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Predictive Model of Inverted Neutrino Mass Hierarchy and Resonant Leptogenesis

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Outline

- Introduction: Atm. & Solar ν-data + Baryon asymmetry → New physics beyond SM/MSSM
- Inverted hierarchical schenario for:

  Predictive relations &

  Resonant leptogenesis

- Model with $U(1) \times S_3$ Symmetry
- Summary & Outlook

Atmospheric & Solar Neutrino Data

$$|\Delta m^2_{\rm atm}| = 2.4 \cdot \left(1^{+0.21}_{-0.26}\right) \times 10^{-3}\ {\rm eV}^2 \qquad \sin^2\theta_{23} = 0.44$$

$$\Delta m^2_{\rm sol} = 7.92 \cdot (1 \pm 0.09) \times 10^{-5}\ {\rm eV}^2 \qquad \sin^2\theta_{12} = 0.314$$

Scales

Bi-large mixing

New physics beyond SM/MSSM

CHOOZ bound: $\theta_{13} \lesssim 0.2$

Sign? $\Delta m^2_{\rm atm} = m_3^2 - m_2^2$ >0 (hierarchical) OR <0 (inverted hier.)

Majorana or Dirac ν? (ν02β-decay)

Baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$

Also requires some extension

Th model giving predictive ν masses/mixing – symmetry principle?

Extension with Right handed neutrinos:

- L-violation→ neutrino oscillations
- & B-asym. Through leptogenesis

Inverted Hierarchical Scenario

Minimal Model:

- ch. Lept matrix M_E-diagonal;
- 2 RHN $N_{1,2}$ & (approximate) L_e-L_μ-L_τ sym.
- + In ν-sector S_2 symmetry $l_2 \leftrightarrow l_3$

$$Y_\nu = \begin{array}{c} \\ l_1 \\ l_2 \\ l_3 \end{array} \begin{array}{c} \begin{array}{cc} N_1 & N_2 \end{array} \\ \begin{pmatrix} \alpha & 0 \\ \beta' & \beta \\ \beta' & \beta \end{pmatrix} \end{array}, \qquad M_N = \begin{array}{c} \\ N_1 \\ N_2 \end{array} \begin{array}{c} \begin{array}{cc} N_1 & N_2 \end{array} \\ \begin{pmatrix} -\delta_N & 1 \\ 1 & -\delta'_N \end{pmatrix} \end{array} M$$

Nearly degenerate RHNs

$$m_\nu = \begin{pmatrix} 2\delta'_\nu & \sqrt{2} & \sqrt{2} \\ \sqrt{2} & \delta_\nu & \delta_\nu \\ \sqrt{2} & \delta_\nu & \delta_\nu \end{pmatrix} \frac{m}{2}$$

Inverted Hierarchical Scenario

$$|\Delta m^2_{\rm atm}| \simeq |m|^2 \qquad \frac{\Delta m^2_{\rm sol}}{|\Delta m^2_{\rm atm}|} \simeq 2\left|\delta^*_\nu + \delta'_\nu\right|$$

Consequence: $\sin^2\theta_{12} = \frac{1}{2} \pm \frac{\kappa}{4}$ $\qquad \kappa = \frac{|\delta_\nu|^2 - |\delta'_\nu|^2}{|\delta^*_\nu + \delta'_\nu|}$

Requirements from observations:

$$\left|\delta^*_\nu + \delta'_\nu\right| = \frac{\Delta m^2_{\rm sol}}{2|\Delta m^2_{\rm atm}|} \simeq 0.016\ , \qquad \frac{|\delta_\nu|^2 - |\delta'_\nu|^2}{|\delta^*_\nu + \delta'_\nu|} = \mp(0.52 - 0.92)$$

WHY?

Otherwise θ_{12} is nearly maximal – i.e. excluded..

Extended Inverted Hier. Schenario

$$W_e = l^T Y_E e^c h_d$$

$$Y_E = \begin{pmatrix} 0 & a' & 0 \\ a & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}$$

$(L_e\text{-}L_\mu\text{-}L_\tau) \times S_2$ is completely broken

[justified later on…]

1-2 rotation → corrects θ_{12} and induces θ_{13}

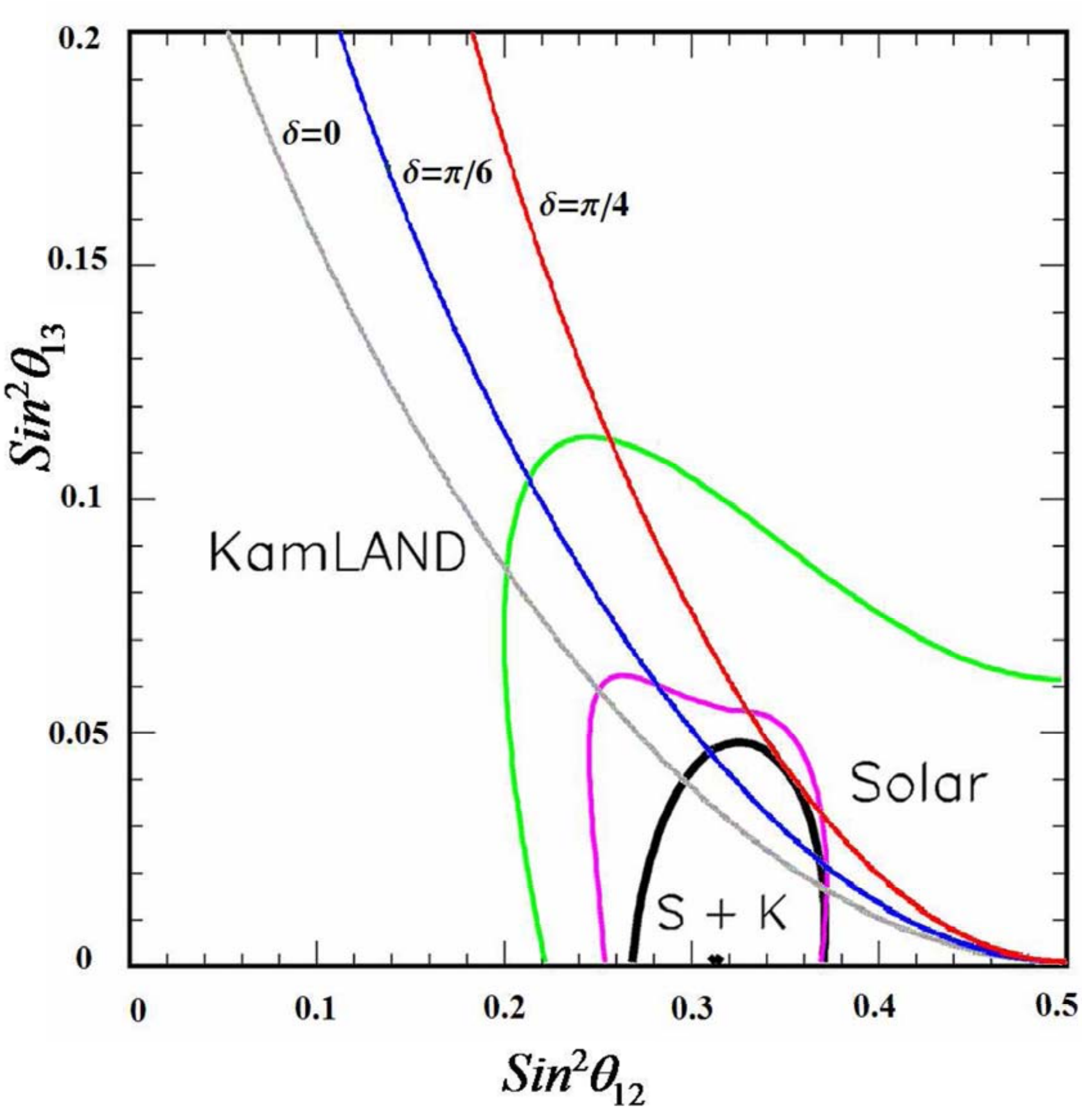
Single complex phase δ appearing in ν-oscil.

Predictive relations:

$$\sin^2\theta_{12} = \frac{1}{2} - \sqrt{1 - \tan^2\theta_{13}}\,\tan\theta_{13}\cos\delta$$

$$\sin^2\theta_{23} = \frac{1}{2}\left(1 - \tan^2\theta_{13}\right) \quad .$$

Predictions



From our model

$$\sin^2\theta_{12} = \frac{1}{2} - \sqrt{1-\tan^2\theta_{13}}\,\tan\theta_{13}\cos\delta$$

$$\sin^2\theta_{23} = \frac{1}{2}\left(1-\tan^2\theta_{13}\right) \ .$$

From Fogli et al. hep-ph/0506083

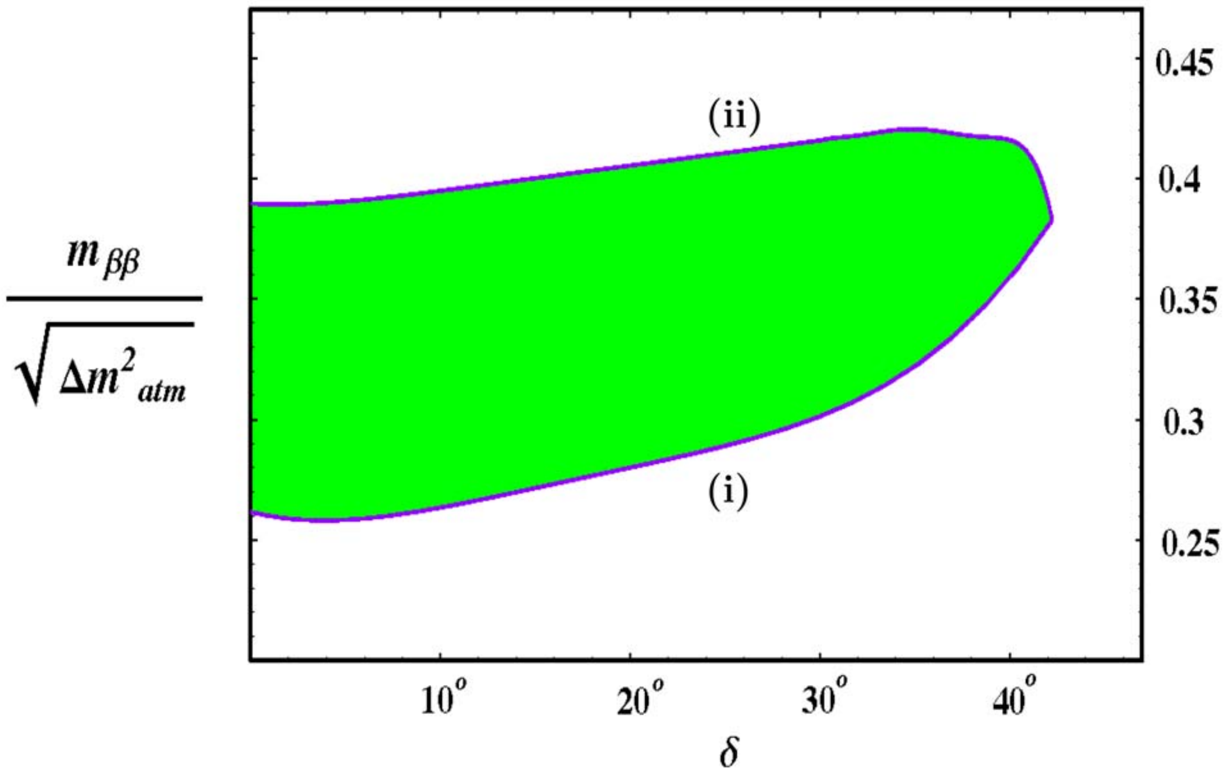
- $\theta_{13} \geq 0.13 \ , \qquad 0 \leq \delta \leq 43^o$

→Testable in future!

Predictions

ν02β-decay:

$$m_{\beta\beta} \simeq 2\sqrt{\Delta m^2_{\rm atm}}\,\tan\theta_{13}\frac{\sqrt{1-\tan^2\theta_{13}}}{\sqrt{1+\tan^2\theta_{13}}}$$



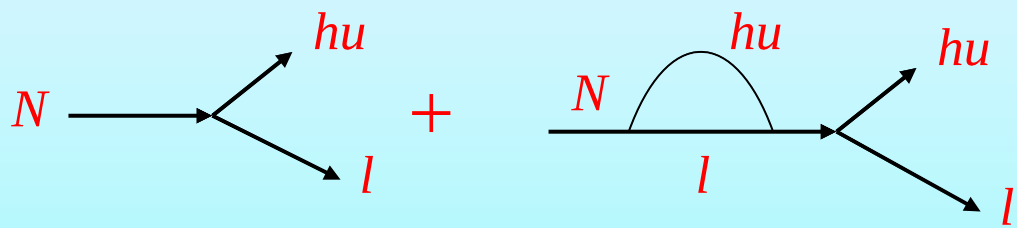
$$0.011 \text{ eV} \lesssim m_{\beta\beta} \lesssim 0.022 \text{ eV}$$

Leptogenesis

RHNs →L, CP viol → Leptogenesis (Fikugita, Yanagida'86)

By out of equilibrium N-decays

N→hu l:



Hierarchical neutrinos → $M_R \geq 10^9 \mathrm{GeV}$ (Davidson-Ibarra bound)

High T_R → SUSY gravitino problem

Flanz et al'96
Pilaftsis'97
Underwood'03

- Quasi Degenerate RHNs → Resonant Leptogenesis

- Allows small M_R → No gravitino Problem

Resonant Leptogenesis

Inverted hier. schenario ←→ Res. L-genesis

$$\epsilon_1 = \frac{\mathrm{Im}(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{21}^2}{(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{11}(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{22}} \frac{(M_2^2 - M_1^2)\, M_1 \Gamma_2}{(M_2^2 - M_1^2)^2 + M_1^2 \Gamma_2^2}$$

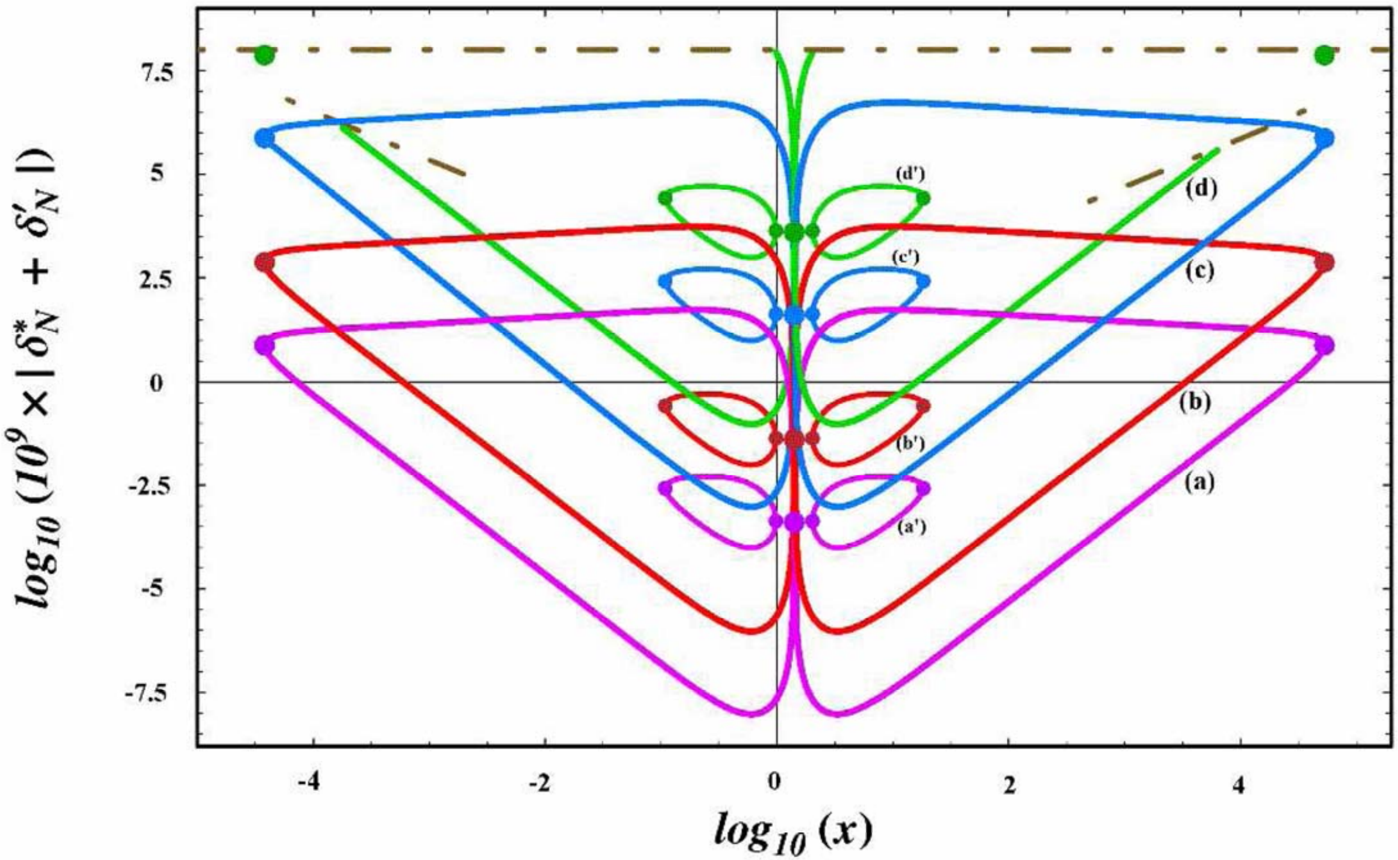
Pilaftsis & Underwood'03

$$\epsilon_1 = \frac{\mathrm{Im}(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{21}^2}{(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{11}} \frac{|\delta_N^* + \delta_N'|}{16\pi |\delta_N^* + \delta_N'|^2 + (\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{22}^2/(16\pi)}\,, \qquad \epsilon_2 = -\epsilon_1(1 \leftrightarrow 2)$$

maximum

$$|\delta_N^* + \delta_N'| = (\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{11}/(16\pi) \quad \Longrightarrow \quad \bar{\epsilon}_1 \simeq \bar{\epsilon}_2 \simeq -\frac{(2-x^2)^2}{2(2+x^2)^2} \sin 2r$$

For arbitrary M_R !



$$\frac{\alpha}{\beta} = x$$

versus

Degeneracy -

$$\left|\delta_N^* + \delta_N'\right| \lesssim 0.1$$

(a) , (b) , (c) , (d) $\quad r = \pi/4$

RHN mass: $M = (10^4, 10^6, 10^9, 10^{11})$ GeV

CP-viol

(a') , (b') , (c') , (d') $\quad r = 5 \cdot 10^{-5}$

For obtained results specific textures were crucial, and their justification is required…

Model with U(1) x S3 Flavor Symmetry

U(1) → desirable hierarchies
S3 → Textures, S2 sym. In neutrino sector

$(l_2, l_3) \sim 2,\ l_1 \sim 1',\ (e_2^c, e_3^c) \sim 2,\ e_1^c \sim 1'$ $\qquad S, T \sim 2,\ X \sim 1'$

Symmetry br. scalars

Couplings:

$$\frac{1}{M_*^2}\left(\vec{l}\cdot\vec{S}\right)_{\mathbf{1}}\left(\vec{e}^{\ c}\cdot\vec{S}\right)_{\mathbf{1}} h_d + \frac{1}{M_{\rm Pl}^2}\vec{l}\cdot\vec{e}^{\ c}\cdot\vec{S}^2 h_d + \frac{X^2}{M_{\rm Pl}^3} l_1 \vec{e}^{\ c}\cdot\vec{S} h_d + \frac{X^4}{M_{\rm Pl}^5} e_1^c \vec{l}\cdot\vec{S} h_d + \frac{X^6}{M_{\rm Pl}^6} l_1 e_1 h_d$$

VEV configuration: $\langle\vec{S}\rangle = (0,\ V)\ ,\quad \langle\vec{T}\rangle = \tilde{V}\cdot(1,\ {\rm i})\ ,\quad \langle X\rangle = V_X$

(may obtained by superpotential)

→ Desirable textures are generated:

$$\begin{array}{c|ccc} & e_1^c & e_2^c & e_3^c \\ \hline l_1 & \epsilon^6 & \epsilon^3 & 0 \\ l_2 & \epsilon^5 & \epsilon^2 & 0 \\ l_3 & 0 & 0 & 1 \end{array}$$

$$\begin{array}{c|cc} & N_1 & N_2 \\ \hline l_1 & \epsilon & \epsilon^{2m+1} \\ \vec{l} & 0 & \frac{\vec{T}}{M_{\rm Pl}}\epsilon^{2m-2} \end{array} \; h_u \;, \qquad \begin{array}{c|cc} & N_1 & N_2 \\ \hline N_1 & 0 & 1 \\ N_2 & 1 & \epsilon^{2m} \end{array} \; \epsilon^{2(m-n-1)} M_R$$

$$Y_\nu = \begin{pmatrix} \epsilon & \epsilon^{2m+1} \\ 0 & \epsilon^{2m-1} \\ 0 & \mathrm{i}\epsilon^{2m-1} \end{pmatrix}$$

Unbroken S_2 → all results are robust

Hierarchies can be also explained:

$$\left|\delta_\nu^* + \delta_\nu'\right| \sim \frac{\epsilon^2}{\sqrt{2}}$$

$$M = M_R \epsilon^{2(m-n-1)} \;, \qquad \alpha \sim \epsilon \;, \qquad \beta \sim \epsilon^{2m-1} \;, \qquad \left|\delta_N^* + \delta_N'\right| \sim \epsilon^{2m}$$

Summary & Outlook

- Predictive inv. hierarchical scenario can be obtained

by approx. $(L_e\text{-}L_\mu\text{-}L_\tau)\times S_2$ symmetry through $U(1)\times S_3$ Model

- Interesting testable relations between various observables in neutrino sector

- Resonant leptogenesis (no gravitino problem)

- Embedding the scenario in GUTs

- In SU(5) – straightforward (by + $N_{1,2}$)

- In SO(10) additional effort required (in progress…)

to get inv. neutrino scenario, due to $\nu_R \subset 16 \supset (q, l, d^c, e^c)$

SO(10) or E_6 increase predictive power ←→ closer relations

between charged & neutral sectors