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Predicting Leptonic CP Violation and Leptogenesis

with A. Achelashvili
Int.J.Mod.Phys. A31 (2016) 1650077
K.S. Babu, Y. Meng
arXiv:0812.4419

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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Exploring the Energy Ladder of the Universe

Aim & motivation

Baryon asym. via Leptogenesis

- Build predictive neutrino models

  [predictive relations between nautrino parameters]

- Relate ν-oscil CP viol. (δ) to leptonic CP asymmetry,

  i.e. have *single* CP phase.

  Perhaps predict phase δ

- Work within framework which avoids various phen./cosm. difficulties

  [like gravitino problem etc.]

Outline:

- Motivated by above, consider system with two quasi-degenerate RHNs → → resonant leptogenesis allowing low $M_R \leq 10^7 \mathrm{GeV}$

Flanz et al'96
Pilaftsis'97
Pilaftsis, underwood'03

- Classify experimentally viable texture zero Dirac Yukawas leading to (testable) predictions

- Cospological CP is related with neutrino osc. δ -phase *

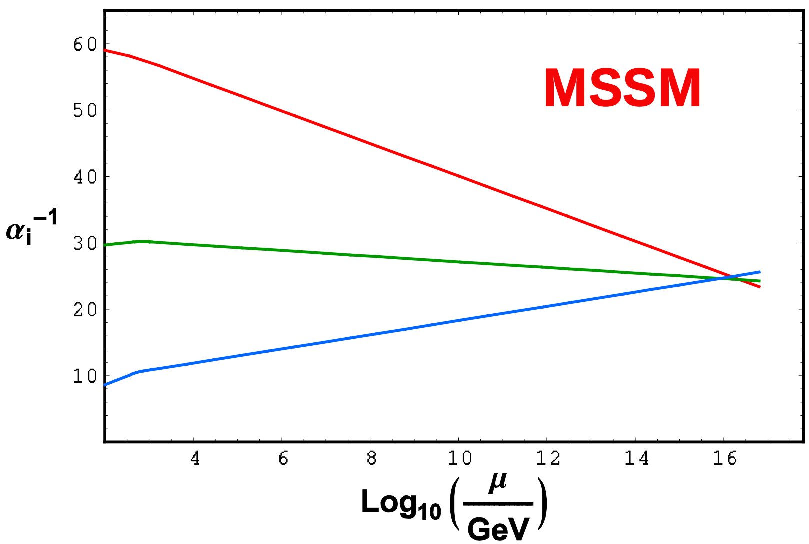
* Idea: with hier. 2 RHNs by:

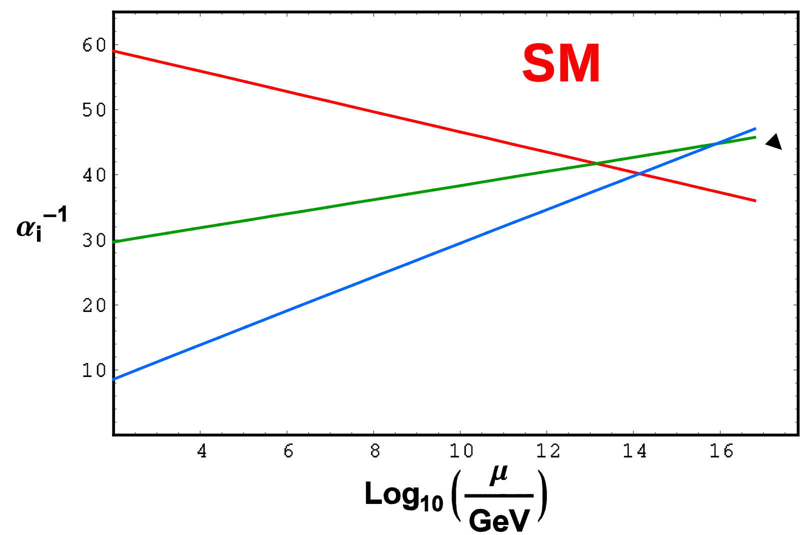
Frampton, Glashow, Marfatia, PLB 536 (2002) 79

Frampton, Glashow, Yanagida'02

SUSY setup

- Successful Coupling Unification **good for GUT**





- low SUSY scale → Stab. Hierarchy
- stab. LSP → Dark Matter Candidate

MSSM: Lepton and sLepton Numbers

With discrete R-parity:

$$R = (-1)^{3(B-L)+2S}$$

$\longrightarrow$ no L and B violation at $d < 5$ level , LSP is stabile.

i.e. No $\Delta L \neq 0$ superpotential couplings:

$$\left(\cancel{\mu_i l_i h_u} + \cancel{\lambda_L e^c l l} + \cancel{\lambda_L{}' q d^c l}\right)_F$$

SUSY $d = 5$ $\Delta L = 2$ operator:

$$\frac{\boldsymbol{1}}{\boldsymbol{M_*}}(ll)h_u h_u$$

With $M_* \sim M_{Pl}$: $\quad m_\nu \sim \frac{M_{EW}^2}{M_{Pl}} \qquad \leftarrow \ \mathbf{m}_\nu \lesssim \mathbf{10^{-4}}\ \mathrm{eV}$

Neutrino Data: Three-flavor oscillation parameters

1409.5439: M. C. Gonzalez-Garcia,[a,b] Michele Maltoni,[c] Thomas Schwetz

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$

Evidences for New Physics:

Atmospheric & Solar Neutrino 'scales'

$$\Delta m^2_{\rm atm} = 2.4 \cdot 10^{-3} {\rm eV}^2 \qquad \Delta m^2_{\rm sol} = 7.5 \cdot 10^{-5} {\rm eV}^2$$

- **Origin of these scales and mixings?**

Unexplained in SM / MSSM $\leftarrow \mathbf{m}_\nu \lesssim \mathbf{10^{-4}}\ {\rm eV}$

Without New Physics

$$m_\nu \sim \frac{M^2_{EW}}{M_{Pl}}$$

Extensions for neutrino masses

-

-- Type I See-Saw – with SM singlet N matter

-- Type II See-Saw – with SU(2) triple scalars (with hypercharge Y=2)

-- Type III See-Saw – with SU(2) triplet matter (with Y=0)

... other possibilities: radiative, inverse see-saw, etc

Extending SM - Neutrino masses via type I see-saw

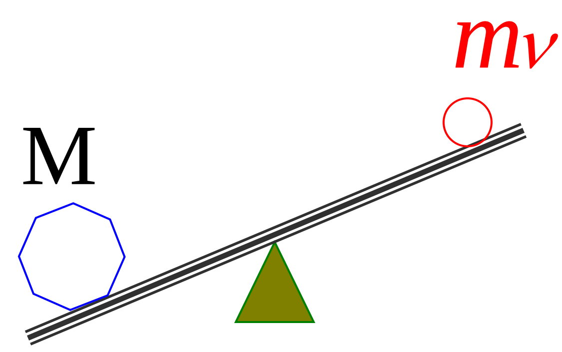
→ nu-masses, oscillations

ν^c ← **SM singlet**

$l\,\nu^c H$ $\qquad$ $M\,\nu^c\nu^c$ → **Δ L=2 Lepton number viol.**

$$\begin{pmatrix} 0 & \langle H \rangle \\ \langle H \rangle & M \end{pmatrix}$$

$$m_\nu \sim \frac{\langle H \rangle^2}{M}$$



$$M_N \simeq M$$

$$M \sim 10^{14}\ \mathrm{GeV} \ \rightarrow \ m_\nu \sim \mathrm{few} \cdot 0.01\ \mathrm{eV}$$

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:

- ν masses/mixing → neutrino oscillations
- & B-asym. Through leptogenesis

• Neutrino parameters

Basis: $Y_e = \mathrm{Diag}\,(\lambda_e,\ \lambda_\mu,\ \lambda_\tau)$

→Lepton mixing matrix from neutrino matrix

$$M_\nu = PU^* P' M_\nu^{\mathrm{diag}} U^+ P$$

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

← Entering in oscillations

$$M_\nu^{\mathrm{diag}} = (m_1, m_2, m_3)$$

$$P' = \mathrm{Diag}(1, e^{i\rho_1}, e^{i\rho_2})$$

← Unknown

Entering in double $\boldsymbol{\beta - decay}$

$$P = \mathrm{Diag}(e^{i\omega_1}, e^{i\omega_2}, e^{i\omega_3})$$

- SUSY setup. Extension of MSSM with 2 RHNs $N_{1,2}$

$$W_e = l^T Y_e e^c h_d \ , \qquad W_\nu = l^T Y_\nu N h_u - \frac{1}{2} N^T M_N N$$

Basis: $Y_e = \mathrm{Diag}\,(\lambda_e, \ \lambda_\mu, \ \lambda_\tau)$

K.S. Babu, Y. Meng , ZT
arXiv:0812.4419

Degenerate RHNs: $M_N = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} M$

Consider all possible textures for Y_ν :

- 2 or more texture zeros do not work;
- 1 texture zero: 3 possibility

- Texture without zero(s) can give only fit – no prediction(s)

One Texture Zeros in Y_ν

$$\text{Texture A}: \quad Y_\nu = \begin{pmatrix} x\alpha_1 & 0 \\ x\alpha_2 & b \\ xe^{i\phi} & 1 \end{pmatrix} \cdot \bar{\beta}$$

$$\mathrm{B}_1: \quad Y_\nu = \begin{pmatrix} x\alpha_1 & b \\ x\alpha_2 & 0 \\ xe^{i\phi} & 1 \end{pmatrix} \cdot \bar{\beta}$$

$$\mathrm{B}_2: \quad Y_\nu = \begin{pmatrix} x\alpha_1 & b \\ x\alpha_2 e^{i\phi} & 1 \\ x & 0 \end{pmatrix} \cdot \bar{\beta}$$

Single complex phase

Build ν Mass matrix:

$$M_\nu = Y_\nu \frac{1}{M_N} Y_\nu^{\ T} \left\langle h_u^{\ 0} \right\rangle^2$$

$$\begin{pmatrix} a_1 e^{i\alpha_1} & b_1 e^{i\beta_1} \\ a_2 e^{i\alpha_2} & 0 \\ a_3 e^{i\alpha_3} & b_3 e^{i\beta_3} \end{pmatrix} = \begin{pmatrix} e^{ix} & 0 & 0 \\ 0 & e^{iy} & 0 \\ 0 & 0 & e^{iz} \end{pmatrix} \begin{pmatrix} a_1 & b_2 \\ a_2 & 0 \\ a_3 & b_3 e^{i\phi} \end{pmatrix} \begin{pmatrix} e^{i\omega} & 0 \\ 0 & e^{i\rho} \end{pmatrix}$$

Can be absorbed in $\boldsymbol{l_i}$

Never matter due to N's degeneracy!

$$\begin{pmatrix} e^{i\omega} & 0 \\ 0 & e^{i\rho} \end{pmatrix} M_N^{-1} \begin{pmatrix} e^{i\omega} & 0 \\ 0 & e^{i\rho} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} e^{i(\omega+\rho)}$$

Overall /non-physical

Single physical phase $\boldsymbol{\phi}$

Texture A → **Normal Hier.**

$$M_\nu = \begin{pmatrix} 0 & \alpha_1 b & \alpha_1 \\ \alpha_1 b & 2\alpha_2 b & \alpha_2 + be^{i\phi} \\ \alpha_1 & \alpha_2 + be^{i\phi} & 2e^{i\phi} \end{pmatrix} \frac{x\bar{\beta}^2}{M}(v \sin\beta)^2$$

Prediction:

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

→ $sin^2\theta_{13} \approx 0.05$

Too large, Excluded.

Texture B1 **Inverted Hier.** **Texture B2**

$$M_\nu = \begin{pmatrix} 2\alpha_1 b & \alpha_2 b & \alpha_1 + b e^{i\phi} \\ \alpha_2 b & 0 & \alpha_2 \\ \alpha_1 + b e^{i\phi} & \alpha_2 & 2 e^{i\phi} \end{pmatrix} ; \begin{pmatrix} 2\alpha_1 b & \alpha_1 + \alpha_2 b e^{i\phi} & b \\ \alpha_1 + \alpha_2 b e^{i\phi} & 2\alpha_2 e^{i\phi} & 1 \\ b & 1 & 0 \end{pmatrix}$$

$$\sin^2\theta_{12} \simeq \frac{1}{2} - \frac{\sin\theta_{13}\tan\theta_{23}\cos\delta}{|\tan^2\theta_{23}\sin^2\theta_{13} + e^{2i\delta}|} + \frac{1}{8}\frac{\Delta m^2_{\rm sol}}{|\Delta m^2_{\rm atm}|}$$

$$\sin^2\theta_{12} \simeq \frac{1}{2} + \frac{\sin\theta_{13}\tan\theta_{23}\cos\delta}{|\tan^2\theta_{23} + \sin^2\theta_{13} e^{2i\delta}|} + \frac{1}{8}\frac{\Delta m^2_{\rm sol}}{|\Delta m^2_{\rm atm}|}$$

Texture B1

$$\sin^2\theta_{12} \simeq \frac{1}{2} - \frac{\sin\theta_{13}\tan\theta_{23}\cos\delta}{|\tan^2\theta_{23}\sin^2\theta_{13} + e^{2i\delta}|} + \frac{1}{8}\frac{\Delta m^2_{\rm sol}}{|\Delta m^2_{\rm atm}|}$$

δ	$sin^2\theta_{12}$	$sin^2\theta_{23}$	$sin^2\theta_{13}$
≈ 0.2	$\mathbf{0.33}$ $(+2\sigma)$	$\mathbf{0.604}$ $(+1\sigma)$	$\mathbf{0.0219}$
≈ 0.4	$\mathbf{0.33}$ $(+2\sigma)$	$\mathbf{0.629}$ $(+2\sigma)$	$\mathbf{0.0219}$
≈ 0.72	$\mathbf{0.344}$ $(+2\sigma)$	$\mathbf{0.664}$ $(+3\sigma)$	$\mathbf{0.0251}$ $(+3\sigma)$

Texture B1

δ	$sin^2\theta_{12}$	$sin^2\theta_{23}$	$sin^2\theta_{13}$
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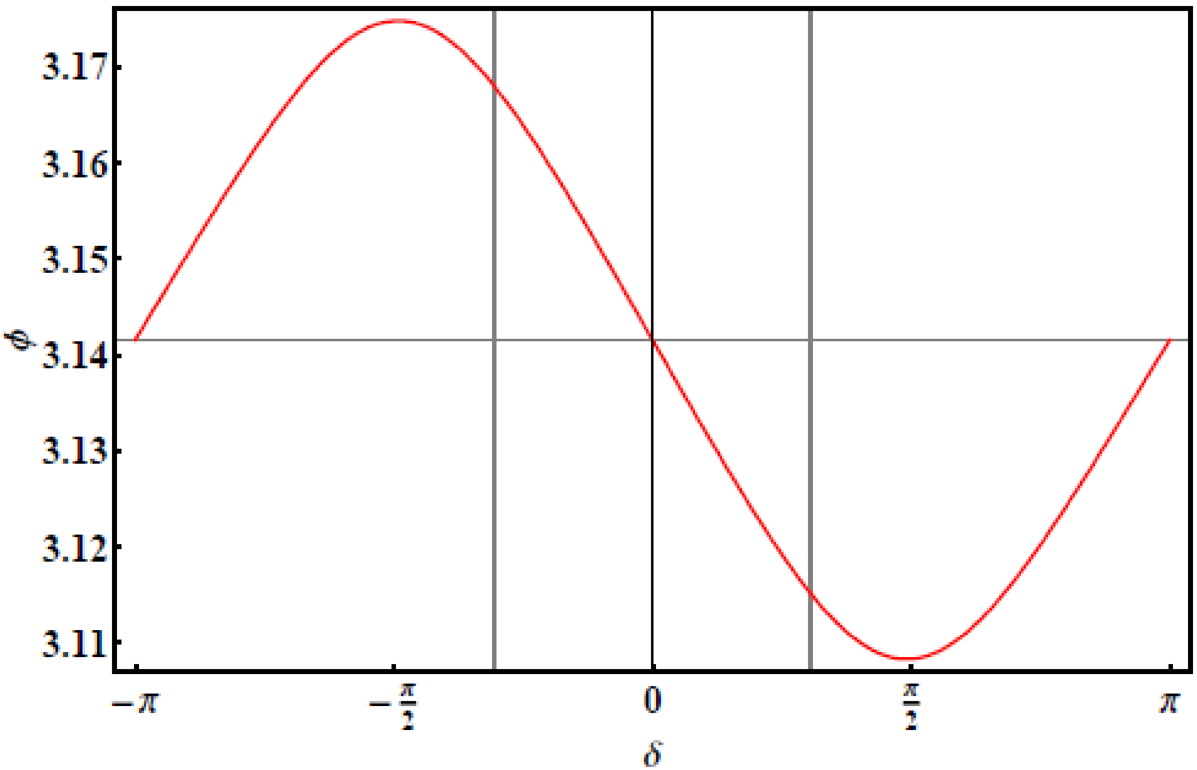


Check for Leptogenesis..

Resonant Leptogenesis

With degenerate N’s, CP asymmetry:

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

Pilaftsis & Underwood’03

Has maximum with $M_1 = M\,|1 - \delta_N|, \quad M_2 = M\,|1+\delta_N|, \quad \delta_N \ll 1$

For arbitrary M !

Needed: 1) to generate δN ; 2) $(\hat{Y}_\nu^+ \hat{Y}_\nu)_{21}$ Complex- CP viol

In considered framewrok:

1) δN emerges at 1-loop;

2) Complex $(\hat{Y}_\nu^+ \hat{Y}_\nu)_{21}$ at 2-loop & related to δ

1-loop RG:
$$16\pi^2 \frac{d}{dt} M_N = 2 M_N Y_\nu^\dagger Y_\nu + 2 Y_\nu^T Y_\nu^* M_N$$

$$\delta M_N^{1-\mathrm{loop}} \simeq -\frac{1}{8\pi^2}\left(M_N Y_\nu^\dagger Y_\nu + Y_\nu^T Y_\nu^* M_N\right)_{\mu=M_G} \ln\frac{M_G}{M}$$

$$\mu = M \qquad\qquad M_N = M\begin{pmatrix} -\delta_N & 1 \\ 1 & -\delta_N^* \end{pmatrix}$$

At 1-loop, phases are correlated and drop out !

No CP at this level

$$Y_\nu = \mathcal{U}\begin{pmatrix} 0 & 0 \\ \hat{a}_2 & 0 \\ \hat{a}_3 & \hat{b}_3 \end{pmatrix}\tilde{P}\,, \qquad \tilde{P} = \mathrm{Diag}\left(1, e^{i\xi}\right)$$

Drops out from 1-loop RG

2-loop RG: $$16\pi^2 \frac{d}{dt} M_N = 2 M_N Y_\nu^\dagger Y_\nu - \frac{1}{8\pi^2} M_N \left(Y_\nu^\dagger Y_e Y_e^\dagger Y_\nu + \right. \dots$$

$$M_N = M \begin{pmatrix} -\delta_N & 1 \\ 1 & -\delta_N^* \end{pmatrix}$$

$$\delta_N \simeq \left(b\alpha_2 + e^{i\phi} - \frac{\lambda_\tau^2}{16\pi^2} e^{i\phi} \right) \frac{x\bar{\beta}^2}{4\pi^2} \ln \frac{M_G}{M}$$

$$\mathrm{B}_1 : \quad Y_\nu = \begin{pmatrix} x\alpha_1 & b \\ x\alpha_2 & 0 \\ xe^{i\phi} & 1 \end{pmatrix} \cdot \bar{\beta}$$

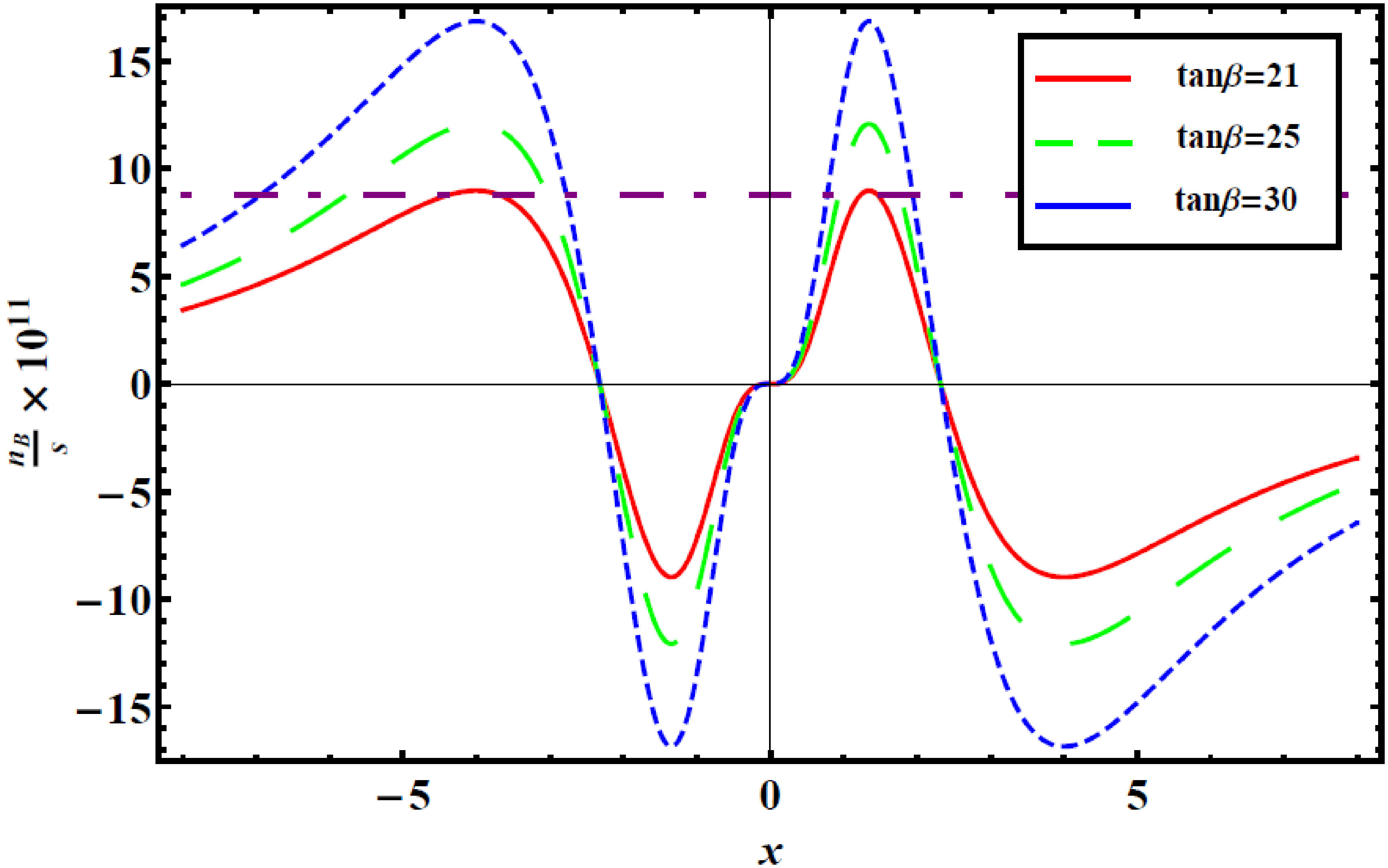
At 1-loop

At 2-loop

All Yukawa parameters, besides one (x), are calculated in terms of observables and M;

For fixed M & δ n_B/s vs. x can be plotted

Baryon Asymmetry: Inverted Hierarchical Case (texture B1)



$$M = 10^4 \ \text{GeV}$$

$$\mathrm{B}_2: \quad Y_\nu = \begin{pmatrix} x\alpha_1 & b \\ x\alpha_2 e^{i\phi} & 1 \\ x & 0 \end{pmatrix} \cdot \bar{\beta}$$

Does not work.
λ_τ do not hit CP phase

With this setup, only one 1 texture zero works (not well..)

Explore more possibilities…

Introducing additional $\mathcal{N}$ states:

$$Y_\nu = \begin{array}{c} (\boldsymbol{N_1} \quad \boldsymbol{N_2} \qquad \mathcal{N} \cdots) \\ \begin{pmatrix} \mathbf{0} & \mathbf{0} & \cdots \\ \mathbf{x} & \mathbf{x} & \cdots \\ \mathbf{x} & \mathbf{x} & \cdots \end{pmatrix} \end{array}$$

Situation will change..

Some assumptions & simplifications

a) $\mathcal{N}$'s are much heavy than $N_{1,2}$

do not contribute to leptogenesis

b) $\mathcal{N}$'s do not spoil degeneracy of $N_{1,2}$

c) Integration of $\mathcal{N}$ → d=5 ops, improve neutrino sector and keep predictions

$$\mathcal{O}^5_{ij} \equiv \frac{\tilde{d}_5 e^{ix_5}}{2M_*} l_i l_j h_u h_u$$

Setup:

(A. Achelashvili, ZT ' 2016)

- 1. Two deg. RHNs (& Ye=diag) $M_N = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} M$

  2. two texture zero Yukawas + single d=5 op.

Helps classification:

$$T_1 = \begin{pmatrix} \times & 0 \\ \times & 0 \\ \times & \times \end{pmatrix}, \quad T_2 = \begin{pmatrix} \times & 0 \\ \times & \times \\ \times & 0 \end{pmatrix}, \quad T_3 = \begin{pmatrix} \times & \times \\ \times & 0 \\ \times & 0 \end{pmatrix}$$

$$T_4 = \begin{pmatrix} 0 & 0 \\ \times & \times \\ \times & \times \end{pmatrix}, \quad T_5 = \begin{pmatrix} \times & 0 \\ 0 & \times \\ \times & \times \end{pmatrix}, \quad T_6 = \begin{pmatrix} \times & 0 \\ \times & \times \\ 0 & \times \end{pmatrix}$$

$$T_7 = \begin{pmatrix} \times & \times \\ 0 & 0 \\ \times & \times \end{pmatrix}, \quad T_8 = \begin{pmatrix} \times & \times \\ \times & 0 \\ 0 & \times \end{pmatrix}, \quad T_9 = \begin{pmatrix} \times & \times \\ \times & \times \\ 0 & 0 \end{pmatrix}$$

$$T_3 = \begin{pmatrix} a_1 e^{i\alpha_1} & b_1 e^{i\beta_1} \\ a_2 e^{i\alpha_2} & 0 \\ a_3 e^{i\alpha_3} & 0 \end{pmatrix} = \begin{pmatrix} e^{ix} & 0 & 0 \\ 0 & e^{iy} & 0 \\ 0 & 0 & e^{iz} \end{pmatrix} \begin{pmatrix} a_1 & b_1 \\ a_2 & 0 \\ a_3 & 0 \end{pmatrix} \begin{pmatrix} e^{i\omega} & 0 \\ 0 & e^{i\rho} \end{pmatrix}$$

$$T_4 = \begin{pmatrix} 0 & 0 \\ a_2 e^{i\alpha_2} & b_2 e^{i\beta_2} \\ a_3 e^{i\alpha_3} & b_3 e^{i\beta_3} \end{pmatrix} = \begin{pmatrix} e^{ix} & 0 & 0 \\ 0 & e^{iy} & 0 \\ 0 & 0 & e^{iz} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ a_2 & b_2 \\ a_3 & b_3 e^{i\phi} \end{pmatrix} \begin{pmatrix} e^{i\omega} & 0 \\ 0 & e^{i\rho} \end{pmatrix}$$

...

$$M_\nu = \langle h_u^0 \rangle^2 Y_\nu M_N^{-1} Y_\nu^T + \frac{\tilde{d}_5 e^{ix_5}}{2M_*} l_i l_j h_u h_u$$

Examples:

$$M_{T_4}^{(11)} = \begin{pmatrix} d_5 & 0 & 0 \\ 0 & 2a_2b_2 & a_3b_2 + a_2b_3e^{i\phi} \\ 0 & a_3b_2 + a_2b_3e^{i\phi} & 2a_3b_3e^{i\phi} \end{pmatrix} \bar{m}$$

$$M_{T_4}^{(12)} = \begin{pmatrix} 0 & d_5 & 0 \\ d_5 & 2a_2b_2 & a_3b_2 + a_2b_3e^{i\phi} \\ 0 & a_3b_2 + a_2b_3e^{i\phi} & 2a_3b_3e^{i\phi} \end{pmatrix} \bar{m}$$

$$M_{T_4}^{(13)} = \begin{pmatrix} 0 & 0 & d_5 \\ 0 & 2a_2b_2 & a_3b_2 + a_2b_3e^{i\phi} \\ d_5 & a_3b_2 + a_2b_3e^{i\phi} & 2a_3b_3e^{i\phi} \end{pmatrix} \bar{m}$$

Obtained neutrino matrices

$$P_2 = \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}$$

$$P_1 = \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix} \qquad P_3 = \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

$$P_4 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$$

$$P_5 = \begin{pmatrix} 0 & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad P_6 = \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & \times \end{pmatrix}, \quad P_7 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

P_1-type: $M_{T_4}^{(12)}$, P_2-type: $M_{T_4}^{(13)}$, P_3-type: $M_{T_7}^{(23)}$, P_4-type: $M_{T_9}^{(23)}$

P_5-type: $M_{T_5}^{(22)}$, $M_{T_6}^{(33)}$, P_6-type: $M_{T_5}^{(11)}$ $M_{T_8}^{(33)}$ P_7-type: $M_{T_6}^{(11)}$, $M_{T_8}^{(22)}$

One example (for demonstration)

$$M_{T_4} = \begin{pmatrix} 0 & d_5 & 0 \\ d_5 & 2a_2b_2 & a_3b_2 + a_2b_3e^{i\phi} \\ 0 & a_3b_2 + a_2b_3e^{i\phi} & 2a_3b_3e^{i\phi} \end{pmatrix} \bar{m}$$

$$m_3^2 = \frac{\Delta m_{atm}^2 + \Delta m_{sol}^2 c_{12}^2}{1 - s_{13}^2 \cot_{23}^2 (1 + t_{13}^2)^2 - t_{13}^4}$$

$$m_1 = 0.00613 \text{ eV}, \quad \mathrm{m}_2 = 0.0106 \text{ eV}, \quad \mathrm{m}_3 = 0.0499 \text{ eV}$$

$$\cos\rho_1 = \frac{m_3^2 t_{13}^4 - m_1^2 c_{12}^4 - m_2^2 s_{12}^4}{2m_1 m_2 c_{12}^2 s_{12}^2} \Rightarrow \rho_1 = \pm 3.036$$

$$\delta = \arg[m_1 c_{12}^2 + m_2 s_{12}^2 e^{i\rho_1}] - \arg[m_1 - m_2 e^{i\rho_1}] \quad \delta = \pm 0.378$$

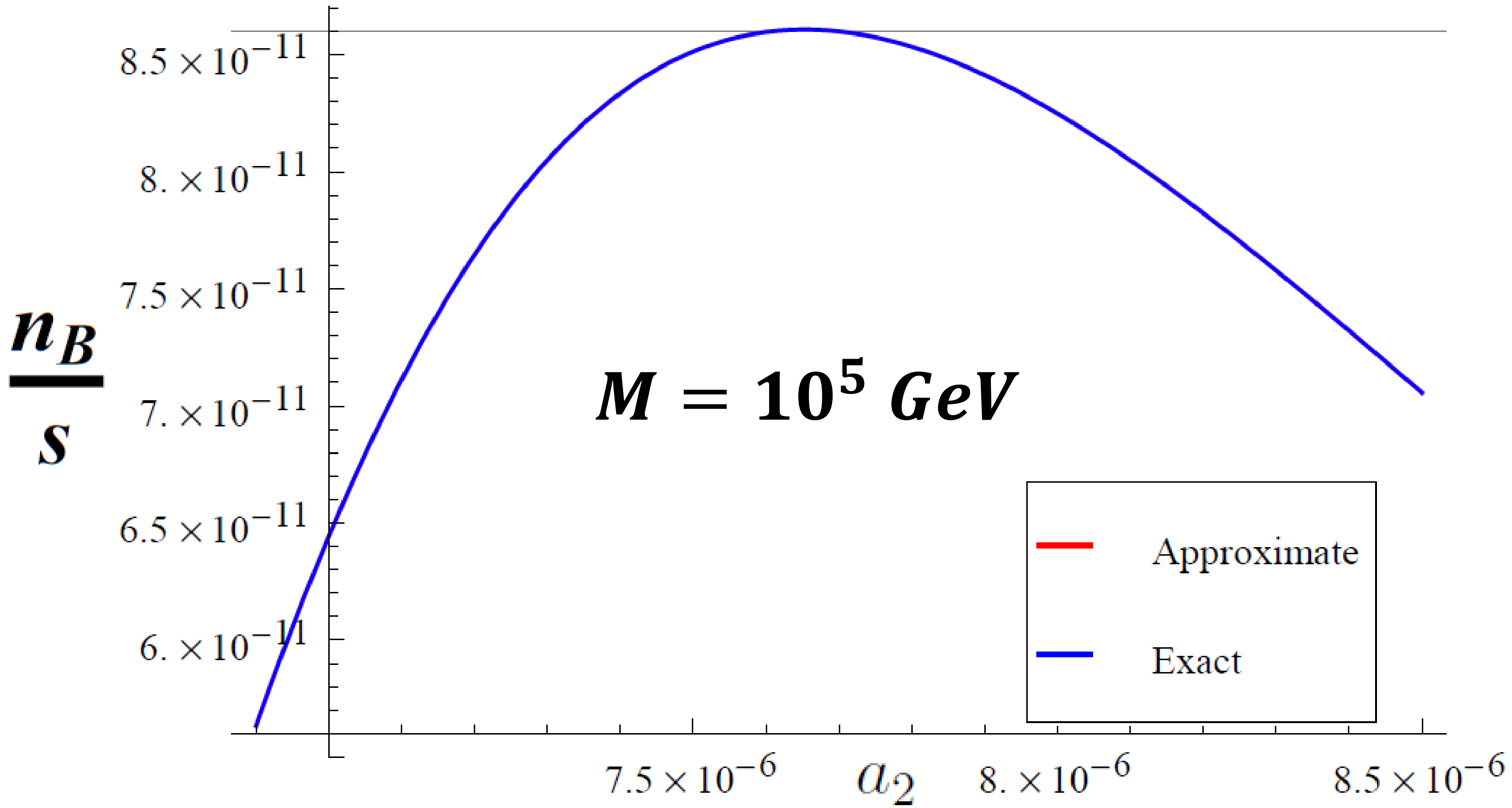
$$\phi = \pm 1.287$$

Preliminary numerical results (for P1 texture)

Resonant leptogenesis works with:

M	$\tan\beta_{min}$	a_2	a_3	b_2	b_3	d_5
10^{16}	3.615	76.43×10^{-6}	88.8×10^{-6}	59.18×10^{-6}	57.28×10^{-6}	3.78×10^{-9}
10^{15}	3.601	24.19×10^{-6}	28.11×10^{-6}	18.73×10^{-6}	18.1×10^{-6}	3.79×10^{-10}
10^{14}	3.597	7.65×10^{-6}	8.89×10^{-6}	5.92×10^{-6}	5.72×10^{-6}	3.79×10^{-11}
10^{13}	3.603	2.421×10^{-6}	2.81×10^{-6}	1.87×10^{-6}	1.81×10^{-6}	3.78×10^{-12}

eV



Summary

- With 2 deg. RHNs (& Ye=diag) neutrino Dirac Yukawas
  only one 1 texture zero works for neutrinos
  & resonant leptogenesis

- With 2 deg. RHNs (& Ye=diag)
  2 texture zero neutrino Dirac Yukawas + single d=5 op.
  Many scenarios are working for neutrinos
  and also for resonant leptogenesis

- Future work: To justify textures by symmetries (flavor sym.)