Neutrino CP Violation and Baryon Asymmetry in the Universe

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Motivation

- **Neutrino Oscillations**
  - $|\Delta m^2_{atm}| = (2.1 - 2.7) \times 10^{-3} eV^2\,(2\sigma)$,
    $|\Delta m^2_{sol}| = (7.3 - 8.1) \times 10^{-5} eV^2\,(2\sigma)$
    Standard model prediction,
    $M_\nu{}^2 \sim \left(\frac{1}{M_{Pl}}(v_u)^2\right)^2 \sim (10^{-10} - 10^{-8})\ \mathrm{eV}^2$ with
    $M_{\mathrm{Pl}} \sim 2 \cdot 10^{18}$ GeV
  - $\sin^2\theta_{23} = 0.38 - 0.63(2\sigma)$, $\sin^2\theta_{12} = 0.28 - 0.37(2\sigma)$
    $\sin^2\theta_{13} \leq 0.050\,(3\sigma)$, δ no constraints.
    Schewtz hep-ph/0710.5027

Motivation

- **Baryogenesis**

  - Sakharov's conditions
    Baryon number violation
    C and CP violation
    Nonequilibrium dynamics

  - $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.15 \pm 0.25) \times 10^{-10}$,
    SM induced CP violation is too small, 10^{-20} .
    Neutrino data and baryon asymmetry require new physics beyond SM. We wish to connect these two phenomena.

Framework

- **Seesaw Mechanism**

(1) $$L^{D+M} = -\frac{1}{2}\bar{N}MN^c - \bar{N}Y_\nu \nu H_u$$

Left neutrino masses are inversely proportional to heavy RH neutrino masses

(2) $$M_\nu = {v_u}^2 {Y_\nu}^T M^{-1} Y_\nu$$

If the number of RH neutrinos $l \leq 2$, $det(M_\nu) = 0$, there must be at least one massless left handed neutrino. If $m_1 = 0$, normal hierarchy, if $m_3 = 0$, inverted hierarchy.

Framework

- **Resonant Leptogenesis**
  For fulfilling of thermal baryogenesis, hierarchical RH neutrino$\rightarrow M > 2 \times 10^9$ GeV $\rightarrow T_{reheat} \geq 10^8 \mathrm{GeV} \rightarrow$ overproduction of gravitinos$\rightarrow$ conflicts with observed light elements abundance.

  Davidson and Ibarra hep-ph/0202239
  Kohri *et. al.* hep-ph/0507245

  Nearly degeneracy of RH neutrino masses enhances CP violation resonantly, resoves this problem.

The Model

Normal hierarchy

We assumed one texture 0 to realize the connection of neutrino and baryon asymmetry. The neutrino Yukawa coupling

$$Y_\nu = \begin{pmatrix} a_1 & a_2 & a_3 e^{i\phi} \\ 0 & b_2 & b_3 \end{pmatrix}, \qquad M_N = M \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

(3)

Through seesaw mechanism,

$$M_\nu = \frac{{v_u}^2}{M} \begin{pmatrix} 0 & a_1 b_2 & a_1 b_3 \\ a_1 b_2 & 2a_2 b_2 & a_2 b_3 + a_3 b_2 e^{i\phi} \\ a_1 b_3 & a_2 b_3 + a_3 b_2 e^{i\phi} & 2a_3 b_3 e^{i\phi} \end{pmatrix}.$$

(4)

(5) $$\tan\theta_{13} = \sin\theta_{12}\sqrt{\frac{m_2}{m_3}}.$$

$\sin^2\theta_{13} = 0.044$, within 3σ accuracy. θ_{12} and θ_{23} within 2σ accuracy.

The Model

Inverted hierarchy

The neutrino Yukawa coupling

(6) $$Y_\nu = \begin{pmatrix} a_1 & a_2 e^{i\phi} & a_3 \\ b_1 & b_2 & 0 \end{pmatrix}$$

Through seesaw mechanism, the LH neutrino Majorana mass matrix is

$$M_\nu = \frac{{v_u}^2}{M} \begin{pmatrix} 2a_1 b_2 & a_1 b_2 + a_2 b_1 e^{i\phi} & a_3 b_1 \\ a_2 b_1 e^{\phi} + a_1 b_2 & 2a_2 b_2 e^{i\phi} & a_3 b_2 \\ a_3 b_1 & a_3 b_2 & 0 \end{pmatrix}.$$

With inverted hierarchy, we made a prediction

(7) $$\sin^2\theta_{12} \simeq \frac{1}{2} - \frac{\sin\theta_{13}\tan\theta_{23}\cos\delta}{|\tan^2\theta_{23} + \sin^2\theta_{13} e^{2i\delta}|}$$

(8) $$-56^\circ \leq \delta \leq 56^\circ$$

Baryogenesis

Sakharov's conditions are satisfied in the expanding universe and the out of equilibrium CP violating decays of RH neutrinos. When two RH neutrino have nearly degenerate masses, the CP violation effect is enhanced resonantly by a factor $\frac{(M_2^2 - {M_1}^2) M_1 \Gamma_2}{(M_2^2 - {M_1}^2)^2 + {M_1}^2 {\Gamma_2}^2}$. The mass split is induced at one loop

(9) $$16\pi^2 \frac{d}{dt} M_N = 2 M_N Y_\nu Y_\nu^\dagger + \mathrm{t.c.}$$

and

(10) $$M_N \rightarrow M \begin{pmatrix} \delta_N & 1 \\ 1 & \delta_N' \end{pmatrix} = M \begin{pmatrix} \delta_N & 1 \\ 1 & \delta_N^* \end{pmatrix},$$

Baryogenesis

4 paremeters of the Yukawa coupling sonstants of E.(3) can be determined with neutrino oscillation data. We defined

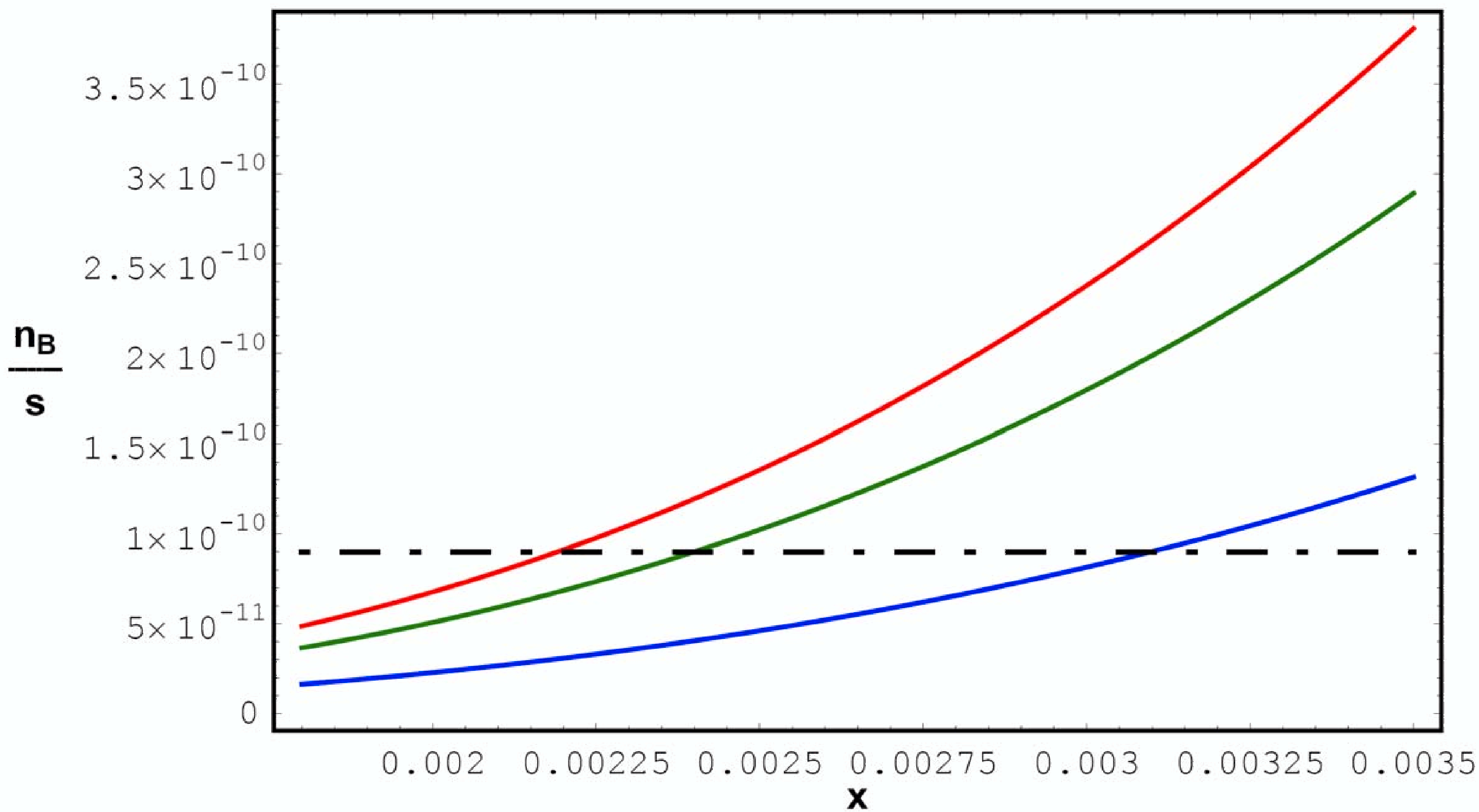
$$x = \frac{a_3}{b}.$$

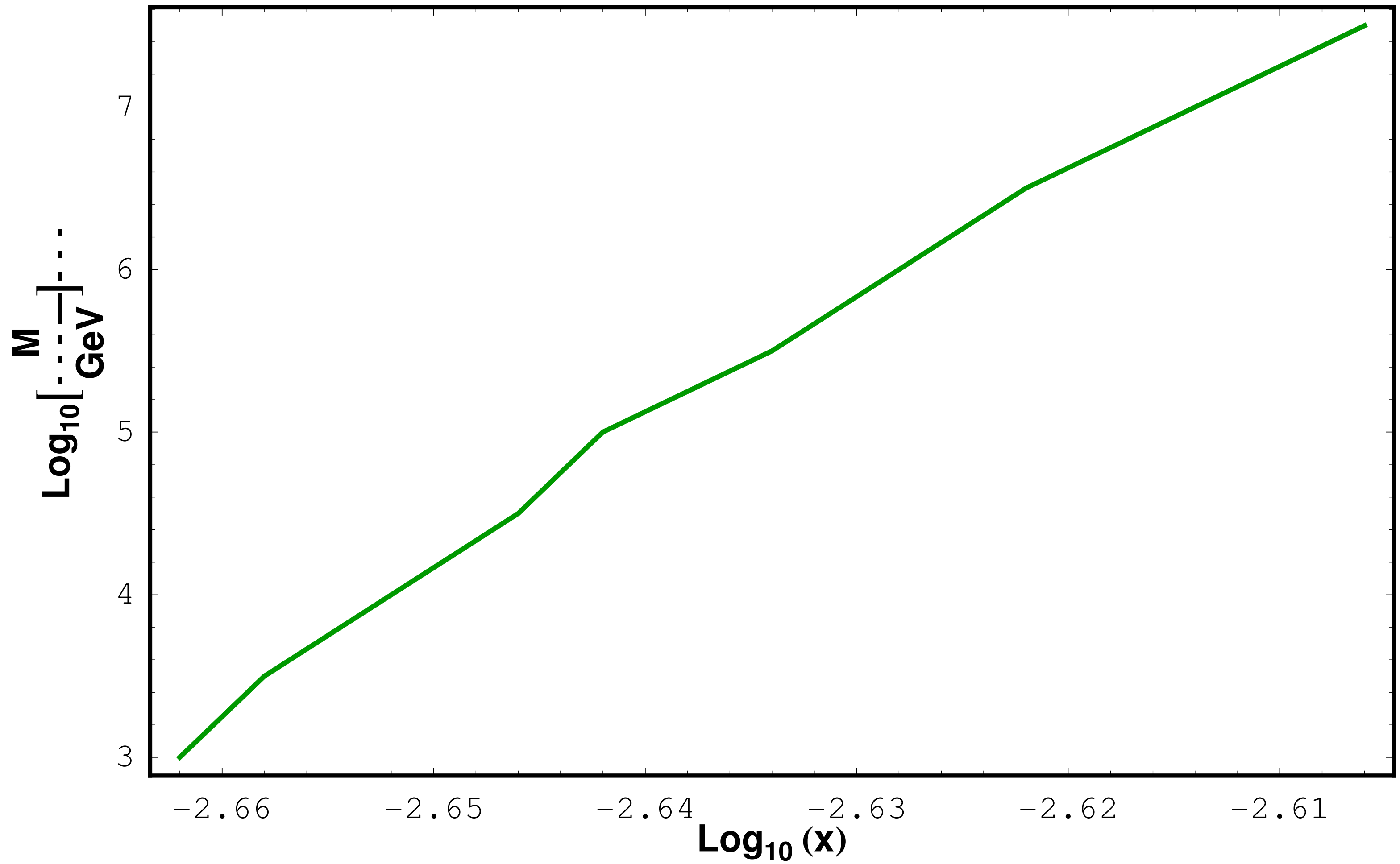
δ has no constraints. We only studied baryogensis with normal hierarchy. Studiy with inverted hierarchy was done before.

Babu *and et.al* hep-ph/0705.4419.

We plot our results below.

$\frac{n_B}{s}$ vs. x *with* $M = 10^6$ GeV. Cases: δ $\pi/4$, $\pi/3$, $\pi/2$





M vs. x with $\frac{n_B}{s} = 9 \cdot 10^{-11}$ and $\delta = \frac{\pi}{3}$.

Conclusions

- We investigated two new models of texture zeros, with the predictions:

  (i) For normal hierarchy:

$$\tan\theta_{13} = \sin\theta_{12}\sqrt{\frac{m_2}{m_3}}$$

  (ii) For inverted hierarchy:

$$\sin^2\theta_{12} \simeq \frac{1}{2} - \frac{\sin\theta_{13}\tan\theta_{23}\cos\delta}{|\tan^2\theta_{23} + \sin^2\theta_{13}e^{2i\delta}|}$$

- The observed baryon asymmetry is generated through resonant leptogenesis. The CP violation in ν-oscillations and leptonic asymmetries are *directly related*.