



Leptogenesis Determined By Low Energy Parameters

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1. Matter- antiMatter Asymmetry in our Universe

2. Seesaw and Leptogenesis

3. Leptogenesis determined by Low Energy Physics

4. Model Predictions and Conclusions



Physics Letters B

Date: 1 October 1987

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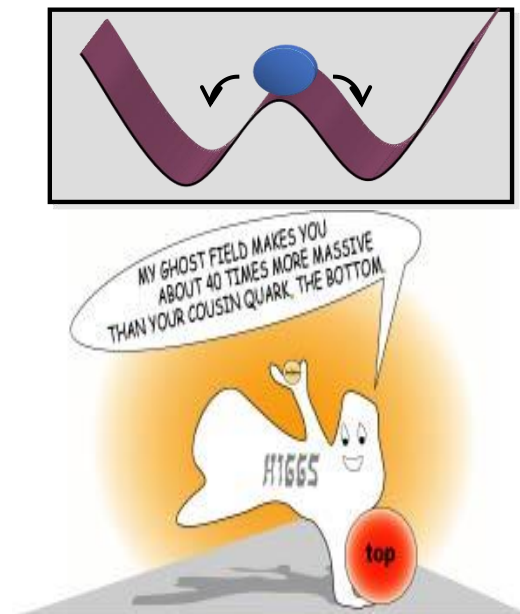
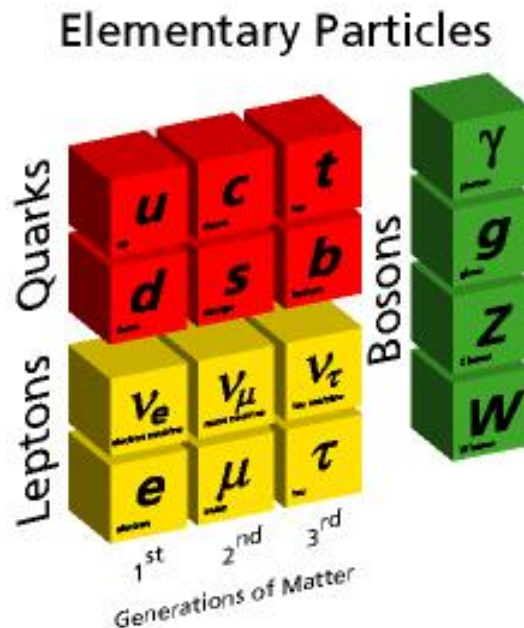
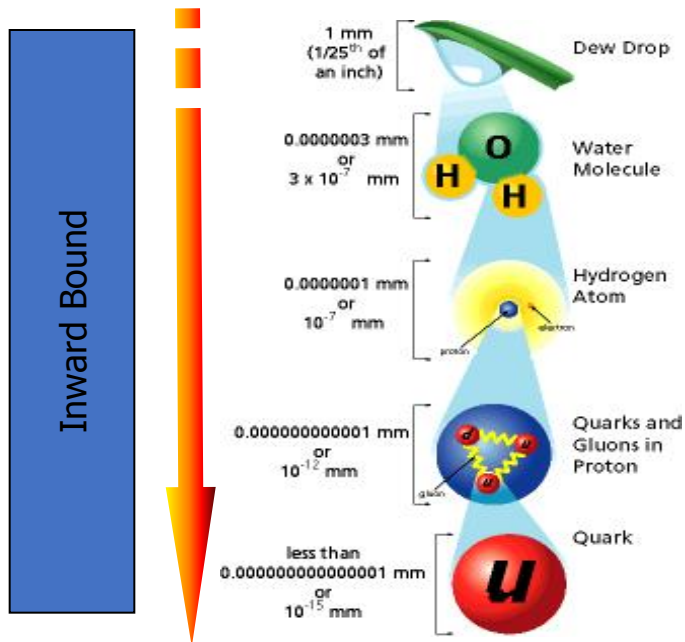
More actions

Particle Standard Model

-4-

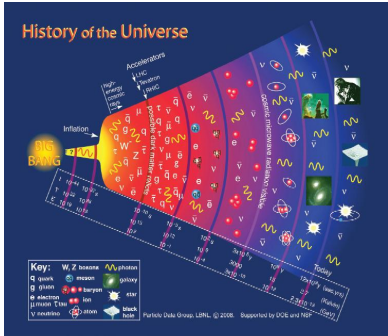
$$SU(3) \times SU(2) \times U(1)$$

Yang-Mills gauge theory for strong and electroweak interaction

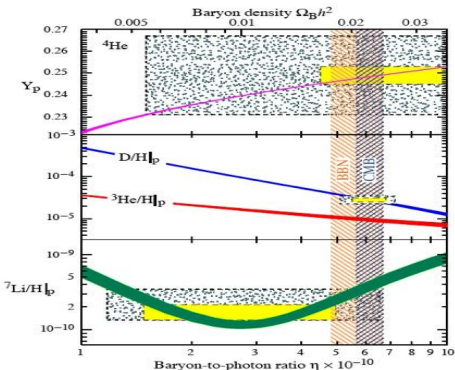
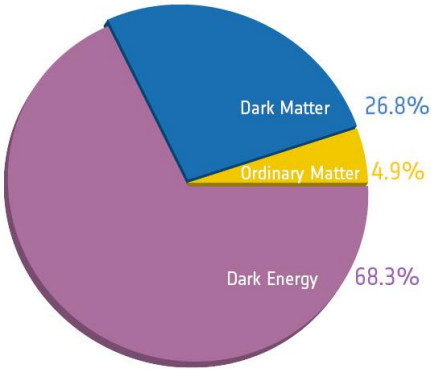
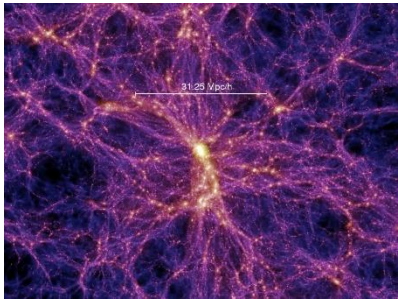
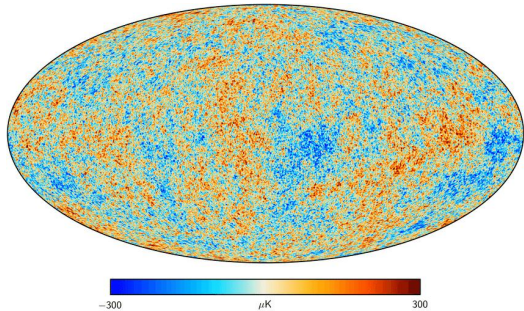


Cosmology Standard Model

Big-Ban Model + Inflation
General relativity with a non-zero cosmological constant



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



DM and DE

Matter- antiMatter Asymmetry

In our Universe, matter dominates over anti-matter

- Why this is so is the problem of Baryon Asymmetry of our Universe (BAU)

In cosmological terms, the problem is as follows

If initially, the universe is matter and anti-matter symmetric

$$n_B/n_\gamma = n_{\bar{B}}/n_\gamma \sim 10^{-20}$$

$n_B(n_{\bar{B}})$ - baryon (anti-baryon) number density, n_γ - photon number density

However observation, BBN and CMB, show that

$$\eta = (n_B - n_{\bar{B}})/n_\gamma \sim 6 \times 10^{-10}$$

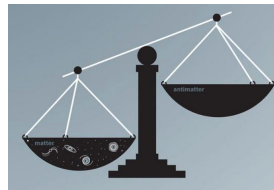
There is a 10^{10} order of magnitude difference.

Initially, there is a baryon asymmetry?

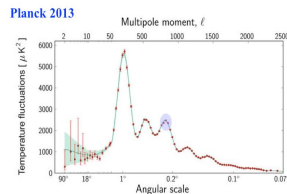
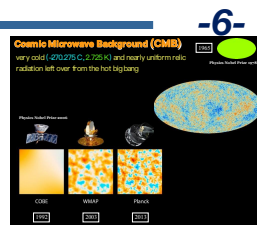
But inflation will dilute any asymmetry to zero.

Possible to generate a η which fits observation

from an, initially, matter anti-matter symmetry universe?



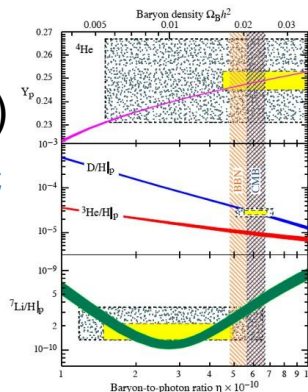
Andrei Sakharov on Soviet Nobel Peace Prize winners, the USSR stamp issued on 14 May 1991



Sakharov Conditions (1967)

**Baryon Number B Violation C
and CP Violation**

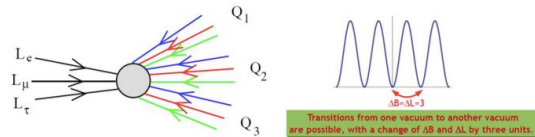
**Interactions Out Of Thermal
Equilibrium**



Standard Model Has All Ingredients, But Too Small a η_B

Baryon number violation: Sphaleron effects-tunneling effects from different vacuum states with non-zero baryon number differences.

Violated $B+L$, but conserves $B-L$.



C and CP violation: Electroweak interaction violates C, and phase in Kobayashi-Maskawa mixing matrix violates CP.

But, CP violation rate too small, out of thermal equilibrium too weak. Not enough to generate a large enough Baryon Asymmetry.

$\eta_B \sim 10^{-20}$ Too small. Needs to go beyond SM!

New physics beyond SM needed! Many possibilities.... Which one?

This talk, a case study of leptogenesis - parameters determined at low energy

Neutrino Mixing and Non-zero Neutrino Masses

$$\begin{pmatrix} \nu_1(0) \\ \nu_2(0) \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \end{pmatrix}$$

At $t=0$, neutrino $\nu_1(0)$ produced, at t , the state becomes

$$|\nu_1(0)\rangle = \cos \theta e^{-i(Et - p_1 L)} |\nu_{m1}\rangle - \sin \theta e^{-i(Et - p_2 L)} |\nu_{m2}\rangle.$$

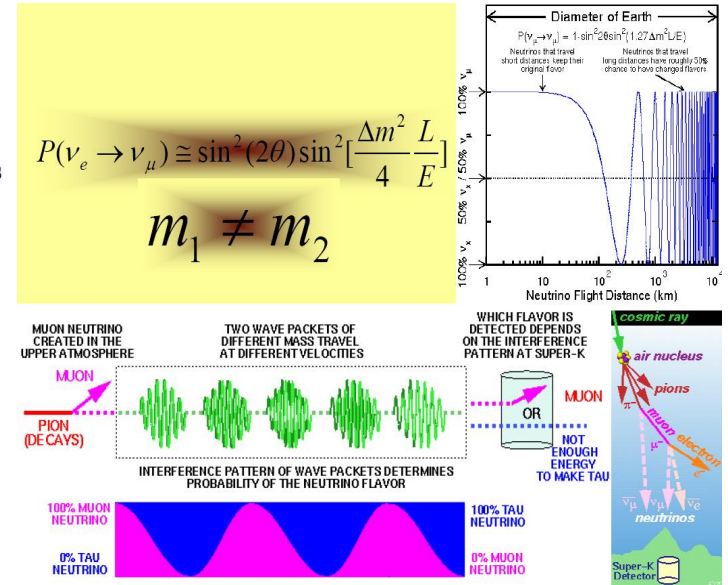
Using $t \approx L$ and $E - P_i = E - \sqrt{E^2 - m_i^2} \approx m_i^2/2E$, the probability amplitude of find $\nu_2(0)$ at time t is given by

$$\langle \nu_2(0) | \nu_1(t) \rangle = \cos \theta \sin \theta (e^{-im_1^2 L/2E} - e^{-im_2^2 L/2E})$$

which leads to the probability of finding $\nu_2(0)$ is

$$P(\nu_1 \rightarrow \nu_2) = |\langle \nu_1(0) | \nu_2(t) \rangle|^2 = \sin^2(2\theta) \sin^2(\Delta m_{21}^2 L/4E),$$

$$\Delta m_{21}^2 = m_2^2 - m_1^2.$$



Need mixing and non-zero mass to have oscillation!

Active neutrinos mix with each other and have non-zero masses!
Must go beyond SM to have neutrino masses!

How To Generate Masses For Neutrinos?

Neutrinos have small mass, they mix with each other

There may be additional light sterile neutrinos

Electrically neutral, has the possibility of being its own anti-particle, Majorana particle. Dirac or Majorana particle?

To have Dirac mass, need to introduce right handed neutrinos ν_R : (1,1)(0)

Dirac neutrino mass term

$$L = -\bar{L}_L Y_\nu \tilde{H} \nu_R + H.C, \rightarrow -\bar{\nu}_L m_\nu \nu_R, \rightarrow m_\nu = \frac{v}{\sqrt{2}} Y_\nu$$
$$m_{\nu_e} < 0.3 \text{ eV}, \rightarrow Y_{\nu_e}/Y_e < 10^{-5}, \text{ very much fine tuned!}$$



Majorana Masses For Neutrinos?

Neutrino is its own anti-particle, particle and anti-particle to pair up for mass terms

The Seesaw Mechanism $L = \bar{\nu}_L(Y_\nu v/\sqrt{2})\nu_R + \bar{\nu}_R^c M_R \nu_R/2$

The Seesaw mechanism refers to the neutrino mass matrix of the form

$$L_m = -\frac{1}{2}(\nu_L^c, \nu_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}.$$

For one generation, if $M_R \gg m_D$, the eigenmasses are

$$m_\nu \approx -m_D M_R^{-1} m_D^T, \quad m_N \approx M_R$$

A very nice way to explain why light neutrino masses are so much lighter than their charged lepton partners.

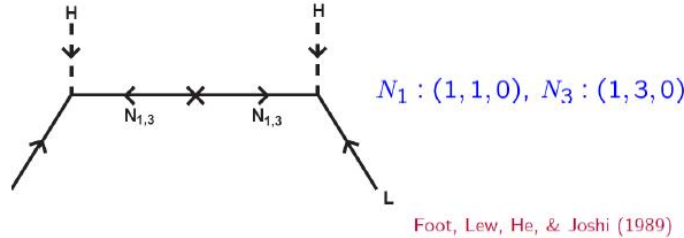
(Minkowski (1977); Gell-Mann, Ramond, and Slansky (1979); Yanagida (1979); Glashow (1980); Mohapatra and Senjanovic(1980))



Majorana Neutrinos and Seesaw Mechanism

Type (I,III) seesaw

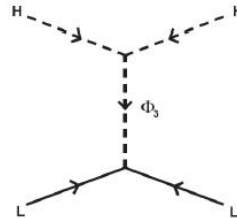
Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, & Slansky (1980)
Mohapatra & Senjanovic (1980)



Foot, Lew, He, & Joshi (1989)

Type II seesaw

Mohapatra & Senjanovic (1980)
Schechter & Valle (1980)
Lazarides, Shafi, & Wetterich (1981)



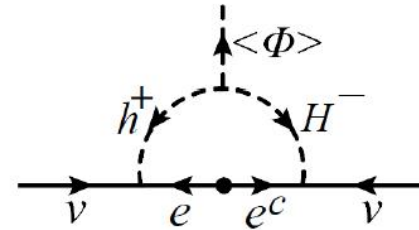
$\Phi_3 : (1, 3, +1)$

$$\mathcal{L}_{\text{eff}} = \frac{LLHH}{M} \Rightarrow m_\nu \sim \frac{v^2}{M}$$

Provide understand why neutrino masses are small
but no information about mixing! May provide some
understadning of BAU because lepton number violation?

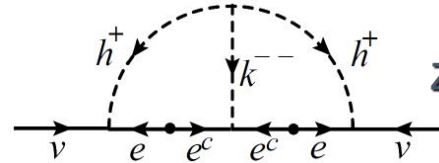
Loop generation neutrino masses

Zee, 1980



Simplest model ruled out
XG He, EPJC34(2004)371

Zee, 1985, Babu 1988



Seesaw and leptogenesis

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Fukugita and Yanagida, PLB174, 45(1986)

Neutrino have Majorana mass, violate lepton number by two units!

Translate lepton number asymmetry generated to baryon number asymmetry!

Requires lepton asymmetry generated before Sphaleron effects to be in effective
($T \sim 10^{12}$ – a few TeV).

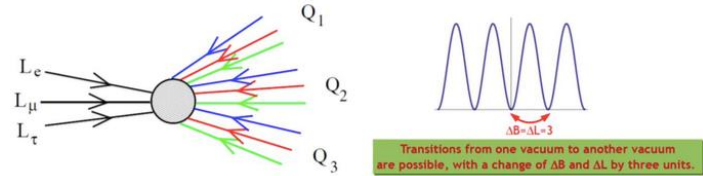
Initial: $a_L(i)=a$, $a_B(i)=0$.

Sphelaron effect: Conserve B-L, but violates B+L

After: $a_L(f)+a_B(f) = 0$, $a_L(i) - a_B(i) = a_L(f) - a_B(f)$

$a_L(f) = a/2$; $a_B(f) = -a/2$

half of initial lepton asymmetry will be translated into baryon asymmetry if complete.



SM Sphaleron effect: $a_B = - (28/79)a_L$ **Generating a none-zero a_L ?**

Seesaw model plays the right role

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$$L = \bar{\nu}_L (Y_\nu v / \sqrt{2}) \nu_R + \bar{\nu}_R^c M_R \nu_R / 2$$

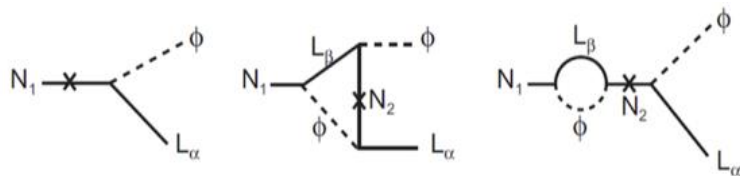
The last term violates lepton number L by two units!

Out of thermal equilibrium decay, new CP violation in $N \rightarrow L h(\phi)$

In M_R diagonalized basis, new CP sources in Y_ν

N decays into L and anti-L differently

$$a_i \approx -\frac{1}{8\pi} \frac{1}{[\hat{Y}_\nu \hat{Y}_\nu^\dagger]_{ii}} \sum_j \text{Im}\{[\hat{Y}_\nu \hat{Y}_\nu^\dagger]_{ij}^2\} f\left(\frac{M_j^2}{M_i^2}\right)$$



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

Sphelaron effect translate lepton number to baryon number;

New CP violation sources in Y_ν and also M_R ;

Out of thermal equilibrium heavy neutrino decay.

Can explain Matter - antiMatter asymmetry, but not much predictions can be made!

Can predictive leptogenesis model work, all parameters determined at low energies?

Leptogenesis determined by Low Energy Physics

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M_D and M_R arbitrary, now predictions can be made.

Efforts have been made **The Seesaw Mechanism** $L = \bar{\nu}_L (Y_\nu v / \sqrt{2}) \nu_R + \bar{\nu}_R^c M_R \nu_R / 2$

to make M_R to be expressed in terms of known low energy parameters:

$M_{u,d,e}, V_{KM}, V_{PMNS} \dots$

The Seesaw mechanism refers to the neutrino mass matrix of the form

$$L_m = -\frac{1}{2} (\nu_L^c, \nu_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}.$$

For one generation, if $M_R \gg m_D$, the eigenmasses are

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A very nice way to explain why light neutrino masses are so much lighter than their charged lepton partners.



X-G He, S. Low and R Volkas, PRD 78 (2008) 113001

$$M_R \simeq \hat{m}_{d,u} U_{PMNS}^* \hat{m}_\nu^{-1} U_{PMNS}^\dagger \hat{m}_{d,u}$$

$$M_R \simeq \hat{m}_d U_{CKM}^T \hat{m}_\nu^{-1} U_{CKM} \hat{m}_d$$

$$M_R \simeq \hat{m}_e U_{PMNS}^* \hat{m}_\nu^{-1} U_{PMNS}^\dagger \hat{m}_e$$

Example: A GUT model to realize: $M_R \simeq \hat{m}_u U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_u$

PHYSICAL REVIEW D **78**, 113001 (2008)

Determining the heavy seesaw neutrino mass matrix from low-energy parameters

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(Received 13 October 2008; published 2 December 2008)

We explore how the seesaw sector in neutrino mass models may be constrained through symmetries to be completely determined in terms of low-energy mass, mixing angle and CP -violating phase observables.

A. Relating m_ν^D to $\hat{m}_u$ via a flipped $SU(5)$ model

We consider a flipped $SU(5)$ group [14] augmented by A_4 flavor symmetry [22,23]:

$$G_1 = SU(5) \otimes U(1)_X \times A_4, \quad (4.1)$$

$$\supset SU(3)_c \otimes SU(2)_L \otimes \underbrace{U(1)_T \otimes U(1)_X}_{U(1)_Y} \times A_4, \quad (4.2)$$

$$\psi_{L\alpha} = \begin{pmatrix} u_R^{1c} \\ u_R^{2c} \\ u_R^{3c} \\ e_L \\ -\nu_L \end{pmatrix} \sim (\bar{5}, -3)(\underline{3});$$

$$\chi_L^{\alpha\beta} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & d_R^{3c} & -d_R^{2c} & -u_L^1 & -d_L^1 \\ -d_R^{3c} & 0 & d_R^{1c} & -u_L^2 & -d_L^2 \\ d_R^{2c} & -d_R^{1c} & 0 & -u_L^3 & -d_L^3 \\ u_L^1 & u_L^2 & u_L^3 & 0 & -\nu_R^c \\ d_L^1 & d_L^2 & d_L^3 & \nu_R^c & 0 \end{pmatrix} \sim (10, 1)(\underline{1} \oplus \underline{1}' \oplus \underline{1}''); \quad e_R^c \sim (1, 5)(\underline{1} \oplus \underline{1}' \oplus \underline{1}'');$$

$$\Phi_{(3)}^\sigma = \begin{pmatrix} h_{1d} \\ h_{2d} \\ h_{3d} \\ \phi_{(3)}^{0*} \\ -\phi_{(3)}^+ \end{pmatrix} \sim (5, -2)(\underline{3}); \quad \Phi_{(\underline{1} \oplus \underline{1}' \oplus \underline{1}'')}^\sigma \sim (5, -2)(\underline{1} \oplus \underline{1}' \oplus \underline{1}''); \quad \Delta^{\alpha\beta\gamma\delta} \sim (\bar{50}, 2)(\underline{1} \oplus \underline{1}' \oplus \underline{1}''),$$

$$\begin{aligned}
-\mathcal{L} &= Y_{\lambda 1} \bar{\psi}_L \Phi_{(3)}^* e_R + \sqrt{2} Y_{\lambda 2} \bar{\psi}_L \chi_L^c \Phi_{(3)} \\
&\quad + \frac{Y_{\lambda 3}}{4} (\bar{\chi}_L)_{\alpha\beta} (\chi_L^c)_{\gamma\delta} (\Phi_{(1\oplus 1' \oplus 1'')}^*)_{\sigma} \epsilon^{\alpha\beta\gamma\delta\sigma} \\
&\quad + Y_{\lambda 4} (\bar{\chi}_L)_{\alpha\beta} (\chi_L^c)_{\gamma\delta} \Delta^{\alpha\beta\gamma\delta} + \text{H.c.}, \\
\langle \bar{\bar{\phi}}_{(3)}^0 \rangle &\equiv \langle \bar{\phi}_{(3)}^{0*} \rangle = (\mathbf{v}_{(3)}, \mathbf{v}_{(3)}, \mathbf{v}_{(3)})
\end{aligned}$$

Neutral components

$$\begin{aligned}
&Y_{\lambda 1} \bar{e}_L \langle \phi_{(3)}^0 \rangle e_R - Y_{\lambda 2} (\bar{u}_L \langle \phi_{(3)}^{0*} \rangle u_R + \bar{\nu}_L \langle \phi_{(3)}^{0*} \rangle \nu_R) \\
&\quad + \frac{Y_{\lambda 3}}{2} (\bar{d}_R^c d_L^c + \bar{d}_L d_R) \langle \phi_{(1\oplus 1' \oplus 1'')}^0 \rangle \\
&\quad + Y_{\lambda 4} \bar{\nu}_R^c \nu_R \langle \Delta_{(1\oplus 1' \oplus 1'')}^0 \rangle + \text{H.c.}.
\end{aligned}$$

$$m_e: \lambda_1 (\bar{e}_L \langle \phi_{(3)}^0 \rangle)_{\underline{1}} e_R + \lambda'_1 (\bar{e}_L \langle \phi_{(3)}^0 \rangle)_{\underline{1}'} e_R'' + \lambda''_1 (\bar{e}_L \langle \phi_{(3)}^0 \rangle)_{\underline{1}''} e_R' + \text{H.c.};$$

$$m_u: -\lambda_2 \bar{u}_L (\langle \phi_{(3)}^{0*} \rangle u_R)_{\underline{1}} - \lambda'_2 \bar{u}_L'' (\langle \phi_{(3)}^{0*} \rangle u_R)_{\underline{1}'} - \lambda''_2 \bar{u}_L' (\langle \phi_{(3)}^{0*} \rangle u_R)_{\underline{1}''} + \text{H.c.};$$

$$m_\nu^D: -\lambda_2 (\bar{\nu}_L \langle \phi_{(3)}^{0*} \rangle)_{\underline{1}} \nu_R - \lambda'_2 (\bar{\nu}_L \langle \phi_{(3)}^{0*} \rangle)_{\underline{1}'} \nu_R'' - \lambda''_2 (\bar{\nu}_L \langle \phi_{(3)}^{0*} \rangle)_{\underline{1}''} \nu_R' + \text{H.c..}$$

$$m_e = U_\omega \hat{m}_e; \quad m_u = -\hat{m}_u U_\omega; \quad m_\nu^D = -U_\omega \hat{m}_u;$$

$$U_\omega = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix}$$

$$\hat{m}_{e,u} = \text{diag}(\sqrt{3}\lambda_{1,2}v_{(3)}, \sqrt{3}\lambda'_{1,2}v_{(3)}, \sqrt{3}\lambda''_{1,2}v_{(3)}).$$

$$V_{eL}^\dagger = U_\omega, \quad V_{uL}^\dagger = V_{eR} = I, \quad V_{uR} = -U_\omega, \quad m_\nu^D = -V_{eL}^\dagger \hat{m}_u.$$

$$\hat{m}_\nu \simeq V_\nu m_\nu^D M_R^{-1} (m_\nu^D)^T V_\nu^T.$$

$$\begin{aligned} \hat{m}_\nu &\simeq V_\nu V_{eL}^\dagger \hat{m}_u M_R^{-1} (V_{eL}^\dagger \hat{m}_u)^T V_\nu^T \\ &= U_{\text{PMNS}}^\dagger \hat{m}_u M_R^{-1} \hat{m}_u U_{\text{PMNS}}^*, \end{aligned}$$

$$M_R \simeq \hat{m}_u U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_u.$$

M_R is completely determined by low energy physics inputs
 m_ν and M_R are rank 3 matrices.

Sample solutions using most recent inputs for Model A

IC24 with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 5.9$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$
$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$
$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.014}$	$0.435 \rightarrow 0.584$	$0.550^{+0.013}_{-0.016}$	$0.439 \rightarrow 0.584$
$\theta_{23}/^\circ$	$43.29^{+0.96}_{-0.79}$	$41.27 \rightarrow 49.86$	$47.90^{+0.73}_{-0.92}$	$41.51 \rightarrow 49.83$
$\sin^2 \theta_{13}$	$0.02248^{+0.00055}_{-0.00059}$	$0.02064 \rightarrow 0.02418$	$0.02262^{+0.00057}_{-0.00056}$	$0.02093 \rightarrow 0.02441$
$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	$8.26 \rightarrow 8.95$	$8.65^{+0.11}_{-0.11}$	$8.32 \rightarrow 8.99$
$\delta_{CP}/^\circ$	212^{+26}_{-36}	$125 \rightarrow 365$	274^{+22}_{-25}	$203 \rightarrow 335$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.823$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.822$
$\frac{\Delta m_{3l}^2}{10^{-3} \text{ eV}^2}$	$+2.511^{+0.021}_{-0.020}$	$+2.450 \rightarrow +2.576$	$-2.483^{+0.020}_{-0.020}$	$-2.547 \rightarrow -2.421$

Quark masses at scale m_Z

$$m_t = 172.1;$$

$$m_c = 3.7 * 10^{-3} * m_t;$$

$$m_u = 2.2 * 10^{-3} * m_c;$$

No Majorana phase case

NO: MR, Mi (GeV)

$$m_{\nu 1} = 10^{-3} \text{ eV}$$

$$\begin{pmatrix} 1.3345 \times 10^6 + 456.629 \text{ i} & -2.39867 \times 10^8 - 3.39607 \times 10^7 \text{ i} & 8.95408 \times 10^{10} - 9.74346 \times 10^9 \text{ i} \\ -2.39867 \times 10^8 - 3.39607 \times 10^7 \text{ i} & 4.84425 \times 10^{10} + 1.19671 \times 10^{10} \text{ i} & -1.68088 \times 10^{13} - 5.3156 \times 10^{11} \text{ i} \\ 8.95408 \times 10^{10} - 9.74346 \times 10^9 \text{ i} & -1.68088 \times 10^{13} - 5.3156 \times 10^{11} \text{ i} & 6.43154 \times 10^{15} - 1.29007 \times 10^{15} \text{ i} \end{pmatrix}$$

$$\{498157., 1.44922 \times 10^{10}, 7.45365 \times 10^{15}\}$$

IO: MR, Mi (GeV)

$$m_{\nu 1} = 10^{-3} \text{ eV}$$

$$\begin{pmatrix} -16946.3 - 6178.04 \text{ i} & 6.73963 \times 10^6 - 9.95557 \times 10^7 \text{ i} & 1.66143 \times 10^9 - 2.43123 \times 10^{10} \text{ i} \\ 6.73963 \times 10^6 - 9.95557 \times 10^7 \text{ i} & 2.20666 \times 10^{11} + 1.2827 \times 10^7 \text{ i} & 5.24977 \times 10^{13} + 2.33634 \times 10^9 \text{ i} \\ 1.66143 \times 10^9 - 2.43123 \times 10^{10} \text{ i} & 5.24977 \times 10^{13} + 2.33634 \times 10^9 \text{ i} & 1.32363 \times 10^{16} + 3.76133 \times 10^{11} \text{ i} \end{pmatrix}$$

$$\{28349.9, 1.24781 \times 10^{10}, 1.3237 \times 10^{16}\}$$

Model A

$$M_R \simeq \hat{m}_u U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_u \quad G_1 = SU(5) \otimes U(1)_X \times A_4$$

Model B

$$M_R \simeq \hat{m}_d U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_d \quad \begin{aligned} G_2 &= G_{q\ell} \times A_4 \times Z_2 , \\ &= \underbrace{SU(3)_\ell \otimes SU(3)_q}_{Z_{QL}} \otimes SU(2)_L \otimes U(1)_X \times A_4 \times Z_2 , \\ &\supset (SU(2)_\ell \otimes U(1)_T) \otimes SU(3)_q \otimes SU(2)_L \otimes U(1)_X \times A_4 \times Z_2 \end{aligned}$$

Model C

$$M_R \simeq \hat{m}_e U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_e \quad G_3 = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \times A_4$$

Model Predictions and Conclusions

Seesaw Lagrangian $-\mathcal{L} \supset \overline{L_{L,\alpha}}(Y_e)_\alpha \Phi E_{R,\alpha} + h_{\alpha i} \overline{L_{L,\alpha}} \tilde{\Phi} N_{R,i} + \frac{1}{2} \overline{N_{R,i}^c} (M_R)_{ij} N_{R,j} + \text{h.c.}$

$L_{L,\alpha} = (\nu_{L,\alpha}, e_{L,\alpha})^T$ are the lepton doublets, $E_{R,\alpha} \equiv e_{R,\alpha}$ represent the charged lepton

$\Phi = (\phi^+, \phi^0)^T$, where $\tilde{\Phi} = i\sigma_2 \Phi^*$

Φ the Higgs doublet. Rotated in the basis where having vev alone ($\Rightarrow (v + \phi^0)/\sqrt{2}$, other components are much heavier). $v = 242$ GeV, h Yukawa coupling:

In the basis, $\bar{m}_\nu^D = hv/\sqrt{2}$

$$\varepsilon_{\alpha\beta}^{(i)} = \frac{3}{32\pi (\tilde{h}^\dagger \tilde{h})_{ii}} \sum_{j \neq i} \left\{ i [\tilde{h}_{\alpha i} \tilde{h}_{\beta j}^* (\tilde{h}^\dagger \tilde{h})_{ji} - \tilde{h}_{\beta i} \tilde{h}_{\alpha j} (\tilde{h}^\dagger \tilde{h})_{ij}] \frac{\xi(x_{ji})}{\sqrt{x_{ji}}} + \frac{2i}{3(x_{ji} - 1)} [\tilde{h}_{\alpha i} \tilde{h}_{\beta j}^* (\tilde{h}^\dagger \tilde{h})_{ij} - \tilde{h}_{\beta i} \tilde{h}_{\alpha j} (\tilde{h}^\dagger \tilde{h})_{ji}] \right\}$$

$$U_R^T M_R U_R = \hat{M}_R \equiv \text{Diag}(M_1, M_2, M_3)$$

$$\tilde{m}_\nu^D = \bar{m}_\nu^D U_R, \quad \tilde{h} = h U_R.$$

$x_{ji} \equiv M_j^2/M_i^2$, and the function $\xi(x)$ is defined as

CP violating lepton number violation is given by

$$\xi(x) = \frac{2}{3}x \left[(1+x) \ln\left(\frac{1+x}{x}\right) - \frac{2-x}{1-x} \right].$$

Evolution of lepton number violation

Boltzmann Equation In the density matrix formalism, the $B - L$ asymmetry is represented by a 3×3 matrix in the charged lepton mass basis. Its diagonal entries describe the flavor asymmetries, while the off-diagonal entries encode flavor coherence. The abundance of the heavy RH Majorana neutrinos N_i satisfies the evolution equations [35]

$$\frac{dN_{N_i}}{dz} = -\frac{M_i}{M_1} D_i(z) (N_{N_i} - N_{N_i}^{\text{eq}}), \quad (3.5)$$

with a dimensionless $N_X \equiv n_X V_c = n_X / n_{N_i}^{\text{eq}} (T \gg M_i)$ denoting the number of X particles (with $X = N_i$), or the amount of $B - L$ charge asymmetry, in a co-moving volume V_c . As a convention, that volume is chosen such that it contains one ultra-relativistic RH neutrino in thermal equilibrium, meaning that $V_c n_{N_i}^{\text{eq}} (T \gg M_i) = 1$, where n_X is the number density. The density matrix evolves as

$$\begin{aligned} \frac{dN_{B-L}^{\alpha\beta}}{dz} = & \sum_{i=1,2,3} \left[\varepsilon_{\alpha\beta}^{(i)} \frac{M_i}{M_1} D_i(z) (N_{N_i} - N_{N_i}^{\text{eq}}) - \frac{1}{2} \frac{M_i}{M_1} W_i(z) \{P^{0(i)}, N_{B-L}^{\text{spec}}\}_{\alpha\beta} \right] \\ & - \sum_{\ell=e,\mu,\tau} \frac{\text{Im}(\Lambda_\ell)}{H(z)z} [\lambda_\ell, [\lambda_\ell, N_{B-L}]]_{\alpha\beta}, \end{aligned} \quad (3.6)$$

Final Baryon Asymmetry After solving the Boltzmann equations in Eqs. (3.5) and (3.6), the final $B - L$ asymmetry is obtained from

$$N_{B-L}^f = \text{Tr} [N_{B-L}(z_f)], \quad (3.12)$$

where the trace sums over the flavor components after the evolution. The corresponding the baryon-to-photon ratio η_B is then related to N_{B-L}^f through the sphaleron process [14, 35, 48]

$$\eta_B = a_{\text{sph}} \frac{N_{B-L}^f}{N_{\gamma}^{\text{rec}}} \simeq 9.6 \times 10^{-3} N_{B-L}^f, \quad (3.13)$$

S. Blanchet, P. Di Bari, D.A. Jones and L. Marzola, *Leptogenesis with heavy neutrino flavours: from density matrix to Boltzmann equations*, *JCAP* **01** (2013) 041 [1112.4528].

$$D_i(z) = K_i z \frac{M_i}{M_1} \frac{\mathcal{K}_1[(M_i/M_1)z]}{\mathcal{K}_2[(M_i/M_1)z]}, \quad W_i(z) = \frac{1}{4} K_i z^3 \left(\frac{M_i}{M_1} \right)^3 \mathcal{K}_1[(M_i/M_1)z],$$

$$K_i \equiv \frac{\Gamma_i + \bar{\Gamma}_i}{H(T = M_i)} = \frac{\tilde{m}_i}{m_*},$$

Taking spectator and sphaleron effect into account,

Applied to our models

There are considerable information for quark and lepton masses and mixing, taking them as known input numbers,

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ -s_{12}s_{23} + c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}s_{23} + s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix} \quad \begin{array}{lll} \text{NO : } m_1 = m_{\text{lightest}} , & m_2 = \sqrt{m_1^2 + \Delta m_{21}^2} , & m_3 = \sqrt{m_1^2 + \Delta m_{31}^2} , \\ \text{IO : } m_3 = m_{\text{lightest}} , & m_1 = \sqrt{m_3^2 + |\Delta m_{31}^2|} , & m_2 = \sqrt{m_3^2 + |\Delta m_{32}^2|} . \end{array}$$

$$\theta_{12} = 33.76^\circ , \quad \theta_{13} = 8.62^\circ \text{ (} 8.65^\circ \text{)} , \quad \theta_{23} = 43.27^\circ \text{ (} 48.15^\circ \text{)}$$

$$\Delta m_{31(2)}^2 = 2.521 \text{ (} -2.500 \text{)} \times 10^{-3} \text{ eV}^2 , \quad \Delta m_{21}^2 = 7.537 \times 10^{-5} \text{ eV}^2$$

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J.P. Pinheiro and T. Schwetz, *NuFit-6.0: updated global analysis of three-flavor neutrino oscillations*, [JHEP](#) **12** (2024) 216 [[2410.05380](#)].

NuFit-6.1 (2025), [www.nu-fit.org](#), .

Unknowns are lightest neutrino mass m_{lightest} , CP violating Dirac phase δ_{CP} and the two Majorana phases α and β .

Scan the parameter space to find η_B around 6.8×10^{-10}

Model A

$$M_R \simeq \hat{m}_u U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_u$$

No solutions for both NO and IO.

Model B

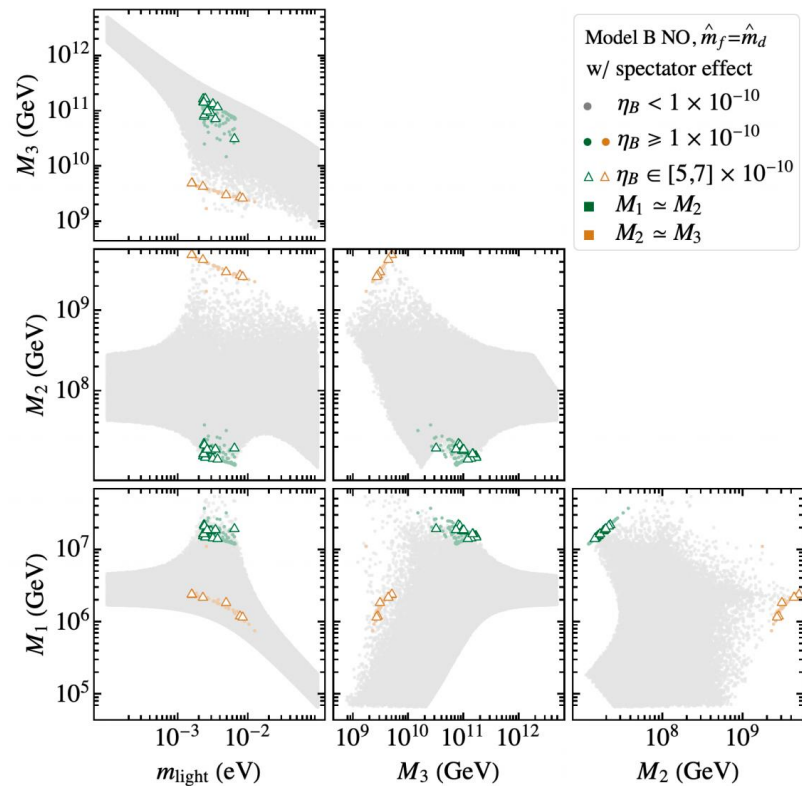
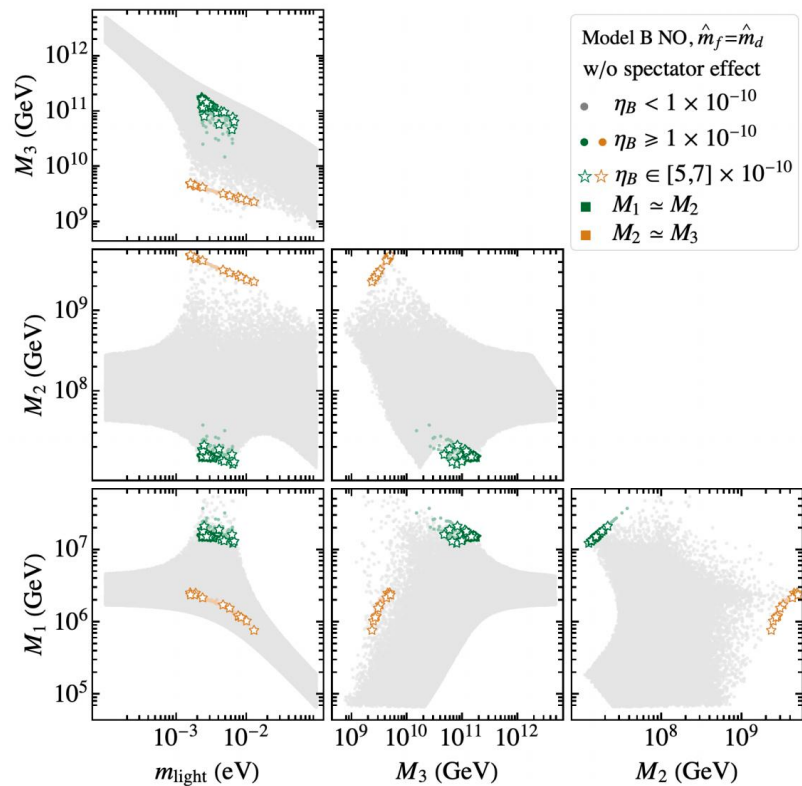
$$M_R \simeq \hat{m}_d U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_d$$

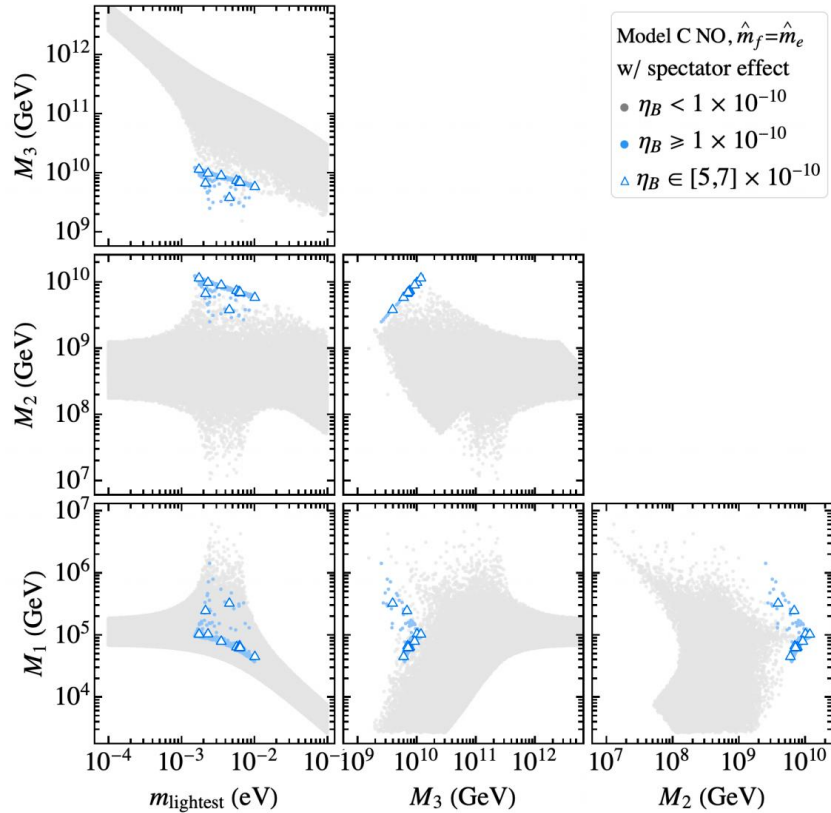
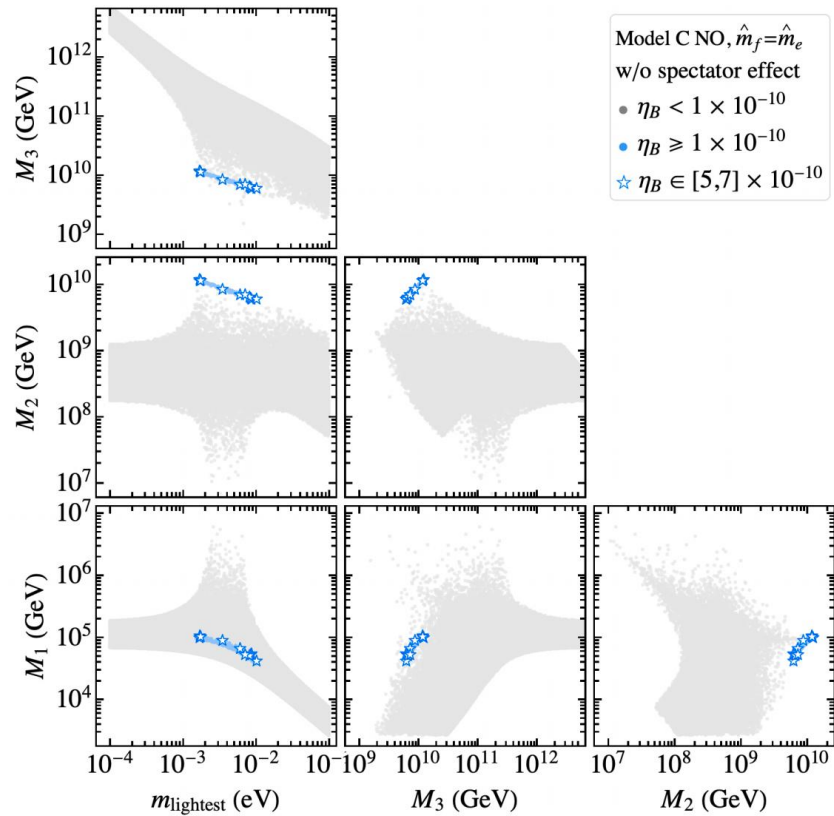
No solution for IO, Yes for NO

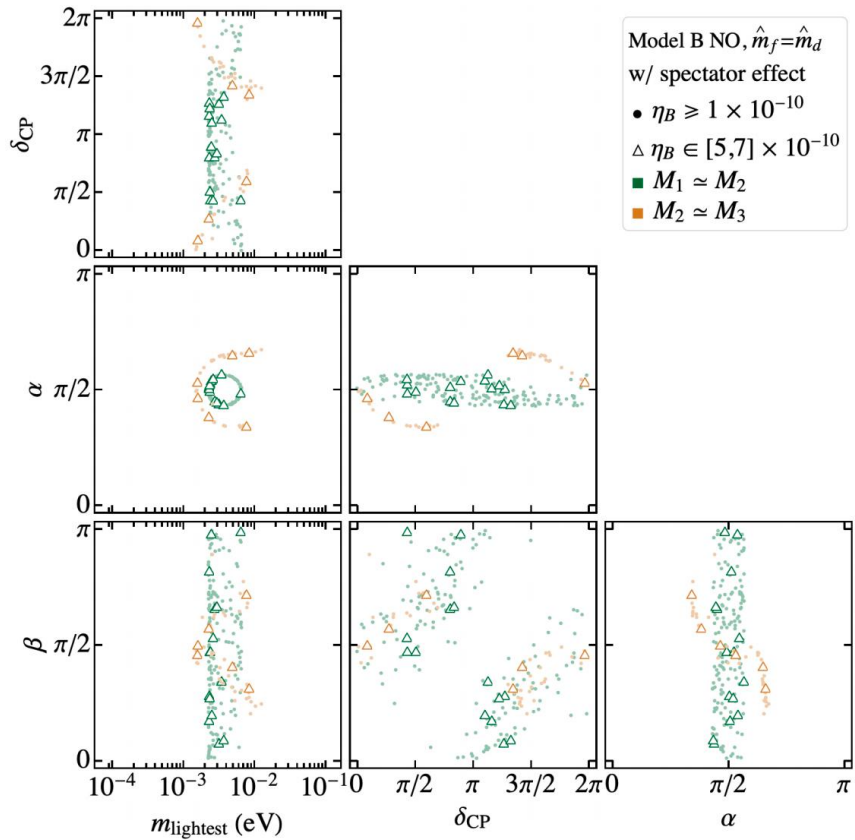
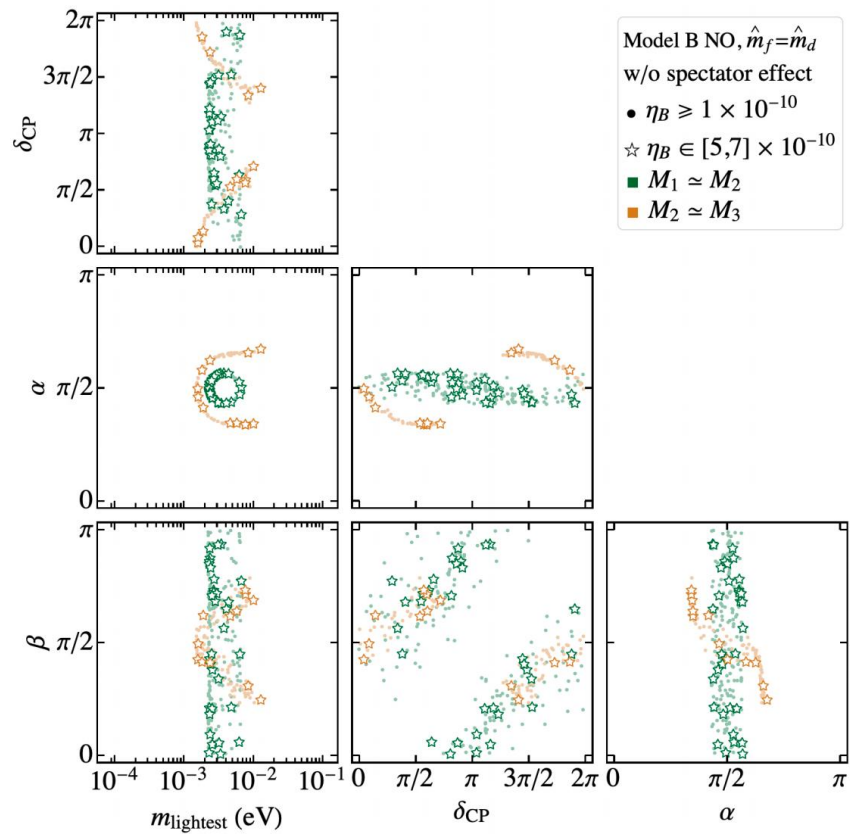
Model C

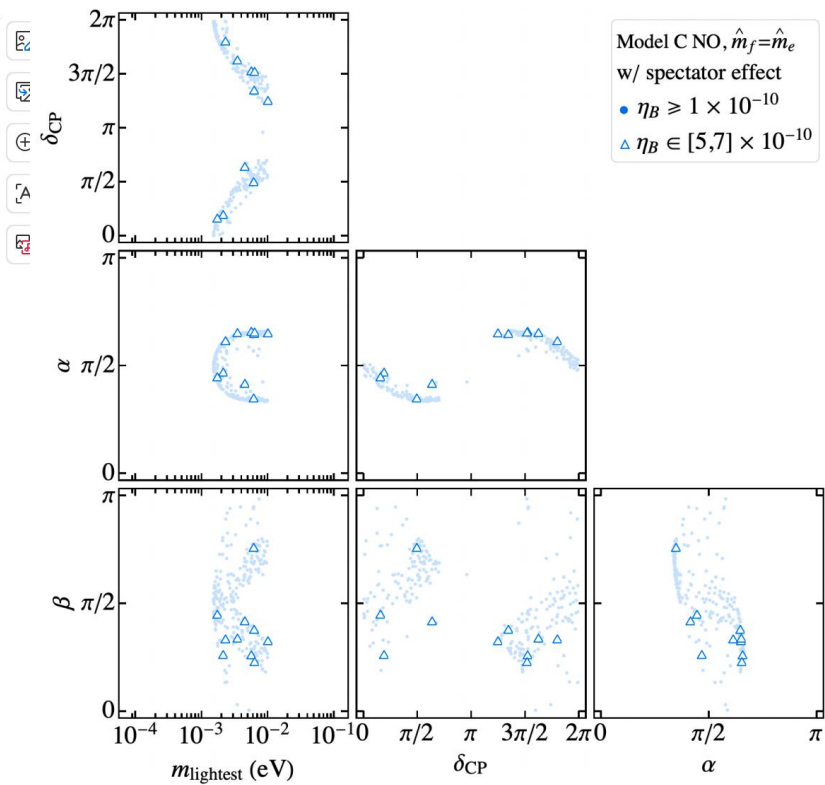
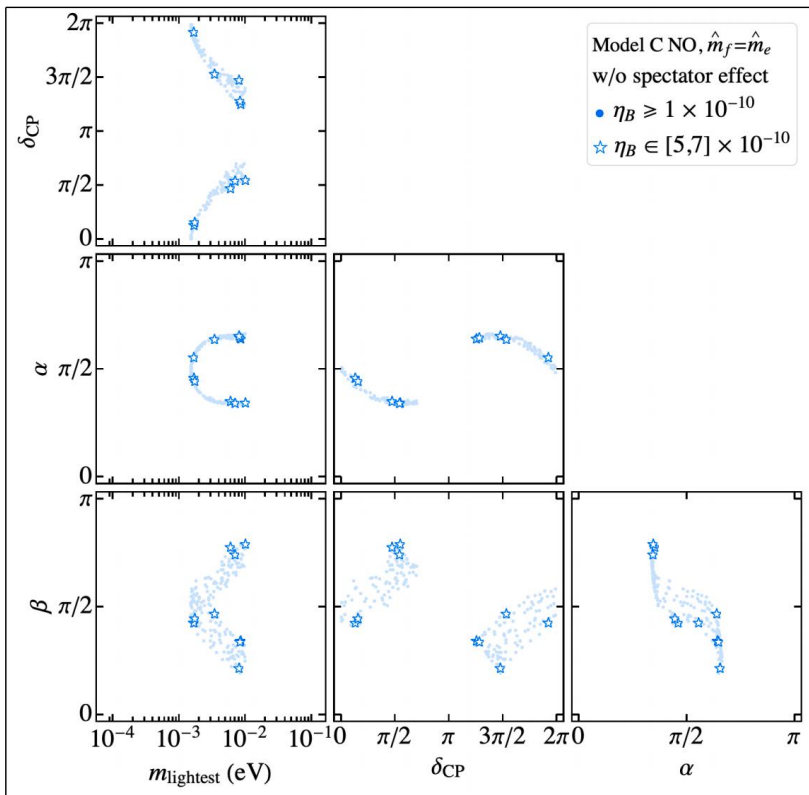
$$M_R \simeq \hat{m}_e U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_e$$

No solution for IO, Yes for NO





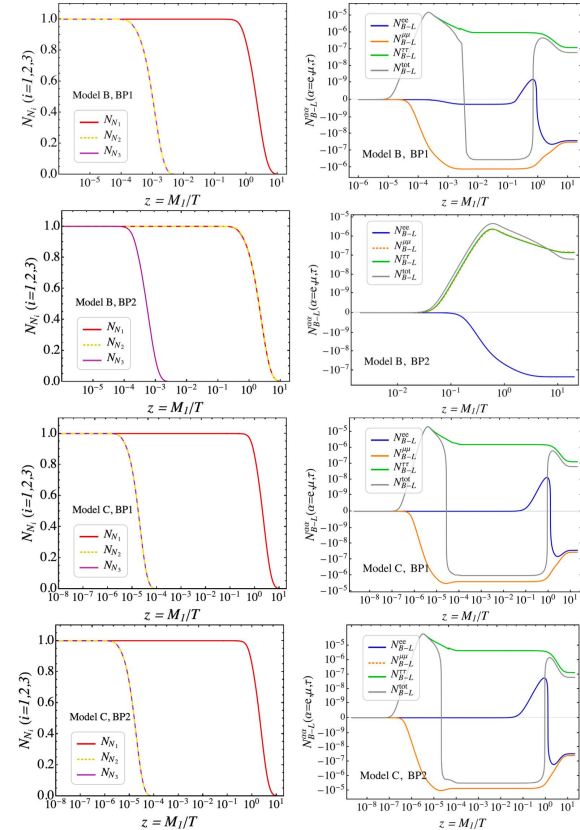




Benchmark solutions

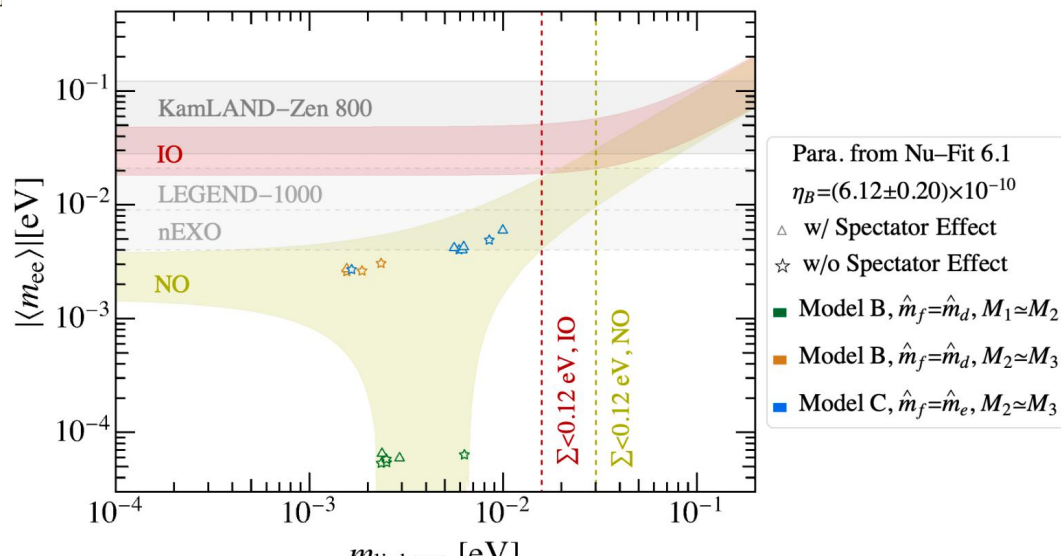
Para.	B, BP1	B, BP2	C, BP1	C, BP2
m_{lightest}	0.001557	0.002369	0.005583	0.009959
δ_{CP}	6.15933	1.34165	4.77529	3.91064
α	1.66069	1.63764	2.05725	2.03482
β	1.43194	1.47476	0.80768	1.01377
M_1	2.4181127×10^6	2.1204273×10^7	6.4710113×10^4	4.5254428×10^4
M_2	4.9651357×10^9	2.1204309×10^7	7.5011335×10^9	5.8975143×10^9
M_3	4.9655608×10^9	8.5369030×10^{10}	7.5012545×10^9	5.8976828×10^9
η_B^{inst}	5.8779×10^{-10}	6.1009×10^{-10}	6.0628×10^{-10}	5.9482×10^{-10}
η_B^{finite}	6.0760×10^{-10}	6.1032×10^{-10}	6.6893×10^{-10}	6.5820×10^{-10}
$\Delta\eta_B$	+3.37%	+0.04%	+10.33%	+10.66%

Evolution of the heavy RH neutrino abundances N_i (left panels) and flavored B — L asymmetries N_{B-L}^{α} together with the total asymmetry N_{tot} (right panels) for the four benchmark points.



Predictions for neutrinoless double beta decays

$$\langle m_{ee} \rangle \equiv \sum_{i=1}^3 U_{ei}^2 m_i = c_{13}^2 c_{12}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i(\beta - \delta_{\text{CP}})},$$



certain cases can be probed by next generation experiments with sub-10 meV sensitivity, such as LEGEND-1000, nEXO, JUNO 50 tons, and CUPID-1T. This framework therefore provides clear targets for future searches.

Leptogenesis May Be Determined By Low Energy Parameters

with lightest neutrino mass fixed
testable consequences in neutrinoless double beta decay