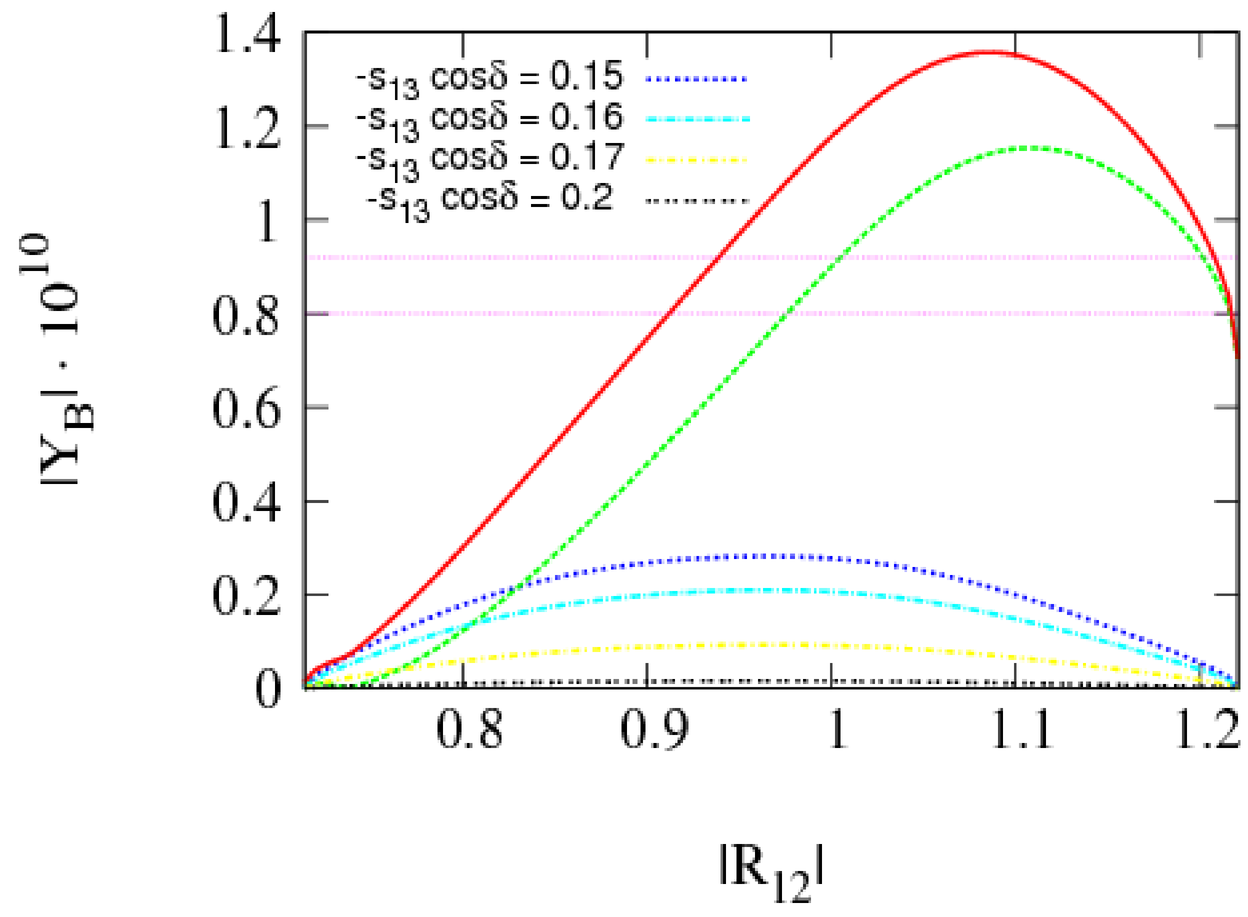
$|Y_B^0 A_{\text{HE}}| \propto |R_{11}|^2 \sin(2\varphi_{11}) \left(|U_{\tau 1}|^2 - |U_{\tau 2}|^2\right)$ - can be suppressed:

$|U_{\tau 1}|^2 - |U_{\tau 2}|^2 \cong (s_{12}^2 - c_{12}^2) s_{23}^2 - 4 s_{12} c_{12} s_{23} c_{23} s_{13} \cos\delta \cong -0.20 - 0.92\, s_{13} \cos\delta$.

$\sin^2\theta_{12} = 0.3$, $\sin^2\theta_{23} = 0.5$: $(-\sin\theta_{13}\cos\delta) \gtrsim 0.15$

$(\sin^2\theta_{12} = 0.38$, $\sin^2\theta_{23} = 0.36$: $0.06 \lesssim (-\sin\theta_{13}\cos\delta) \lesssim 0.12)$

E. Molinaro, S.T.P., 2008, 2010.



$m_3 \ll m_1 < m_2$ (IH)), $R_{13} = 0$, Majorana and R-matrix CPV,
$\alpha_{21} = \pi/2$, $(-s_{13}\cos\delta) = 0.15$, $|R_{11}| = 1.2$, $M_1 = 10^{11}$ GeV;
$|Y_B^0 A_{\rm HE}|$ (R CPV, blue), $|Y_B^0 A_{\rm MIX}|$ (U CPV, green), total $|Y_B|$ (red line).

E. Molinaro, S.T.P., 2008

We have shown in the article that for a certain range of values of $\sin(\theta_{13})\cos(\delta)$ in the case of IH light neutrino mass spectrum and hierarchical heavy Majorana neutrino mass spectrum, the "high energy" contribution to the baryon asymmetry of the Universe will be strongly suppressed if the complex R_{13} element of the R-matrix satisfies the inequality: $|R_{13}|^2|\sin(2\tilde{\varphi}_{13})| << \min(|R_{11}|^2|\sin(2\tilde{\varphi}_{11})|, |R_{12}|^2|\sin(2\tilde{\varphi}_{12})|)$. In this Addendum we extend the analysis to the case of arbitrary complex R_{13}: we abandon the condition on $|R_{13}|^2|\sin(2\tilde{\varphi}_{13})|$ given above and determine the ranges of values of $|R_{13}|$ for which the indicated strong suppression of the "high energy" contribution to the baryon asymmetry still takes place even when the phase of R_{13}, $\tilde{\varphi}_{13}$, is allowed to assume large CP-violating values. In this case the contribution to the corresponding CP asymmetry due to the low energy Majorana CP violating phases is essential for producing baryon asymmetry compatible with the observations.

It follows from the numerical analysis performed in this Addendum that for, e.g., $M_1 = 10^{11}$ GeV, the scenario described above is realised and we have subdominant (strongly suppressed) "high energy" contribution to the observed value of the baryon asymmetry for arbitrary $\tilde{\varphi}_{13}$ if i) for $|R_{11}| < 0.5$, $|R_{13}|$ satisfies $|R_{13}| \lesssim |R_{11}|$; ii) for $0.5 \lesssim |R_{11}| < 1$ we have $|R_{13}| < 0.5$, and if iii) for $|R_{11}| > 1$ we have $|R_{13}| < |R_{11}|/2$. In each of the cases i) - iii) we can have successful leptogenesis, as our results show, due to the contribution to the baryon asymmetry associated with the Majorana CP violating phase(s) in the neutrino mixing matrix.

The results obtained in the present Addendum are illustrated in next figure where we show the total baryon asymmetry Y_B (red dots/line), the purely "high energy" contribution (blue dots/line) and the "mixed" term as function of $|R_{12}|$ for fixed values of $|R_{11}|$ and $|R_{13}|$. The lightest neutrino mass m_3 is set to zero and the lightest RH Majorana neutrino mass corresponds to $M_1 = 10^{11}$ GeV. The figure is obtained for $\sin(\theta_{13})\cos(\delta) = -0.2$. In the upper left panel, we have set $|R_{11}| = 0.7$ and have taken a real R_{13}, with $R_{13} = 0.3$. The phase of R_{11}, $\tilde{\varphi}_{11}$, was varied in the interval $[3\pi/2, 2\pi]$, while the $R_{12} = |R_{12}|e^{i\tilde{\varphi}_{12}}$ is determined by the orthogonal condition: $R_{11}^2 + R_{12}^2 + R_{13}^2 = 1$. In all the other panels of Fig. 1 we consider a complex $R_{13} = |R_{13}|e^{i\tilde{\varphi}_{13}}$ and the "high energy" phase $\tilde{\varphi}_{13}$ was assumed to take random values in the interval $[0, 2\pi]$. We plot the behavior of each term contributing to the baryon asymmetry as a function of $|R_{12}|$ for fixed $|R_{11}|$ and $|R_{13}|$, following the procedure described above.

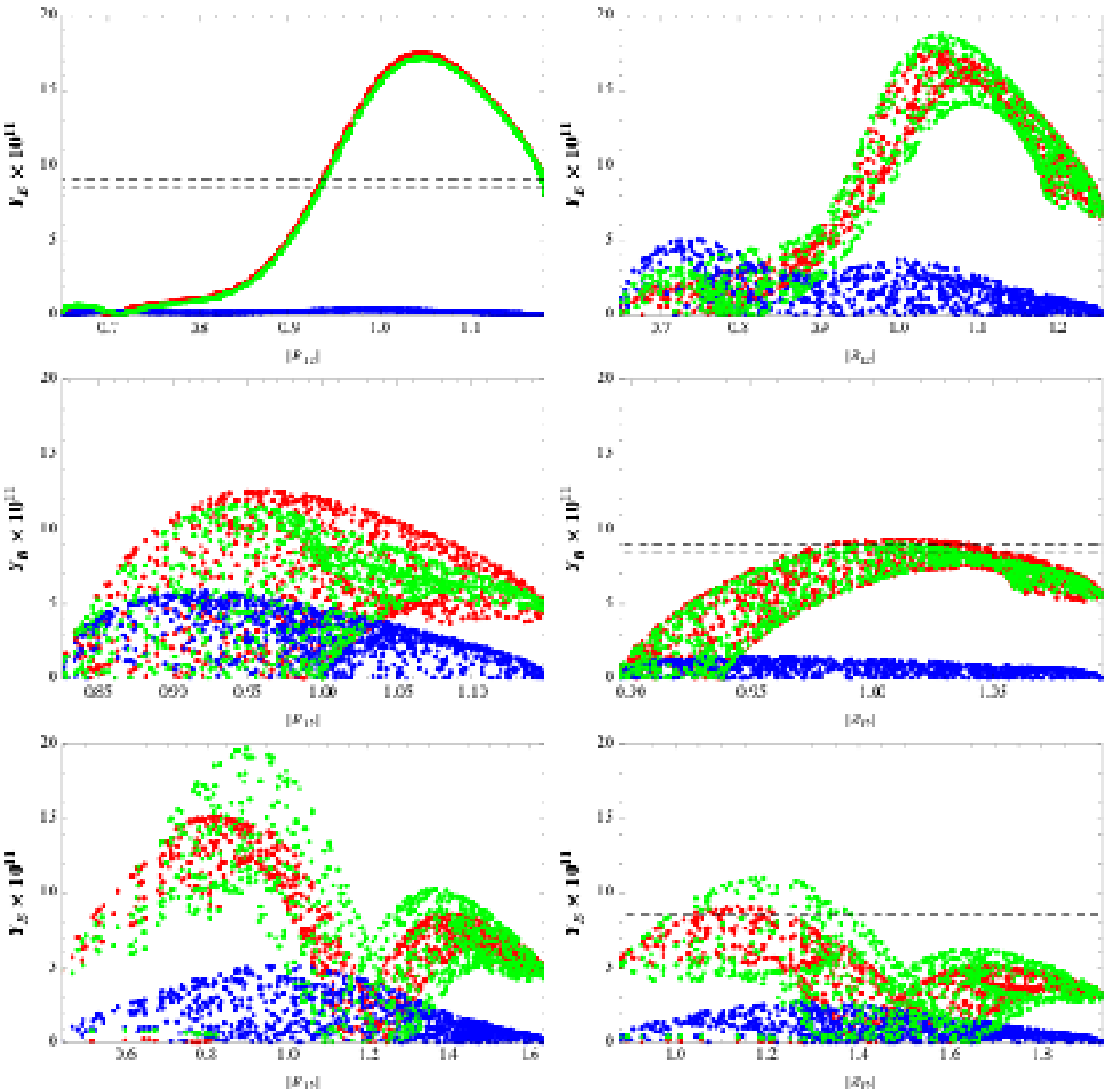


Figure 3: Total baryon asymmetry Y_B (red dots), "high energy" term (blue dots) and "mixed" term (green dots) vs $|R_{12}|$ for $M_1 = 10^{11}$ GeV, $m_3 = 0$, $\alpha_{21} = \pi/2$, $s_{13} = 0.2$, $\delta = \pi$, complex R_{11}, R_{12}, and *i*) $|R_{11}| = 0.7$ and real $R_{13} = 0.8$ (upper left panel); *ii*) $|R_{11}| = 0.7$ and $R_{13} = 0.3$ (upper right panel); *iii*) $|R_{11}| = 0.4$ and $|R_{13}| = 0.4$ (middle left panel); *iv*) $|R_{11}| = 0.4$ and $|R_{13}| = 0.2$ (middle right panel); *v*) $|R_{11}| = 1.3$ and $|R_{13}| = 0.6$ (lower left panel); *vi*) $|R_{11}| = 1.5$ and $|R_{13}| = 0.7$ (lower right panel). The figures in the upper right panel, the middle and lower panels are obtained for complex R_{13}. The horizontal lines indicate the allowed range of the baryon asymmetry: $Y_B = (8.77 \pm 0.24) \times 10^{-11}$.

Total baryon asymmetry Y_B (red dots), "high energy" term (blue dots) and "mixed" term (green dots) vs $|R_{12}|$ for $M_1 = 10^{11}$ GeV, $m_3 = 0$, $\alpha_{21} = \pi/2$, $s_{13} = 0.2$, $\delta = \pi$, complex R_{11}, R_{12}, and $i)$ $|R_{11}| = 0.7$ and real $R_{13} = 0.3$ (upper left panel); $ii)$ $|R_{11}| = 0.7$ and $|R_{13}| = 0.3$ (upper right panel); $iii)$ $|R_{11}| = 0.4$ and $|R_{13}| = 0.4$ (middle left panel); $iv)$ $|R_{11}| = 0.4$ and $|R_{13}| = 0.2$ (middle right panel); $v)$ $|R_{11}| = 1.3$ and $|R_{13}| = 0.6$ (lower left panel); $vi)$ $|R_{11}| = 1.5$ and $|R_{13}| = 0.7$ (lower right panel). The figures in the upper right panel, the middle and lower panels are obtained for complex R_{13}. The horizontal lines indicate the allowed range of the baryon asymmetry: $Y_B = (8.77 \pm 0.24) \times 10^{-11}$.

Conclusions

The see-saw mechanism provides a link between the ν-mass generation and the baryon asymmetry of the Universe (BAU).

Any of the CPV phases in U_{PMNS} can be the leptogenesis CPV parameters.

Obtaining information on Dirac and Majorana CPV is a remarkably challenging problem.

Dirac and Majorana CPV may have the same source.

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 experimental searches for Dirac and/or Majorana leptonic CP-violation at low energies.