A flavor model for cobimaximal neutrino mixing

FLASY 2022

9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

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Outline

- **Introduction:**

  ∗ Historically, neutrino oscillation data indicates that the lepton mixing matrix can be described by various mixing schemes at the zeroth order.

  ∗ Most of the proposed mixing schemes are outdated by data.

  ∗ Cobimaximal is still a viable option for recent fits to the neutrino oscillation data.

- **The set-up:**

  ∗ particle contents and symmetries

  ∗ light neutrino mass generated by Type-I see-saw

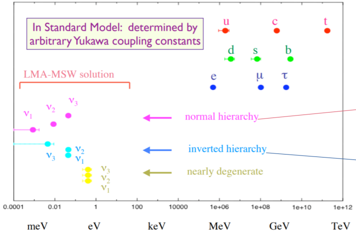
  ∗ parameters involved and their correlation

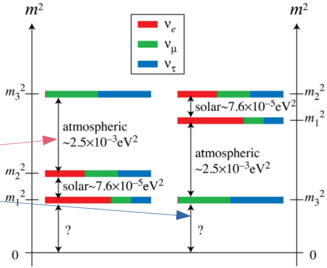
- **Leptogenesis:**

  Baryon asymmetry can be realized with NLO contribution to the neutrino Yukawa coupling

- **Conclusions**

Neutrino parameters and the known unknowns





	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

Flavor symmetries, why?

$$U_{PMNS} = \begin{pmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{13}S_{23}e^{i\delta} & C_{12}C_{23} - S_{12}S_{13}S_{23}e^{i\delta} & C_{13}S_{23} \\ S_{12}S_{23} - C_{12}S_{13}C_{23}e^{i\delta} & -C_{12}S_{23} - S_{12}S_{13}C_{23}e^{i\delta} & C_{13}C_{23} \end{pmatrix}$$

$\Downarrow$

(Prior to 2012)

$$\boxed{s_{23} = 1/\sqrt{2}\ (\theta_{23} = 45^\circ) \text{ and } \theta_{13} = 0}$$

$\Downarrow$

$$U_0 = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -\frac{s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}.$$

- $\theta_{12} = 45^\circ (s_{12} = 1/\sqrt{2})$ Bimaximal Mixing
- $\theta_{12} = 35.26^\circ (s_{12} = 1/\sqrt{3})$ Tribimaximal Mixing
- $\theta_{12} = 31.7^\circ$ Golden Ratio Mixing
- $\theta_{12} = 30^\circ (s_{12} = 1/2)$ Hexagonal Mixing

$$U_0 = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \frac{\varphi}{\sqrt{2+\varphi}} & \frac{1}{\sqrt{2+\varphi}} & 0 \\ \frac{-1}{\sqrt{4+2\varphi}} & \frac{\varphi}{\sqrt{4+2\varphi}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{4+2\varphi}} & \frac{-\varphi}{\sqrt{4+2\varphi}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{3}{4}} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Fukugita, Tanimoto, Yanagida PRD98; Harrison Perkins, Scott PLB02; Dutta,Ramond NPB03; Rodejohann et. al. EPJC10
(GR: $\tan\theta_{12} = 1/\phi$ where $\phi = (1+\sqrt{5})/2$)

Flavor symmetries, why?

- Using the diagonalization relation

$$m_\nu = U_0^\star \,\mathrm{diag}(m_1, m_2, m_3) U_0^\dagger ,$$

such a mixing matrices can easily diagonalize a $\mu - \tau$ symmetric (transformations $\nu_e \to \nu_e$, $\nu_\mu \to \nu_\tau$, $\nu_\tau \to \nu_\mu$ under which the neutrino mass term remains unchanged) neutrino mass matrix of the form

$$m_\nu = \begin{pmatrix} A & B & B \\ B & C & D \\ B & D & C \end{pmatrix} ,$$

With $A + B = C + D$ this matrix yields tribimaximal mixing pattern where $s_{12} = 1/\sqrt{3}$ *i.e.*, $\theta_{12} = 35.26^\circ$

$*$ Tribimaximal mixing pattern can be easily realize incorporating various discrete groups

Ma,Rajasekharan PRD64; Babu,Valle,Ma PLB512
Altarelli,Feruglio NPB741, Varzielas,King,Ross PLB648
....Many more...

Non-zero θ_{13}

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Bimaximal Mixing | Tribimaximal Mixing | Golden Ratio Mixing | Hexagonal Mixing

$$U_0 = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \frac{\varphi}{\sqrt{2+\varphi}} & \frac{1}{\sqrt{2+\varphi}} & 0 \\ \frac{-1}{\sqrt{4+2\varphi}} & \frac{\varphi}{\sqrt{4+2\varphi}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{4+2\varphi}} & \frac{-\varphi}{\sqrt{4+2\varphi}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{3}{4}} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Decendents of fixed pattern mixing schemes

Non-zero θ_{13}: Decendents of tribimaximal mixing

$$U_{TBM} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix},$$

$$|U_{\mathrm{TM}_1}| = \begin{pmatrix} \frac{2}{\sqrt{6}} & * & * \\ \frac{1}{\sqrt{6}} & * & * \\ \frac{1}{\sqrt{6}} & * & * \end{pmatrix} \qquad |U_{\mathrm{TM}_2}| = \begin{pmatrix} * & \frac{1}{\sqrt{3}} & * \\ * & \frac{1}{\sqrt{3}} & * \\ * & \frac{1}{\sqrt{3}} & * \end{pmatrix},$$

$$U_{\mathrm{TM}_1} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{c_\theta}{\sqrt{3}} & \frac{s_\theta}{\sqrt{3}} e^{-i\gamma} \\ -\frac{1}{\sqrt{6}} & \frac{c_\theta}{\sqrt{3}} - \frac{s_\theta}{\sqrt{2}} e^{i\gamma} & -\frac{s_\theta}{\sqrt{3}} e^{-i\gamma} - \frac{c_\theta}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{c_\theta}{\sqrt{3}} - \frac{s}{\sqrt{2}} e^{i\gamma} & -\frac{s_\theta}{\sqrt{3}} e^{-i\gamma} + \frac{c_\theta}{\sqrt{2}} \end{pmatrix}, U_{\mathrm{TM}_2} = \begin{pmatrix} \frac{2c_\theta}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{2s_\theta}{\sqrt{6}} e^{-i\gamma} \\ -\frac{c_\theta}{\sqrt{6}} + \frac{s}{\sqrt{2}} e^{i\gamma} & \frac{1}{\sqrt{3}} & -\frac{s_\theta}{\sqrt{3}} e^{-i\gamma} - \frac{c_\theta}{\sqrt{2}} \\ -\frac{c_\theta}{\sqrt{6}} + \frac{s}{\sqrt{2}} e^{i\gamma} & \frac{1}{\sqrt{3}} & -\frac{s_\theta}{\sqrt{3}} e^{-i\gamma} + \frac{c_\theta}{\sqrt{2}} \end{pmatrix}$$

Cobimaximal Mixing

- Predicts specific values for the atmospheric mixing angle $\theta_{23} = 45^\circ$ and Dirac CP phase $\delta = -90^\circ$.
- Still remains as good approximation for the observed neutrino oscillation data.
- The mixing matrix satisfy the condition :

$$|U_{\mu i}| = |U_{\tau i}| \quad \text{with } i = 1, 2, 3.$$

- the mass matrix leading to the above mixing matrix can be written as

$$m_\nu = \begin{pmatrix} a & b & b^\star \\ b & c & d \\ b^\star & d & c^\star \end{pmatrix},$$

where b and c are in general complex while c and d remain real.

Fukuura, Miura, Takasugi, Yoshimura PRD 99;
Miura, Takasugi, Yoshimura PRD01;
Harrison, Scott PLB02; Grimus, Lavoura PLB04
Babu, Ma, Valle, PLB03.. .. ..

Neutrino Mass Generation

- Dirac Mass: $m_D \overline{\nu_R} \nu_L$ + h.c.
- Majorana Mass: $\frac{1}{2} m_L \nu_L^T \mathcal{C}^\dagger \nu_L + \frac{1}{2} M_R \nu_R^T \mathcal{C}^\dagger \nu_R$ + h.c.

Type-I see-saw

$$\mathcal{L} = \frac{1}{2} \psi_L^T \mathcal{C}^\dagger M_\nu \psi_L + \text{h.c.},$$
$$\text{here } \psi_L = \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix} = \begin{pmatrix} \nu_L \\ \mathcal{C} \overline{\nu_R}^T \end{pmatrix}.$$

Mass matrix:

$$M_\nu = \begin{bmatrix} m_L & m_D^T \\ m_D & M_R \end{bmatrix}$$

with $m_L = 0$ and $m_D << M_R$,

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

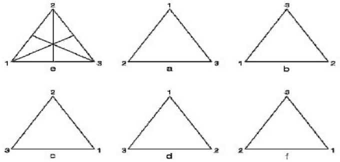
- For three generation case m_D, M_R are all $3X3$ matrices.
- Non-Abelian discrete groups have enough potential to explore these substructures.

- Non-Abelian discrete Groups:

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

Altarelli, Feruglio RMP10; Xing PR19;
Grimus, Ludl JPA 12; King, Luhn RPP13;
Ishimori, Kobayashi, Shimizu, Okada, Tanimoto PTPS10

Example 1- S_3 : Permutation group of three objects. It has $3! = 6$ elements.



An equilateral triangle can reproduce six elements of S_3. e is the identity element. Reflection transformations of e are given by a, b and c. d and f are from rotations.

Example 2- S_4 :

- Permutation group of four object.
- Geometrically S_4 is symmetry group of a tetrahedron.
- It has $4! = 24$ elements.

Example 3- A_4 :

- Even permutation group of four object.
- It has $4!/2 = 12$ elements.
- It is a subgroup of S_4.

A_4 group multiplication [arXiv:1002:0211]

- Discrete group A_4 has three 1D representation $1, 1', 1''$ and a irreducible 3D representation 3. Product of the singlet and triplets are given by

$$1 \otimes 1 = 1,\ 1' \otimes 1' = 1'',$$
$$1' \otimes 1'' = 1,$$
$$1'' \otimes 1'' = 1'\&$$
$$3 \otimes 3 = 1 \oplus 1' \oplus 1'' \oplus 3_a \oplus 3_s$$

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

$$\begin{aligned}
(A \times B)_1 &\backsim a_1 b_1 + a_2 b_2 + a_3 b_3, \\
(A \times B)_{1'} &\backsim a_1 b_1 + \omega^2 a_2 b_2 + \omega a_3 b_3, \\
(A \times B)_{1''} &\backsim a_1 b_1 + \omega a_2 b_2 + \omega^2 a_3 b_3, \\
(A \times B)_{3_s} &\backsim (a_2 b_3 + a_3 b_2, a_3 b_1 + a_1 b_3, a_1 b_2 + a_2 b_1), \\
(A \times B)_{3_a} &\backsim (a_2 b_3 - a_3 b_2, a_3 b_1 - a_1 b_3, a_1 b_2 - a_2 b_1),
\end{aligned}$$

here ω $(= e^{2i\pi/3})$ is the cube root of unity.

Cobimaximal : A flavor model

- Compatible mass matrix can take the form $m_\nu \sim \begin{pmatrix} a & b & b^\star \\ b & c & d \\ b^\star & d & c^\star \end{pmatrix}$
- Can you use discrete symmetry to reproduce this mixing scheme?
- Yes !! $\Delta(27)$ Herńandez, Varzielas PLB20
- Can we use A_4 ?

■ **Symmetries and Particle Content:** **Soon to be appear on arXiv**

	$\ell_{e,\mu,\tau}$	e_R, μ_R, τ_R	H	N_R	$\phi_{1,2,3}$	ξ	ϕ_S
A_4	$1, 1', 1''$	$1, 1'', 1'$	1	3	3	1	3
Z_3	1	1	1	ω^2	ω	ω^2	ω^2
Z_4	-i,-1,i	i,-1,- i	1	1	i,-1,- i	1	1

■ **Charged Leptons:**

$$-\mathcal{L}_{CL} = y_e(\bar{\ell}_e)_1 H(e_R)_1 + y_\mu(\bar{\ell}_\mu)_{1'} H(\mu_R)_{1''} + y_\tau(\bar{\ell}_\tau)_{1''} H(\mu_R)_{1'} + h.c.,$$

■ **Neutrinos:**

$$-\mathcal{L}_\nu = \frac{y_1}{\Lambda}\left(\bar{\ell_e}\right)_1 \tilde{H}\left(N_R\phi_1\right)_1 + \frac{y_2}{\Lambda}\left(\bar{\ell_\mu}\right)_{1'} \tilde{H}\left(N_R\phi_2\right)_{1''} + \frac{y_3}{\Lambda}\left(\bar{\ell_\tau}\right)_{1''} \tilde{H}\left(N_R\phi_3\right)_{1'}$$
$$+(y_x\xi + y_\phi\phi_S)\overline{N_R^c}N_R + h.c.$$

■ **Considered VEV alignment:**

$$\langle\phi_1\rangle = v_1(1,0,0),\ \langle\phi_2\rangle = v_1(0,1,0),\ \langle\phi_3\rangle = v_1(0,0,\omega),\ \langle\xi\rangle = v_\xi \text{ and } \langle\phi_S\rangle = (v_2, v_3, v_3).$$

Cobimaximal : A flavor model

■ **Charged Leptons** **Dirac Neutrinos** **Majorana Neutrinos**

$$m_\ell = \frac{v}{\sqrt{2}}\begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}; \quad m_D = \frac{y v v_1}{\sqrt{2}\Lambda}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix} = v Y_\nu^0; \quad M = \begin{pmatrix} p & q & q \\ q & p & s \\ q & s & p \end{pmatrix} = p\begin{pmatrix} 1 & \kappa_2 & \kappa_2 \\ \kappa_2 & 1 & \kappa_1 \\ \kappa_2 & \kappa_1 & 1 \end{pmatrix}$$

where we have considered $y_1 = y_2 = y_3 = y$ (say) and $p = 2y_x v_\xi$, $s = 2y_\phi v_2$, $q = 2y_\phi v_3$. Here $\kappa_1 = s/p$ and $\kappa_2 = q/p$ are two dimensionless quantities.

■ **Light neutrino mass via type-I seesaw:**

$$\begin{aligned} m_\nu &\sim -\, m_D M^{-1} m_D^T \\ &\sim \lambda \begin{pmatrix} 1-\kappa_1^2 & (\kappa_1\kappa_2-\kappa_2)\omega & (\kappa_1\kappa_2-\kappa_2)\omega^2 \\ (\kappa_1\kappa_2-\kappa_2)\omega & (1-\kappa_2^2)\omega^2 & \kappa_2^2-\kappa_1 \\ (\kappa_1\kappa_2-\kappa_2)\omega^2 & \kappa_2^2-\kappa_1 & (1-\kappa_2^2)\omega \end{pmatrix}; \end{aligned}$$

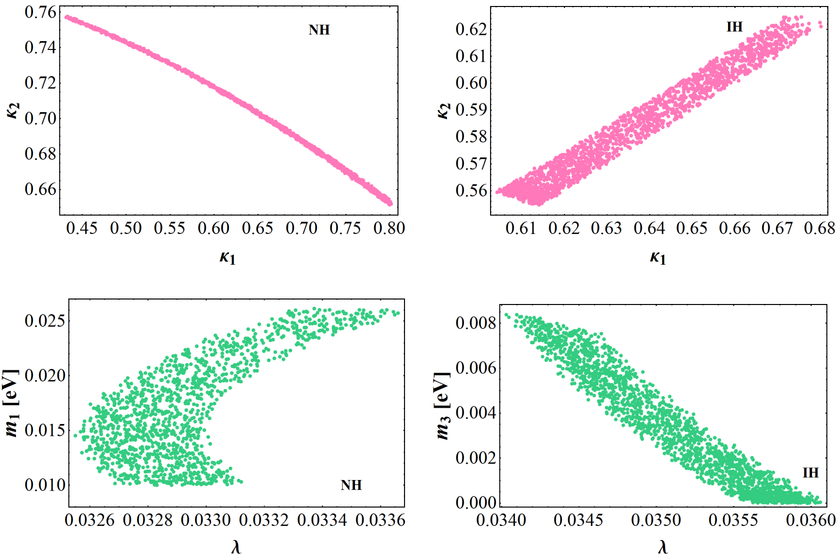
■ **Diagonalization**

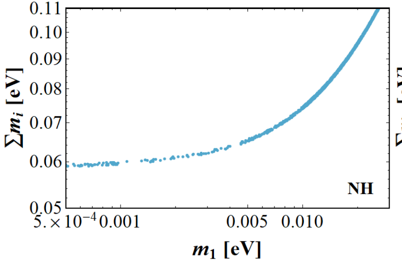
$$m_\nu = U^\star \mathrm{diag}(m_1, m_2, m_3) U^\dagger$$

$$U = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} = \begin{pmatrix} \cos\vartheta_{12}\cos\vartheta_{13} & -\sin\vartheta_{12}\cos\vartheta_{13} & -\sin\vartheta_{13} \\ \frac{\sin\vartheta_{12} - i\cos\vartheta_{12}\sin\vartheta_{13}}{\sqrt{2}} & \frac{\cos\vartheta_{12} + i\sin\vartheta_{12}\sin\vartheta_{13}}{\sqrt{2}} & -\frac{i\cos\vartheta_{13}}{\sqrt{2}} \\ \frac{\sin\vartheta_{12} + i\cos\vartheta_{12}\sin\vartheta_{13}}{\sqrt{2}} & \frac{\cos\vartheta_{12} - i\sin\vartheta_{12}\sin\vartheta_{13}}{\sqrt{2}} & \frac{i\cos\vartheta_{13}}{\sqrt{2}} \end{pmatrix}.$$

$$\delta = \arcsin\left[\frac{\mathrm{Im}[U_{23}U_{13}^\star U_{12}U_{22}^\star]}{\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}}\right] = -\pi/2; \quad \sin^2\theta_{23} = \frac{|U_{23}|^2}{1-|U_{13}|^2} = \frac{1}{2}$$

- Allowed regions for model parameters :




0.11
0.10
0.09
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0.05
$\sum m_i$ [eV]
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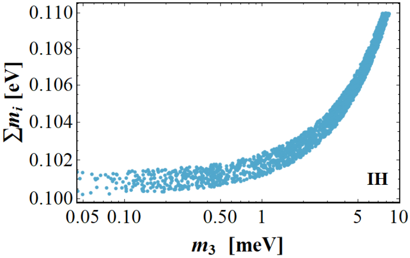
$5.\times10^{-4}$ 0.001
0.005 0.010
m_1 [eV]


0.110
0.108
0.106
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0.102
0.100
$\sum m_i$ [eV]
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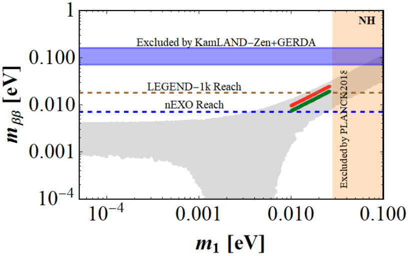
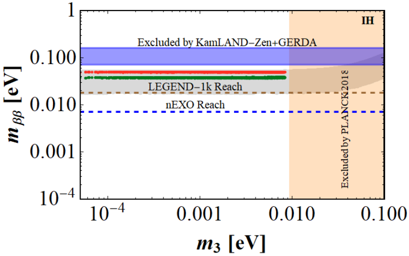
0.05 0.10 0.50 1 5 10
m_3 [meV]


1
0.100
0.010
0.001
10^{-4}
$m_{\beta\beta}$ [eV]
NH
Excluded by KamLAND−Zen+GERDA
LEGEND−1k Reach
nEXO Reach
Excluded by PLANCK2018
10^{-4} 0.001 0.010 0.100
m_1 [eV]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m_3 [eV]

Leptogenesis

- The presence of right handed neutrinos in the seesaw realization of light neutrino mass provides an opportunity to study leptogenesis from the CP-violating out-of-equilibrium decay of RH neutrinos into lepton and Higgs doublets in the early universe. Fukugita, Yanagida, 1986; Covi, Roulet, Vissani 9605319
- The CP asymmetry parameter :

$$\epsilon_i^\alpha = \frac{\Gamma(N_i \to \ell_\alpha H) - \Gamma(N_i \to \overline{\ell}_\alpha \bar{H})}{\Gamma(N_i \to \ell_\alpha H) + \Gamma(N_i \to \overline{\ell}_\alpha \bar{H})}$$

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

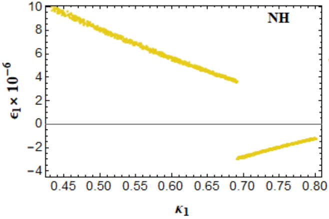
where the loop factor $f(x)$ in the above expression has been defined as follows

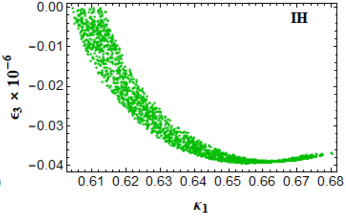
$$f(x) = \sqrt{x}\left[\frac{2-x}{1-x} - (1-x)\ln\left(1+\frac{1}{x}\right)\right]$$

with $x = m_i^2/m_j^2$.

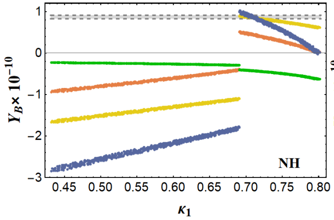
- CP asymmetry $\epsilon_i \propto \mathrm{Im}[(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{ij}^2] \Longrightarrow Y_\nu^\dagger Y_\nu \propto \mathrm{I} \Longrightarrow \epsilon_i \propto 0$
- NLO contribution in Dirac Yukawa $\Longrightarrow \ell_\alpha H \alpha_R \phi_i f f^\dagger/\Lambda^3 \Longrightarrow Y_\nu = Y_\nu^0 + \delta Y_\nu$

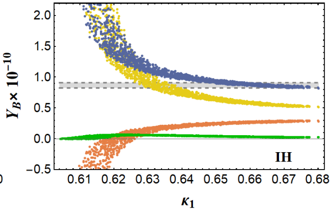
- Estimation of CP asymmetry :





- Estimation of Baryon asymmetry :





Conclusion

- Guided by the neutrino data : Various mixing schemes are proposed
- Neutrino oscillation data entered in the precision era.
- Cobimaximal mixing can accommodate current data.
- An predictive flavor symmetric set-up based on A_4 discrete symmetry
- Tiny neutrino mass is explained by type-I seesaw mechanism while matter-antimatter asymmetry is also addressed via leptogenesis.
- Leptogenesis becomes viable once higher order contribution to the Dirac Yukawa is considered.


Thank You
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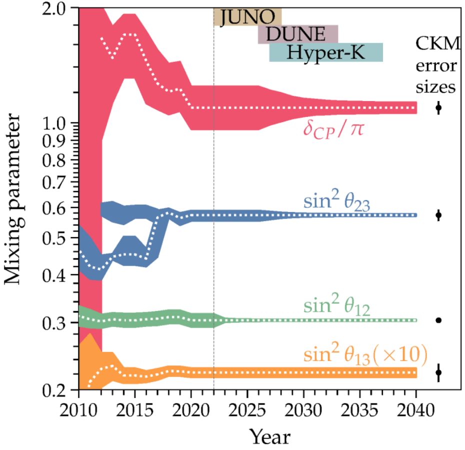
Current and future precision of neutrino experiments

Song, Li, Argüelles, Bustamante & Vincent [2021]



courtesy of Shirley Li

$$\sin^2\theta_{13} = |U_{13}|^2 = \sin^2\vartheta_{13} \tag{2}$$

$$\sin^2\theta_{12} = \frac{|U_{12}|^2}{1-|U_{13}|^2} = \sin^2\vartheta_{12} \tag{3}$$

$$\sin^2\theta_{23} = \frac{|U_{23}|^2}{1-|U_{13}|^2} = \frac{1}{2} \tag{4}$$

$$Y_B \approx \sum Y_{Bi} \tag{5}$$

where

$$Y_{Bi} \simeq -1.48 \times 10^{-3} \epsilon_i \eta_{ii}. \tag{6}$$

Y_{Bi}'s are coming from decay of each RH neutrinos and η_{ii} stands for efficiency factor [hep-ph/0310123] when $M_i < 10^{14}$ GeV,

$$\frac{1}{\eta_{ii}} \approx \frac{3.3 \times 10^{-3} \ \mathrm{eV}}{\tilde{m}_i} + \left(\frac{\tilde{m}_i}{0.55 \times 10^{-3} \ \mathrm{eV}} \right)^{1.16}, \tag{7}$$

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