Leptogenesis and nonzero θ_{13} : a flavor symmetric connection

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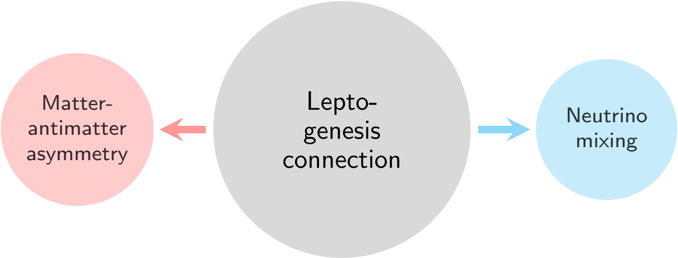
Difficulties with Standard Model

Neutrino Masses mixing and CP violation

Cosmological puzzles like
Matter-antimatter asymmetry
Dark Matter etc.

What role neutrinos can play?


Matter-
antimatter
asymmetry
Lepto-
genesis
connection
Neutrino
mixing

Matter-antimatter asymmetry:

1. Satisfy Sakharov Conditions
2. Lepton asymmetry : $\epsilon_i = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$
   (Can contain information from neutrino mixing)
3. Lepton asymmetry $\Rightarrow$ Baryon asymmetry

Details: talks by Bhupal Dev and Debasish Borah

Neutrino Sector:

SM Prediction : Neutrinos are massless

- Observation of **neutrino oscillation** : neutrinos have **tiny nonzero mass**
- Beyond SM physics is inevitable

What is the underlying theory behind neutrino mixing?

How to give neutrinos mass?

Neutrino Mixing Matrix : Pontecorvo-Maki-Nakagawa-Sakata parametrization

$$U_{PMNS} = \begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{13}S_{23}e^{i\delta} & C_{12}C_{23} - S_{12}S_{13}S_{23}e^{i\delta} & C_{13}S_{23} \\ S_{12}S_{23} - C_{12}S_{13}C_{23}e^{i\delta} & C_{12}S_{23} - S_{12}S_{13}C_{23}e^{i\delta} & C_{13}C_{23} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{bmatrix}$$

here $C_{ij} = \cos\theta_{ij}$ and $S_{ij} = \sin\theta_{ij}$.

- **Neutrino mixing parameters**
  - Three mixing angles: θ_{12}, θ_{23} and θ_{13}
  - Dirac CP violating phase: δ
  - Two mass squared differences: $\Delta m^2_{\odot} = m^2_2 - m^2_1$, $\Delta m^2_A = m^2_3 - m^2_1$
  - Two Majorana phase: α_{21} and α_{31}

- **This is very similar to the quark mixing matrix V_{CKM} (Cabibbo-Kobayashi-Maskawa matrix)**

Quark Mixing Matrix

$$|V_{CKM}| = \begin{bmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{bmatrix} \; PDG2014$$

Lepton Mixing Matrix

$$|U_{PMNS}| = \begin{bmatrix} 0.801 - 0.845 & 0.514 - 0.580 & 0.137 - 0.158 \\ 0.225 - 0.517 & 0.441 - 0.699 & 0.614 - 0.739 \\ 0.246 - 0.529 & 0.464 - 0.713 & 0.590 - 0.776 \end{bmatrix}$$

Gonzalez-Garcia *et. al.* arXiv: 1409.5439

Mixing angles

- Quark mixing angles: $\theta^q_{12} \approx 13^\circ, \theta^q_{23} \approx 2.5^\circ, \theta^q_{13} \approx 0.21^\circ$
- Lepton mixing angles: $\theta^l_{23} \approx 45^\circ, \theta^l_{12} \approx 35^\circ, \theta^l_{13} \approx 9^\circ$.

• Understanding the flavor puzzle : detailed study of neutrino mixing is essential in the light of $U_{e3} = \sin\theta_{13} e^{-i\delta}$.

Prior to 2012: Tribimaximal(TBM) mixing

Global analysis of neutrino oscillation data suggests $\sin^2\theta_{12} = 1/3$ and $\sin^2\theta_{23} = 1/2$. With $\theta_{13} = 0$, neutrino mixing matrix takes the form

$$U_{PMNS} \approx U_{TB} = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Measurement of θ_{13} in 2012

- Daya Bay : $\sin^2 2\theta_{13} = 0.089 \pm 0.010(stat.) \pm 0.005(syst.)$, arXiv:1203:1669
  DOUBLE-CHOOZ: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(stat.) \pm 0.025(syst.)$, :1112:6353
  RENO : $\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$, arXiv:1204:0626
  hence $\sin\theta_{13} \approx 0.155 \rightarrow \theta_{13} \approx 9^o$

Parameter Status: arXiv 1405.7540 (Nobel in Physics 2015)

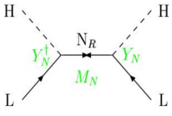
Parameter	Best Fit	1σ range	3σ range
$\Delta m^2_{\odot}$ $[\times 10^{-5} eV^2]$	7.60	7.42 – 7.79	7.11 – 8.18
$\|\Delta m^2_A\|$ $[\times 10^{-3} eV^2]$	2.48 2.38	2.41 – 2.53 2.32 – 2.43	2.30 – 2.65 2.20 – 2.54
$\sin^2\theta_{12}$	0.323	0.307 – 0.339	0.278 – 0.375
$\sin^2\theta_{23}$	0.567 0.573	0.439 – 0.599 0.530 – 0.598	0.392 – 0.643 0.403 – 0.640
$\sin^2\theta_{13}$	0.0234 0.0240	0.0214 – 0.0254 0.0221 – 0.0259	0.0177 – 0.0294 0.0183 – 0.0297
δ	1.34π	$0 - 2\pi$	$0 - 2\pi$

• Bound on absolute neutrino mass: $\sum_i m_{\nu_i} < 0.230$ eV (95% CL) [PLANCK Collaboration]

Theory of Massive Neutrinos

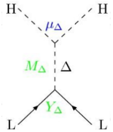
Details: talk by K. S. Babu

Right-handed singlet:
(type-I seesaw)



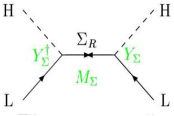
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Fermion triplet:
(type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Type-I Seesaw: Heavy Majorana neutrinos included

$$
\begin{aligned}
-\mathcal{L}_Y &= y\overline{L}\widetilde{H}\nu_R + \frac{1}{2}M_R\overline{\nu_R^c}\nu_R + H.c. \\
m_\nu &= \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \\
m_\nu^{light} &= -M_D^T M_R^{-1} M_D, m_\nu^{heavy} = M_R \text{ with } M_D << M_R
\end{aligned}
$$

Flavor Symmetries and Neutrino mass and mixing matrices

Tribimaximal Mixing

$$
\begin{aligned}
m_\nu^{TBM} &= U_{TB}^T m_{diag} U_{TB} \\
&= \begin{pmatrix} A & B & B \\ B & C & D \\ B & D & C \end{pmatrix} \qquad \Rightarrow \theta_{13} = 0
\end{aligned}
$$

• Such special structure of neutrino mass matrix indicates some flavor symmetry in lepton sector

Talk by Biswajit Adhikari

• Non-Abelian discrete Groups:

A_4, A_5, S_3, S_4, $\Delta(27)$ etc.

• A_4 Discrete group: (i) Even permutation group of four object
(ii) It has $4!/2 = 12$ elements
(iii) Three 1D representation $1, 1', 1''$
(iv) One irreducible 3D representation 3
(v) Generates the required mass matrices in an economic way

Mohapatra, Yu 06; Jenkins, Manohar 08; Hagedorn, Molinaro, Petcov 09; ....

Adhikary, Ghosal 08; Branco, Felipe, Joaquim, Serodio 12; Borah 14; Huang 14; BK, Sil 15; Samanta, Chakraborty, Roy, Ghosal 16; Borah, Das, Mukherjee 17; Sruthilaya, Mohanta, Patra 17; ...

Neutrino masses and mixing

1. A genral Type-I seesaw mechanism
2. Standard Model + 3 RH neutrinos (gauge singlets) + **only one additional flavon** in existing TBM scenario
3. pure type-I seesaw provides TBM and **additional flavon contribution in RH neutrino mass matrix generates** θ_{13}

Leptogenesis

1. Decay of RH neutrinos: Leptogenesis
2. Leading order contribution in neutrino Yukawa matrix : Vanishing lepton asymmetry
3. Higher contribution in neutrino Yukawa matrix : Observed lepton asymmetry
4. Involvement of θ_{13} and Majorana phases in leptogenesis

based on BK, Arunansu Sil PRD 15

Altarelli-Feruglio (AF) Model : hep-ph/0512103

1. SM + Three RH neutrinos + A_4 flavons (triplets: ϕ_S, ϕ_T, Singlet ξ)
2. Vacuum expectation values (vev) of the scalar fields
   $\langle\phi_T\rangle = (v_T, 0, 0)$, $\langle\phi_S\rangle = (v_S, v_S, v_S)$, $\langle\xi\rangle = u$
3. Charged Leptons: Diagonal
4. Dirac + Majorana Neutrinos: $yLNH + x_A\xi NN + x_B\phi_S NN$

$$m_D = yv\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 1\\ 0 & 1 & 0\end{bmatrix}; M_R = \begin{bmatrix}a+2b/3 & -b/3 & -b/3\\ -b/3 & 2b/3 & a-b/3\\ -b/3 & a-b/3 & 2b/3\end{bmatrix};$$

$a = 2x_A u, b = 2x_B v_s$

Predictions of AF model

- Previous structure of Majorana mass makes the neutrino mixing matrix to be tri-bimaximal one.

$$U_{TB} = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{bmatrix}$$

- Prediction for mixing angles:

$\sin^2\theta_{12} = 1/3$ and $\sin^2\theta_{23} = 1/2$ along with $\boxed{\theta_{13} = 0}$.

- Altarelli-Feruglio class of model also predicts light neutrino mass sum rule to be

$$\frac{1}{m_1} - \frac{e^{i\alpha_{21}}}{m_2} = \frac{e^{i\alpha_{31}}}{m_3}.$$

Therefore, any modification the theory will also effect this relation.

Clearly, observation of $\theta_{13} \neq 0$ requires modification in Altarelli-Feruglio model.

Deviation from TBM mixing

- To make $\theta_{13} \neq 0$, introduce new scalar singlet ξ' (vev $\langle \xi' \rangle = u_N$), which contributes in the heavy Majorana neutrino sector through $x_N \xi' NN$.

Shimizu,Tanimoto,Watanabe PTP126; Brahmachari, Choubey, Mitra, 08; King,Lnhn JHEP1109

- Mojarana mass matrix is then given by

$$M_{Rd} = \begin{bmatrix} a+2b/3 & -b/3 & -b/3 \\ -b/3 & 2b/3 & a-b/3 \\ -b/3 & a-b/3 & 2b/3 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d \\ 0 & d & 0 \\ d & 0 & 0 \end{bmatrix} ; d = 2x_N u_N$$

- Above structure of RH neutrino mass matrix is no longer diagonalizable by U_{TB} only.
- Additional rotation is required. Let us consider a matrix U_1 (parametrized by θ and ψ), which do this job.
- Then RH neutrino mass matrix can be diagonalized by

$$\mathrm{diag}(M_1 e^{i\varphi_1}, M_2 e^{i\varphi_2}, M_3 e^{i\varphi_3}) = (U_{TB} U_1)^T M_{Rd} U_{TB} U_1.$$

Here, $M_{1,2,3}$ all are real, positive eigenvalues of M_{Rd}.

Neutrino masses and mixings

- Without loss of generality we will work with $\boxed{\phi_{da} = 0}$ and say $\mathrm{K} = \sqrt{1 - \lambda_1 + \lambda_1^2}$, then we have RH neutrino masss as

$$M_{1,3} = |a| \left|\lambda_2 e^{i\phi_{ba}} \pm \mathrm{K}\right| \qquad \varphi_{1,3} = \arg(b \pm a\mathrm{K}),$$
$$M_2 = |a|\,|1 + \lambda_1| \qquad \varphi_2 = \arg(a + d),$$

where $\lambda_1 = |d/a|$ and $\lambda_2 = |b/a|$, also $\phi_{da} = \phi_d - \phi_a$ and $\phi_{ba} = \phi_b - \phi_a$ are phase difference between (d, a) and (b, a) respectively.

- Light neutrino masses obtained via $m_\nu = m_D^T M_{Rd}^{-1} m_D = U_\nu^* m_\nu^{diag} U_\nu^\dagger$, here

$$U_\nu = \frac{m_D^T}{yv} U_{TB} U_1^* \,\mathrm{diag}(e^{i\varphi_1/2}, e^{i\varphi_2/2}, e^{i\varphi_3/2}).$$

King, Luhn JHEP1109

- Light neutrino masses given by $m_i = \frac{(yv)^2}{M_i}$

- We can now remove one common phase by setting $\varphi_1 = 0$ and we find the Majorana phases as :$\varphi_2 = \alpha_{21}, \varphi_3 = \alpha_{31}$

Majorana phases will be extremely important when we will study Leptogenesis.

Light neutrino masses and mixings

- Final form of unitary matrix that diagonalizes m_ν is given by

$$U_\nu = \frac{m_D^T}{y v_u} U_{TB} \begin{bmatrix} \cos\theta & 0 & \sin\theta e^{-i\psi} \\ 0 & 1 & 0 \\ -\sin\theta e^{+i\psi} & 0 & \cos\theta \end{bmatrix} diag(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$$

$$= \begin{bmatrix} \sqrt{\frac{2}{3}}\cos\theta & 1/\sqrt{3} & \sqrt{\frac{2}{3}}\sin\theta e^{-i\psi} \\ -\frac{\cos\theta}{\sqrt{6}} + \frac{\sin\theta}{\sqrt{2}} e^{i\psi} & 1/\sqrt{3} & -\frac{\cos\theta}{\sqrt{2}} - \frac{\sin\theta}{\sqrt{6}} e^{-i\psi} \\ -\frac{\cos\theta}{\sqrt{6}} - \frac{\sin\theta}{\sqrt{2}} e^{i\psi} & 1/\sqrt{3} & \frac{\cos\theta}{\sqrt{2}} - \frac{\sin\theta}{\sqrt{6}} e^{-i\psi} \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{bmatrix}.$$

here we have parametrized the extra U_1 matrix by θ and ψ as mentioned earlier.

- We find a general sum rule for light neutrino masses as given by,

$$\frac{1}{m_1} - \frac{2\mathrm{K} e^{i\alpha_{21}}}{m_2(1+\lambda_1)} = \frac{e^{i\alpha_{31}}}{m_3}.$$

- When, $\mathrm{K}\left(= \sqrt{1-\lambda_1+\lambda_1^2}\right) \rightarrow 1$ (i.e. with $\lambda_1 = 0$), the sum rule is reduced to the one found in Altarelli,Meloni JPG36 and Hagedorn,Molinaro,Petcov JHEP0909.

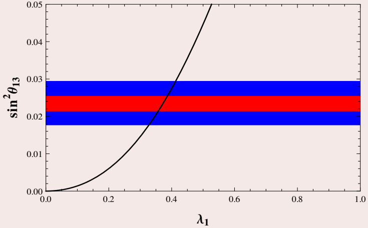
Generation of nonzero θ_{13} and effect on other mixing angles

- Comparing U_{PMNS} and U_ν we get

$$\sin\theta_{13} = \sqrt{\frac{2}{3}}\sin\theta, \qquad \delta_{CP} = \psi \qquad \tan 2\theta = \frac{\sqrt{3}\lambda_1}{(2-\lambda_1)},$$

$$\sin^2\theta_{12} = \frac{1}{3(1-\sin^2\theta_{13})} \qquad \text{and} \qquad \sin^2\theta_{23} = \frac{1}{2} + \frac{1}{\sqrt{2}}\sin\theta_{13}\cos\psi.$$

$\sin^2\theta_{13}$ vs α_1



- Here $\psi = 0$. Now, for 3σ (blue patch) and 1σ (red patch) range of $\sin^2\theta_{13}$ we get $\lambda_1 = 0.328 - 0.413$ and $\lambda_1 = 0.357 - 0.386$ respectively. Best-fit value of $\sin^2\theta_{13}$ makes $\lambda_1 = 0.37\&0.38$ for NH and IH respectively.

Correlation of parameters involved

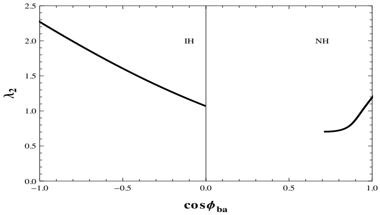
- Parameters involved Majorana neutrino masses: $\boxed{\lambda_1, \lambda_2, \ |a|, \ \phi_{ba}.}$
- These can be constrained by low energy neutrino oscillation data through ratio of solar and atmospheric mass squared difference defined as

$$r = \frac{\Delta m^2_{\odot}}{|\Delta m^2_A|}, \ \ \Delta m^2_{\odot} = \Delta m^2_{21} \equiv m^2_2 - m^2_1, \ \ |\Delta m^2_A| = |\Delta m^2_{31}| \equiv |\Delta m^2_{32}|.$$

- Hence using above relations we get

$$r = \frac{[\lambda_2^2 + 2\lambda_2 \mathrm{K} \cos\phi_{ba} + \mathrm{K}^2 - (1+\lambda_1)^2](\lambda_2^2 - 2\lambda_2 \mathrm{K}\cos\phi_{ba} + \mathrm{K}^2)}{4(1+\lambda_1)^2 \lambda_2 \mathrm{K} |\cos\phi_{ba}|}.$$

- Variation of $\cos\phi_{ba}$ with λ_2 for $r = 0.03$ (using best fit values)



- From the above plot for NH $\cos\phi_{ba} > 0$ ($\lambda_2 = 0.71 - 1.2$) and for IH $\cos\phi_{ba} < 0$ ($\lambda_2 = 1.1 - 2.3$) .

Constraints on Light Neutrino Mass

- Using the best fit value of $|\Delta m_A^2| = 2.55 \times 10^{-3}\mathrm{eV}^2$ [NH] ($2.43 \times 10^{-3}\mathrm{eV}^2$ [IH]), $r = 0.03$ and $\alpha_1 = 0.38$, we can estimate m_i's from the above relation for both the NH (and IH) as follows

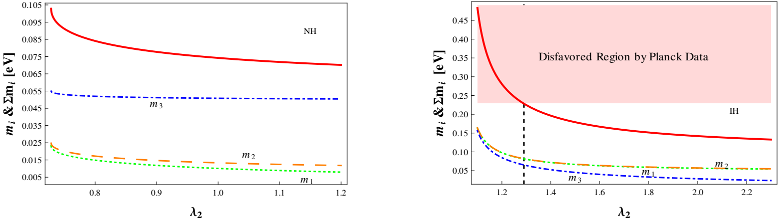


Figure : Light neutrino masses m_1 (green dotted), m_2 (orange dashed), m_3 (blue dot-dashed) and $\sum m_i$ (red continuous) vs λ_2 for $\lambda_1 = 0.38$. Here in the right panel horizontal shaded region indicated disfavored region for $\sum m_i$ from Planck Collaboration.

$$0.07 \text{ eV} \leq \sum m_i \leq 0.10 \text{ eV} (\text{NH}, \lambda_2 = 0.73 - 1.20),$$
$$0.13 \text{ eV} \leq \sum m_i \leq 0.23 \text{ eV} (\text{IH}, \lambda_2 = 1.30 - 2.30).$$

Constraints on Majorana phases

$$\tan\alpha_{21} = -\frac{\lambda_2 \sin\phi_{ba}}{\mathrm{K} + \lambda_2 \cos\phi_{ba}}\,, \qquad \tan\alpha_{31} = \frac{2\mathrm{K}\lambda_2 \sin\phi_{ba}}{\lambda_2^2 - \mathrm{K}^2}\,.$$

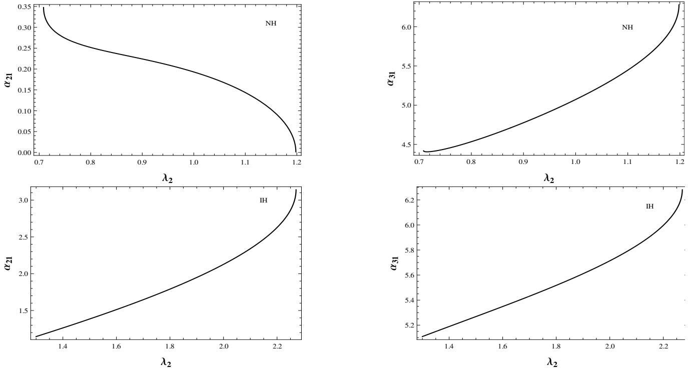


Figure : Majorana phases $\alpha_{21,31}$ as function of λ_2 for NH (upper row with $\cos\phi_{ba} > 0$ and $\sin\phi_{ba} < 0$) and IH (lower row with $\cos\phi_{ba} < 0$ and $\sin\phi_{ba} < 0$) respectively.

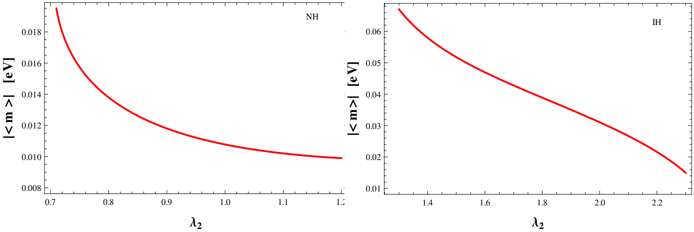
Bound on neutrinoless double beta decay:

- Effective neutrino mass parameter $|\langle m \rangle|$

$$|\langle m \rangle| = \left| \frac{2}{3} m_1 \cos^2\theta + \frac{1}{3} m_2 e^{i\alpha_{21}} + \frac{2}{3} m_3 \sin^2\theta e^{i\alpha_{31}} \right| .$$

with $\delta_{CP} = \pi$

- $|\langle m \rangle|$ vs λ_2 Plot:



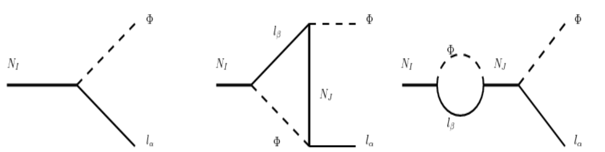
- Summary: 0.01 eV $\lesssim |\langle m \rangle| \lesssim$ 0.02 eV (NH); 0.015 eV $\lesssim |\langle m \rangle| \lesssim$ 0.07 eV (IH).

- The current upper limit on $|\langle m \rangle|$ varies between 0.177 eV and 0.339 eV [arXiv:1407.4357].

Leptogenesis

• Out of equilibrium decay of heavy Majorana neutrinos can produce lepton asymmetry in the basis where RH Majorana neutrinos are diagonal.

Decay of RH neutrinos



• If we consider the generation of lepton asymmetry happens at a temperature of the Universe

$$T \sim M_i \gtrsim 10^{12} \text{ GeV}$$

Blachet,Bari,Raffelt JCAP 0703

the notion of flavor becomes insignificant. This is called ‘one flavor approximation’.

• Final lepton asymmetry is produced from decay of all three RH Majorana neutrinos.

Leptogenesis

- In the basis where RH Majorana neutrinos are diagonal, lepton asymmetry parameter is defined as

$$\epsilon_i = \frac{1}{8\pi} \sum_{j \neq i} \frac{\mathrm{Im}\left[\left((\hat{Y}_\nu \hat{Y}_\nu^\dagger)_{ji}\right)^2\right]}{(\hat{Y}_\nu \hat{Y}_\nu^\dagger)_{ii}} f\left(\frac{m_i}{m_j}\right)$$

where $\hat{Y}_\nu = \mathrm{diag}(1, e^{-i\alpha_{21}/2}, e^{-i\alpha_{31}/2}) U_R^T Y_\nu$.

- The loop factor $f(x)$ in above expression has been defined as follows

$$f(x) \equiv -x\left(\frac{2}{x^2-1} + \log\left(1 + \frac{1}{x^2}\right)\right)$$

with $x = m_i/m_j$.

- Leptogenesis can be linked to baryon asymmetry as

$$Y_B \approx \sum Y_{Bi}$$

where

$$Y_{Bi} \simeq -1.48 \times 10^{-3} \epsilon_i \eta_{ii}.$$

Y_{Bi}'s are coming from decay of each Majorana neutrinos and η_{ii} stands for efficiency factor

$$\frac{1}{\eta_{ii}} \approx \frac{3.3 \times 10^{-3}\ \mathrm{eV}}{\tilde{m}_i} + \left(\frac{\tilde{m}_i}{0.55 \times 10^{-3}\ \mathrm{eV}}\right)^{1.16},$$

with washout mass parameter, $\tilde{m}_i = \frac{(\hat{Y}_\nu \hat{Y}_\nu^\dagger)_{ii} v_u^2}{M_i}$ for $M_i < 10^{14}$ GeV.

Leptogenesis

- At LO, $\hat{Y}_{\nu 0}\hat{Y}^{\dagger}_{\nu 0} \propto |y^2|\mathbf{1}$
- Results, vanishing asymmetry parameter ϵ_i and zero matter-antimatter asymmetry .
- Possible remedy: NLO correction in Yukawa sector [arXiv:0807.4176].
- Relevant contribution Yukawa sector:

$$y(LN^c)H_u + x_C N^c(L\phi_T)_{3_S}H_u/\Lambda + x_D N^c(L\phi_T)_{3_A}H_u/\Lambda$$

- Yukawa matrix and $\hat{Y}_\nu\hat{Y}^{\dagger}_\nu$:

$$\begin{aligned} Y_\nu &= Y_{\nu 0} + \delta Y_\nu \\ &= y\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 1\\ 0 & 1 & 0\end{bmatrix} + \frac{x_C v_T}{\Lambda}\begin{bmatrix}2 & 0 & 0\\ 0 & 0 & -1\\ 0 & -1 & 0\end{bmatrix} + \frac{x_D v_T}{\Lambda}\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & -1\\ 0 & 1 & 0\end{bmatrix}, \end{aligned}$$

- Charged lepton mass-matrix remains diagonal

$$\epsilon_1 = \frac{-1}{2\pi}\left(\frac{v_T}{\Lambda}\right)^2\left[\sin\alpha_{21}\left(2\mathrm{Re}(x_C)^2\cos^2\theta + \frac{2\mathrm{Re}(x_D)^2}{3}\sin^2\theta + \frac{2\mathrm{Re}(x_C)\mathrm{Re}(x_D)}{\sqrt{3}}\sin 2\theta\right) f\left(\frac{m_1}{m_2}\right)\right.$$
$$\left. + \sin\alpha_{31}\left(\mathrm{Re}(x_C)^2\sin^2 2\theta + \frac{\mathrm{Re}(x_D)^2}{3}\cos^2 2\theta + \frac{\mathrm{Re}(x_C)\mathrm{Re}(x_D)}{\sqrt{3}}\sin 4\theta\right) f\left(\frac{m_1}{m_3}\right)\right]$$

and similar expressions for ϵ_2 and ϵ_3.

- Here, $y >> (\mathrm{Re}(x_{C,D})v_T/\Lambda)$ since $\mathrm{Re}(x_{C,D})$ are of same order of y and (v_T/Λ) is a suppression factor. Small value of (v_T/Λ) is required to reproduce $|\epsilon_i| \gtrsim 10^{-6}$ for generating baryon asymmetry of proper order. With this consideration, the washout mass parameters becomes identical to light neutrino masses (i.e $\tilde{m}_i \approx m_i$).

Leptogenesis

Baryon Asymmetry

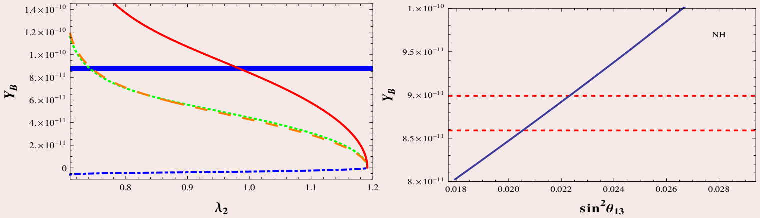


Figure : Left: Green, orange and blue dashed lines stands for Y_{B1}, Y_{B2} and Y_{B3} respectively and red line for total baryon asymmetry Y_B. Right: Y_B vs $\sin^2\theta_{13}$

Parameters involved and their contribution:

- $\frac{v_T}{\Lambda} \sim 10^{-2}$, and typical magnitude of lepton asymmetry $|\epsilon_i| \gtrsim 10^{-6}$
- $\lambda_1 = 0.37$ and 0.38 for best fit value of $\sin^2\theta_{13}$ for NH and IH respectively.
- $x_C = x_D = 0.2$ for NH and $x_C = x_D = 0.05$ for IH. $Y_B = (8.77 \pm 0.24) \times 10^{-11}$.

Conclusions

- We have modified the original A_4 symmetry model of AF by extending the flavon sector with additional scalar singlet.
- **Modified neutrino mass matrix (through Type-I seesaw) generates adequate θ_{13}; other mixing angles are in desired range**.
- A new sum rule for the model is obtained.
- Correlation among entries in mass parameters and Majorana phases are studied.
- **Able to generate required matter-antimatter asymmetry of the universe, where Majorana phases play important role**.
- **This model shows nonvanishing lepton asymmetry even if Dirac CP violating phase is zero**

Thank You

Original Altarelli-Feruglio (AF) [arXiv:hep-ph/0512103] model with $A_4 \times Z_3$

Particle Content

	e^c	μ^c	τ^c	L	N^c	$H_{u,d}$	ϕ_S	ϕ_T	ξ	$\tilde{\xi}$	ϕ_0^S	ξ_0
SU(2)	1	1	1	2	1	2	1	1	1	1	1	1
A_4	1	$1''$	$1'$	3	3	1	3	3	1	1	3	1
Z_3	ω^2	ω^2	ω^2	ω	ω^2	1	1	ω^2	ω^2	ω^2	1	ω^2
$U(1)_R$	1	1	1	1	1	0	0	0	0	0	2	2

Vacuum expectation values: $\langle\phi_T\rangle = (v_T, 0, 0)$, $\langle\phi_S\rangle = (v_S, v_S, v_S)$, $\langle H_{u,d}\rangle = v_{u,d}$ and $\langle\xi\rangle = u$.

- The Superpotential is given by

$$w_L = \left[y_e e^c(\phi_T L) + y_\mu \mu^c(\phi_T L)' + y_\tau \tau^c(\phi_T L)''\right]\frac{H_d}{\Lambda} + yLN^c H_u + (x_A\xi + \tilde{x_A}\tilde{\xi})(N^c N^c) + x_B\phi_S(N^c N^c)$$

- Relevant contribution for Dirac neutrino mass matrix

$$yLN^c H_u.$$

- Here, L (say- $\nu_{l1}, \nu_{l2}, \nu_{l3}$) and N^c (say- N_1^c, N_2^c, N_3^c) are A_4 triplets and H_u is a singlet.
- Following A_4 multiplication rule,

$$(L \otimes N^c)_1 = \nu_{l1}N_1^c + \nu_{l2}N_3^c + \nu_{l3}N_2^c$$

- Hence we have,

$$yLN^c H_u = \begin{array}{c c} & \begin{array}{ccc} N_1^c & N_2^c & N_3^c \end{array} \\ \begin{array}{c} \nu_{l1} \\ \nu_{l2} \\ \nu_{l3} \end{array} & \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \end{array} yH_u \quad \Longrightarrow \quad m_D = yv_u \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Dirac and Majorana Mass matrices

$$m_D = y v_u \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}; \;\; M_R = \begin{bmatrix} a + 2b/3 & -b/3 & -b/3 \\ -b/3 & 2b/3 & A - b/3 \\ -b/3 & a - b/3 & 2b/3 \end{bmatrix}$$

with $a = 2x_A u$ and $b = 2x_B v_s$.

- Light neutrino masses can be obtained via canonical seesaw mechanism as

$$m_\nu = m_D^T M_R^{-1} m_D \; .$$

- Diagonalization is done by

$$m_\nu = U^*_{PMNS} diag(m_1, m_2, m_3) U^\dagger_{PMNS} \; .$$

- In the present context diagonalizing matrix is U_ν,
$m_\nu^{diag} = U_\nu^T m_\nu U_\nu$, where $U_\nu = U_{TB} diag(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$.

Light neutrino masses

Light neutrino mass eigenvalues obtained as

$$m_1 = \frac{y^2}{a+b}\frac{v_u^2}{u}, \;\; m_2 = \frac{y^2}{a}\frac{v_u^2}{u}, \;\; m_3 = \frac{y^2}{-a+b}\frac{v_u^2}{u}$$

A_4 group multiplication [arXiv:1002:0211]

- Product of the singlet and triplets are given by

$$\begin{aligned} 1 \otimes 1 = 1,\ 1' \otimes 1' = 1'', \\ 1' \otimes 1'' = 1, \\ 1'' \otimes 1'' = 1' \& \\ 3 \otimes 3 = 1 \oplus 1' \oplus 1'' \oplus 3_A \oplus 3_S \end{aligned}$$

where subscripts A and S stands for "asymmetric" and "symmetric" respectively. If we have two triplets (a_1, a_2, a_3) and (b_1, b_2, b_3), their products are given by

$$\begin{aligned} 1 &\sim a_1 b_1 + a_2 b_3 + a_3 b_2, \\ 1' &\sim a_3 b_3 + a_1 b_2 + a_2 b_1, \\ 1'' &\sim a_2 b_2 + a_3 b_1 + a_1 b_3, \\ 3_S &\sim \begin{bmatrix} 2a_1 b_1 - a_2 b_3 - a_3 b_2 \\ 2a_3 b_3 - a_1 b_2 - a_2 b_1 \\ 2a_2 b_2 - a_1 b_3 - a_3 b_1 \end{bmatrix}, \\ 3_A &\sim \begin{bmatrix} a_2 b_3 - a_3 b_2 \\ a_1 b_2 - a_2 b_1 \\ a_3 b_1 - a_1 b_3 \end{bmatrix}. \end{aligned}$$

Vacuum Alignment

- Driving part of the LO superpotential, invariant under $A_4 \times Z_3$ with $R = 2$, is

$$w_d = M(\phi_0^T \phi_T) + g(\phi_0^T \phi_T \phi_T) + \phi_0^S(g_1 \phi_S \phi_S + g_2 \phi_S \xi + g_3 \phi_S \xi') + \xi_0(g_4 \phi_S \phi_S + g_5 \xi \xi).$$

Equations which give vacuum structure of ϕ_T are given by:

$$\begin{aligned}
\frac{\partial w}{\partial \phi_{01}^T} &= M\phi_{T1} + \frac{2g}{3}\left(\phi_{T1}^2 - \phi_{T2}\phi_{T3}\right) = 0, \\
\frac{\partial w}{\partial \phi_{02}^T} &= M\phi_{T1} + \frac{2g}{3}\left(\phi_{T2}^2 - \phi_{T1}\phi_{T3}\right) = 0, \\
\frac{\partial w}{\partial \phi_{03}^T} &= M\phi_{T1} + \frac{2g}{3}\left(\phi_{T3}^2 - \phi_{T1}\phi_{T2}\right) = 0.
\end{aligned}$$

Solution of these equations can be given by: $\boxed{\langle \phi_T \rangle = (v_T, 0, 0)}$ where $v_T = -\frac{3M}{2g}$.

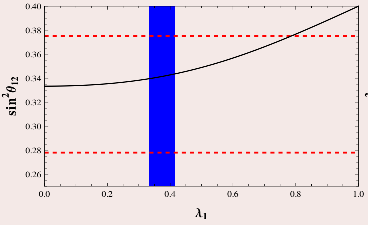
- Again, equations responsible for vacuum alignments of ϕ_S, ξ and ξ' are:

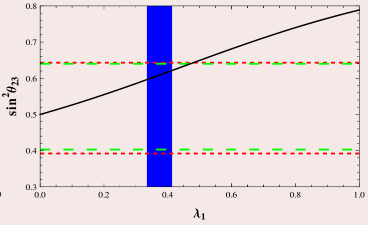
$$\begin{aligned}
\frac{\partial w}{\partial \phi_{01}^S} &= \frac{2g_1}{3}\left(\phi_{S1}^2 - \phi_{S2}\phi_{S3}\right) + g_2 \xi \phi_{S1} + g_3 \xi' \phi_{S3} = 0 \\
\frac{\partial w}{\partial \phi_{02}^S} &= \frac{2g_1}{3}\left(\phi_{S2}^2 - \phi_{S1}\phi_{S3}\right) + g_2 \xi \phi_{S3} + g_3 \xi' \phi_{S2} = 0 \\
\frac{\partial w}{\partial \phi_{03}^S} &= \frac{2g_1}{3}\left(\phi_{S3}^2 - \phi_{S1}\phi_{S2}\right) + g_2 \xi \phi_{S2} + g_3 \xi' \phi_{S1} = 0 \\
\frac{\partial w}{\partial \xi_0} &= g_4(\phi_{S1}^2 + 2\phi_{S2}\phi_{S3}) + g_5 \xi \xi = 0 \qquad (1)
\end{aligned}$$

From these equations we obtain $\boxed{\langle \phi_S \rangle = (v_S, v_S, v_S),\ \langle \xi \rangle = u \text{ and } \langle \xi' \rangle = u' \neq 0}$ with $v_S^2 = \frac{-g_5 u^2}{3 g_4}$ and $u' = \frac{-g_2 u}{g_3}$.

Non-zero θ_{13} and effect on other mixing angles

• Correlation plots: $\sin^2\theta_{12}$ vs α_1 $\sin^2\theta_{23}$ vs α_1





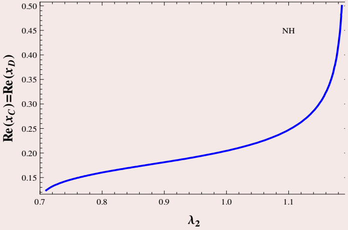
•Here, vertical blue patch indicates allowed value for α_1 corresponding to 3σ range of $\sin^2\theta_{13}$ and horizontal red dashed line represents 3σ allowed range for $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$

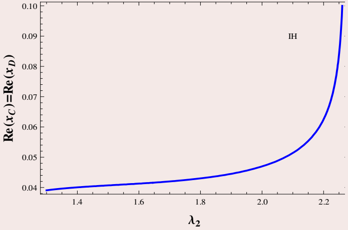
• Summary:

Range of λ_1 obtained from Fig.1	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$
$0.36 \lesssim \lambda_1 \lesssim 0.39$	0.341-0.342	0.604-0.614
$0.33 \lesssim \lambda_1 \lesssim 0.41$	0.339-0.343	0.595-0.620

Table : Allowed regions of $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$ obtained from Fig.2 for a restricted range of λ_1 (corresponding to Fig.1) in our set-up.

Allowed Region for the NLO couping constant:





$\lambda_1 = 0.37$ $\lambda_1 = 0.38$

For $Y_B = (8.79 \pm 0.20) \times 10^{-11}$.