

Leptogenesis Determined by Low-Energy Parameters

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In collaboration with
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2609.12542

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- **Brief Introduction**

Generic Type-I seesaw, predictive seesaw

- **Leptogenesis framework**

Mechanism, CP asymmetry,
decay/inverse decay, BEs

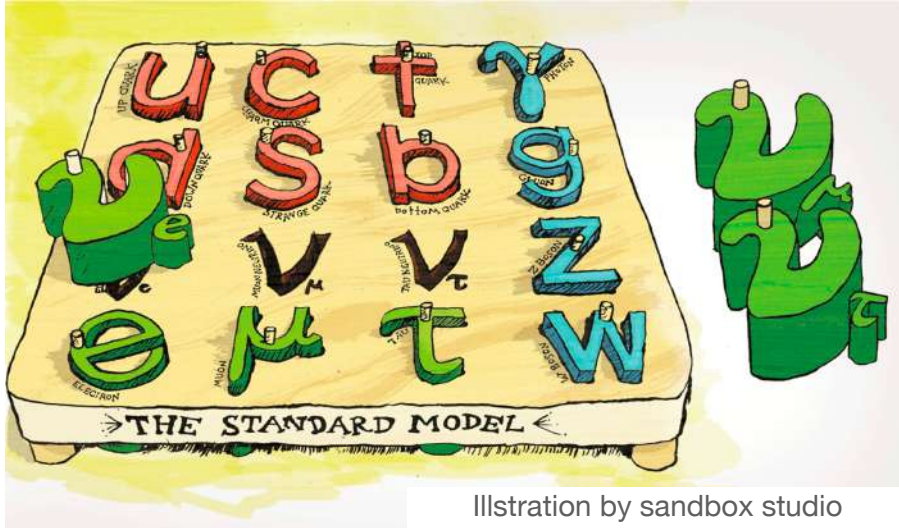
- **Numerical results**

Scanning results on mass and phases, evolution

- **Other phenomenologies**

collider, $0\nu\beta\beta$, $\sum m_\nu$

Introduction



Big question 1: NEUTRINO MASS



How to generate
neutrino masses?

Introduction

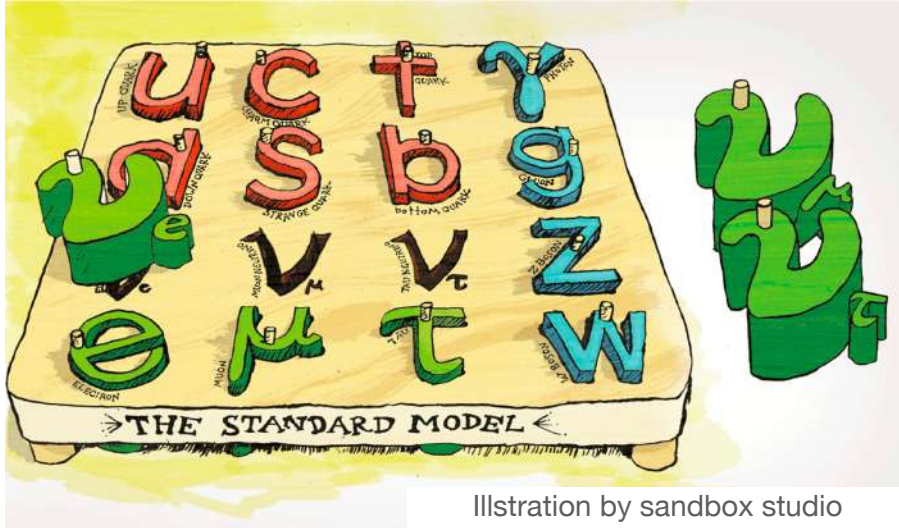
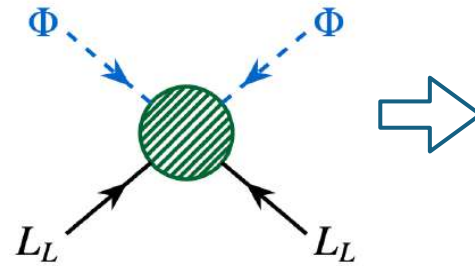
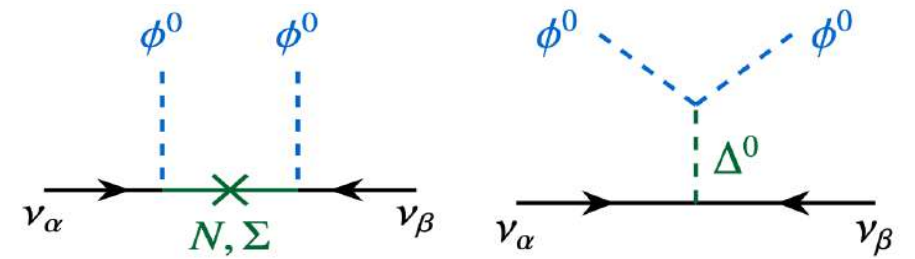


Illustration by sandbox studio

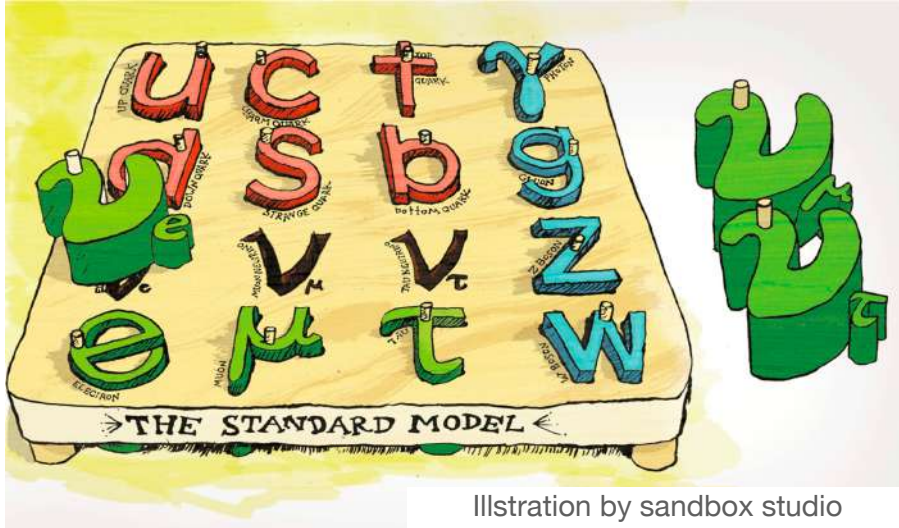
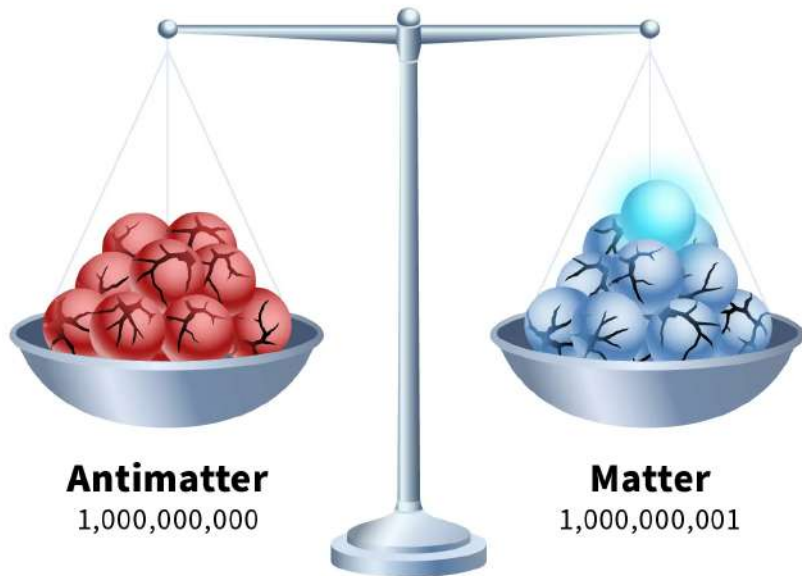
Big question 1: NEUTRINO MASS

Weinberg op.

Type-I/II/III seesaw



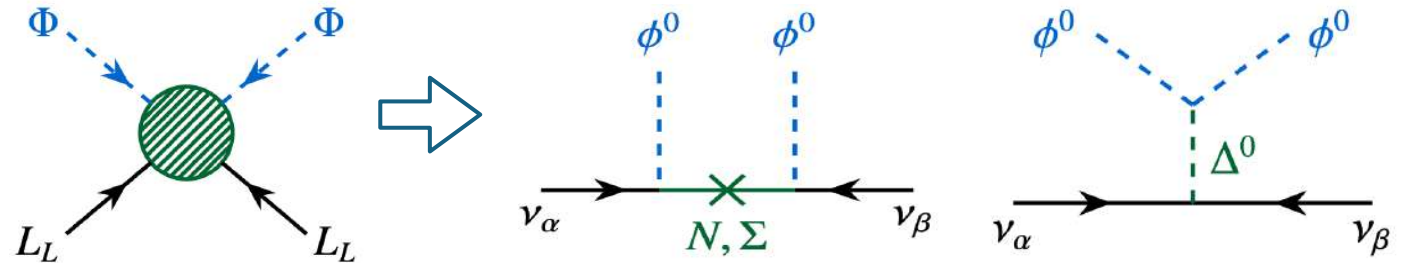
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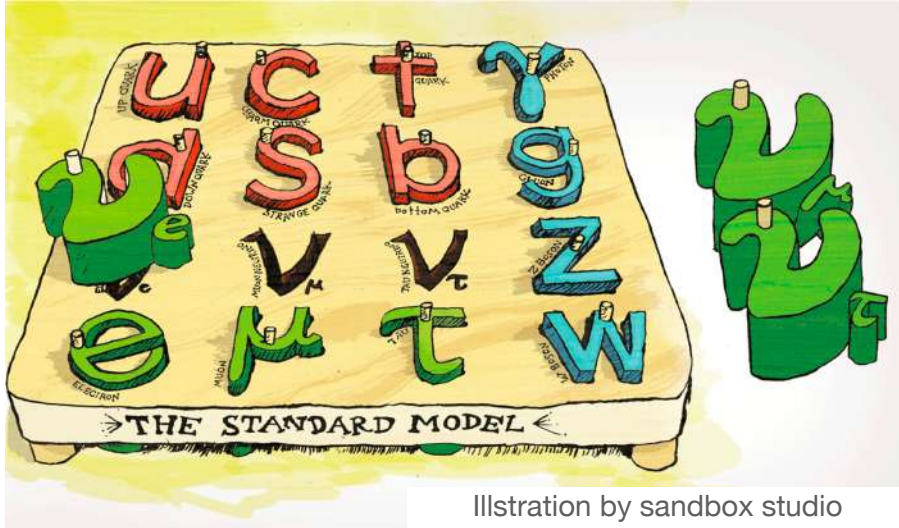


Big question 2: MATTER-ANTIMATTER ASYMMETRY

Sakharov conditions:

- Violation of $B/B-L$
- C / CP violation
- Departure from thermal equilibrium

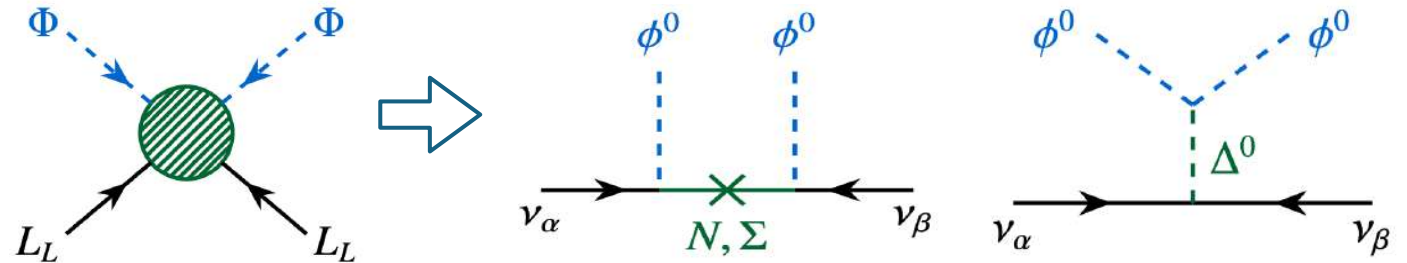
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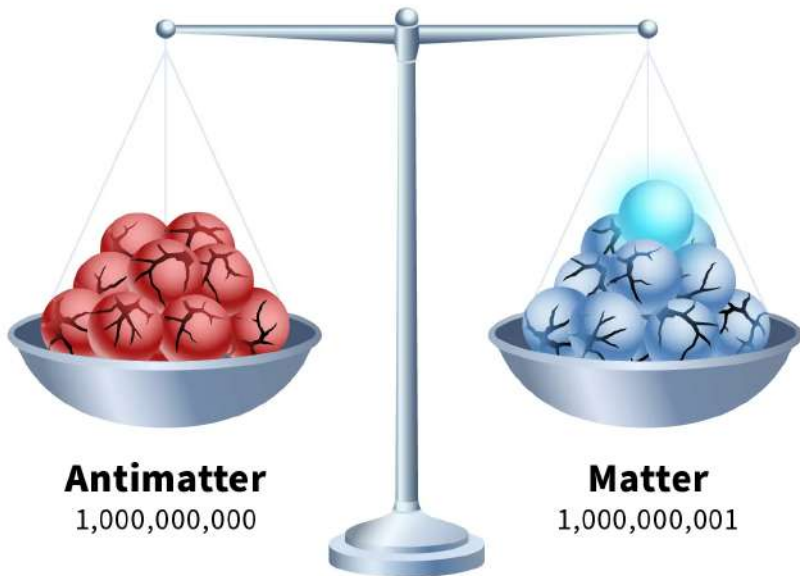
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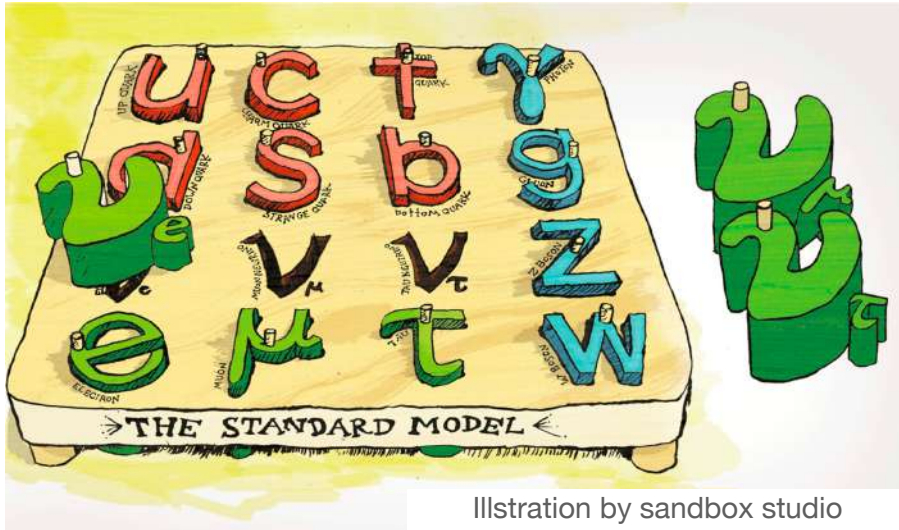
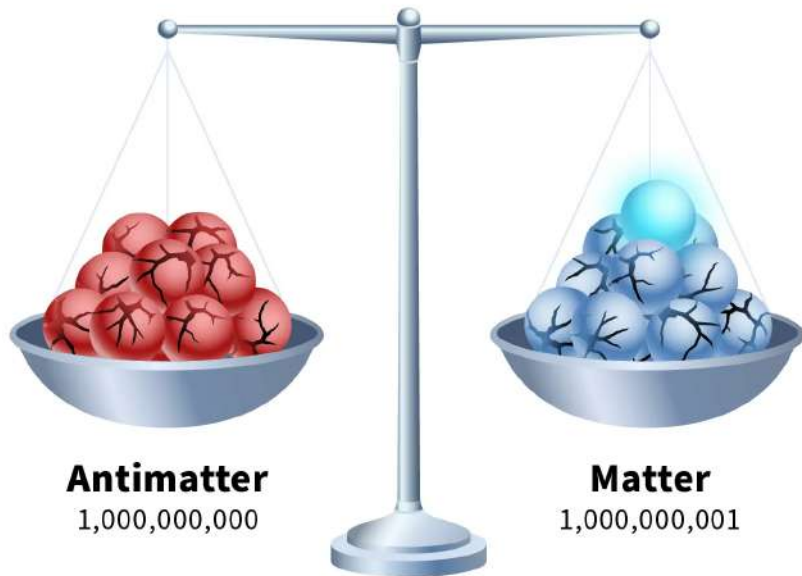
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but not sufficient

How to solve?



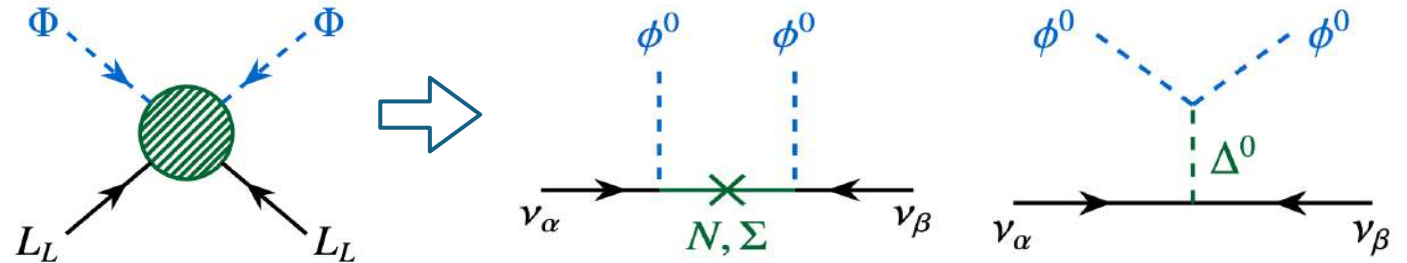
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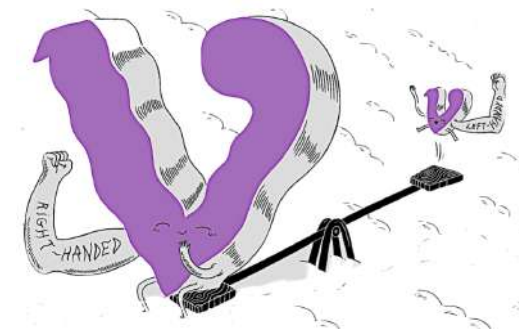
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Type-I seesaw!!

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Neutrino masses motivate the seesaw

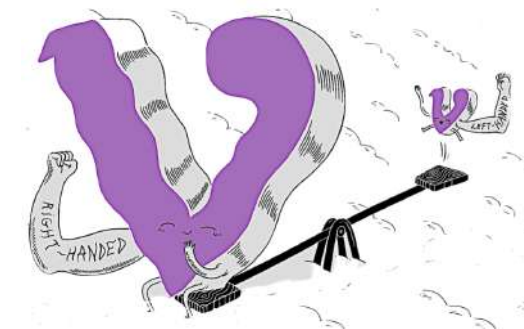
$$-\mathcal{L} \supset \overline{L_{L,\alpha}} (Y_e)_\alpha \Phi E_{R,\alpha} + h_{\alpha i} \overline{L_{L,\alpha}} \tilde{\Phi} N_{R,i} + \frac{1}{2} \overline{N_{R,i}^c} (M_R)_{ij} N_{R,j} + \text{h.c.}$$
$$m_\nu^D = hv/\sqrt{2}, \quad m_\nu \approx -m_\nu^D M_R^{-1} (m_\nu^D)^T = U_{\text{PMNS}} \hat{m}_\nu U_{\text{PMNS}}^T$$



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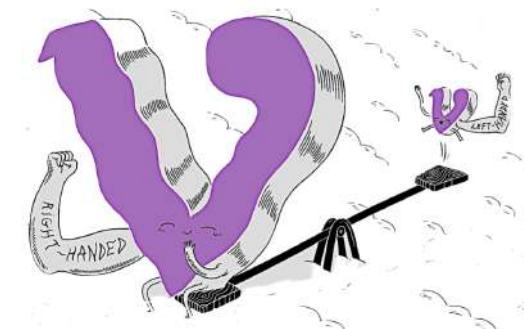
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- Independent heavy masses and complex Yukawa structure.

NOT PREDICTIVE !

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Symmetry constrained seesaw

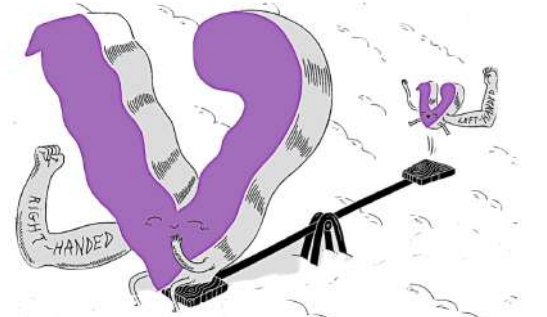
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He, Law & Volkas, PRD 2008

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Model	$\hat{m}_f$	Symmetry setting
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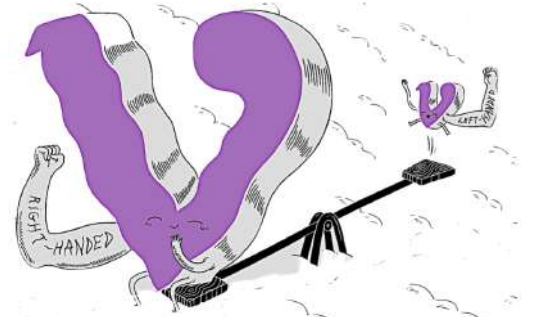
$$\Omega = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix} \quad \omega = \exp(2\pi i/3)$$

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Degrees of freedom are reduced,

lightest neutrino mass, 1 Dirac and 2 Majorana phases

MUCH MORE PREDICTIVE!

Leptogenesis

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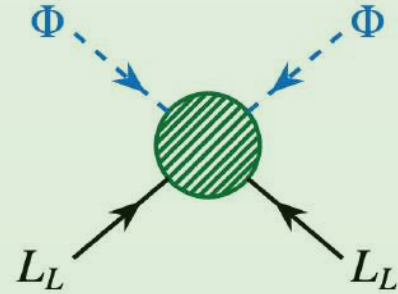
Majorana neutrinos

- C / CP violation: ✓

complex neutrino Yukawa couplings

- Departure from thermal equilibrium: ✓

cosmic expansion naturally induce it



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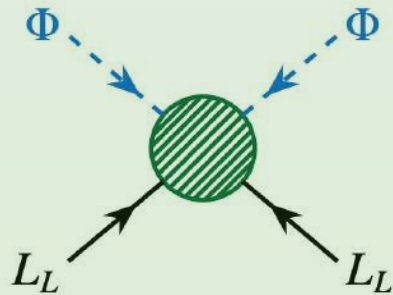
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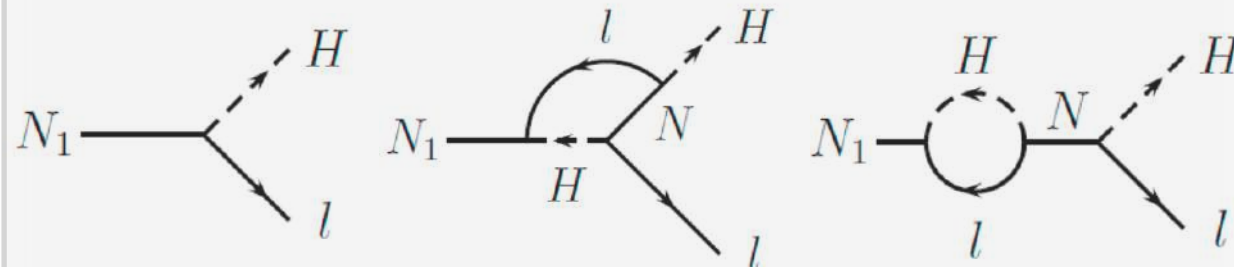
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STEP1: Generation of lepton asymmetry

$$N_i \rightarrow \ell_a H, \quad N_i \rightarrow \bar{\ell}_a H^\dagger,$$



$$\Gamma(N_i \rightarrow \ell_a H) \neq \Gamma(N_i \rightarrow \bar{\ell}_a H^\dagger). \text{ CPV source}$$

STEP2: washout of lepton asymmetry (BEs)

inverse decays erase part of the source

STEP3: lepton asymmetry $\Rightarrow$ baryon asymmetry

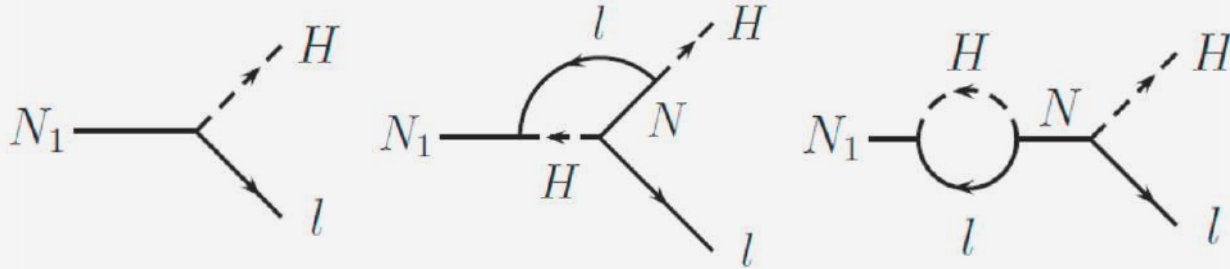
$$Y_B = \frac{28}{79} Y_{B-L}, \quad Y_X \equiv n_X / s.$$

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.12 \times 10^{-10}$$

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Heavy mass basis: $U_R^T M_R U_R = \text{Diag}(M_1, M_2, M_3)$, $\tilde{h} = h U_R$, $M_1 \leq M_2 \leq M_3$.

CP asymmetry source

$$\epsilon = \frac{\Gamma(N \rightarrow LH) - \Gamma(N \rightarrow \bar{L}H^\dagger)}{\Gamma(N \rightarrow LH) + \Gamma(N \rightarrow \bar{L}H^\dagger)}$$

Generate by the 3 diagrams

$$\epsilon_{\alpha\beta}^{(i)} = \frac{3}{32\pi (\tilde{h}^\dagger \tilde{h})_{ii}} \sum_{j \neq i} \left\{ i [\tilde{h}_{\alpha i} \tilde{h}_{\beta j}^* (\tilde{h}^\dagger \tilde{h})_{ji} - \tilde{h}_{\beta i}^* \tilde{h}_{\alpha j} (\tilde{h}^\dagger \tilde{h})_{ij}] \frac{\xi(x_{ji})}{\sqrt{x_{ji}}} \right. \\ \left. + \frac{2i}{3(x_{ji} - 1)} [\tilde{h}_{\alpha i} \tilde{h}_{\beta j}^* (\tilde{h}^\dagger \tilde{h})_{ij} - \tilde{h}_{\beta i}^* \tilde{h}_{\alpha j} (\tilde{h}^\dagger \tilde{h})_{ji}] \right\},$$
$$\xi(x) = \frac{2}{3}x \left[(1+x) \ln\left(\frac{1+x}{x}\right) - \frac{2-x}{1-x} \right] \quad x_{ji} \equiv M_j^2/M_i^2$$

Blanchet, Di Bari, et al, JCAP 2013

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Decay / washout strength

$$K_i = \frac{\Gamma_i^{\text{tot}}}{H(T = M_i)}$$

total decay parameter for N_i

Decay term

$$D_i(z) = K_i z \frac{M_i}{M_1} \frac{\mathcal{K}_1[(M_i/M_1)z]}{\mathcal{K}_2[(M_i/M_1)z]},$$

$$z = M_1/T$$

$\mathcal{K}_n$ are the modified Bessel functions

Washout term

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

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Evolutions:

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

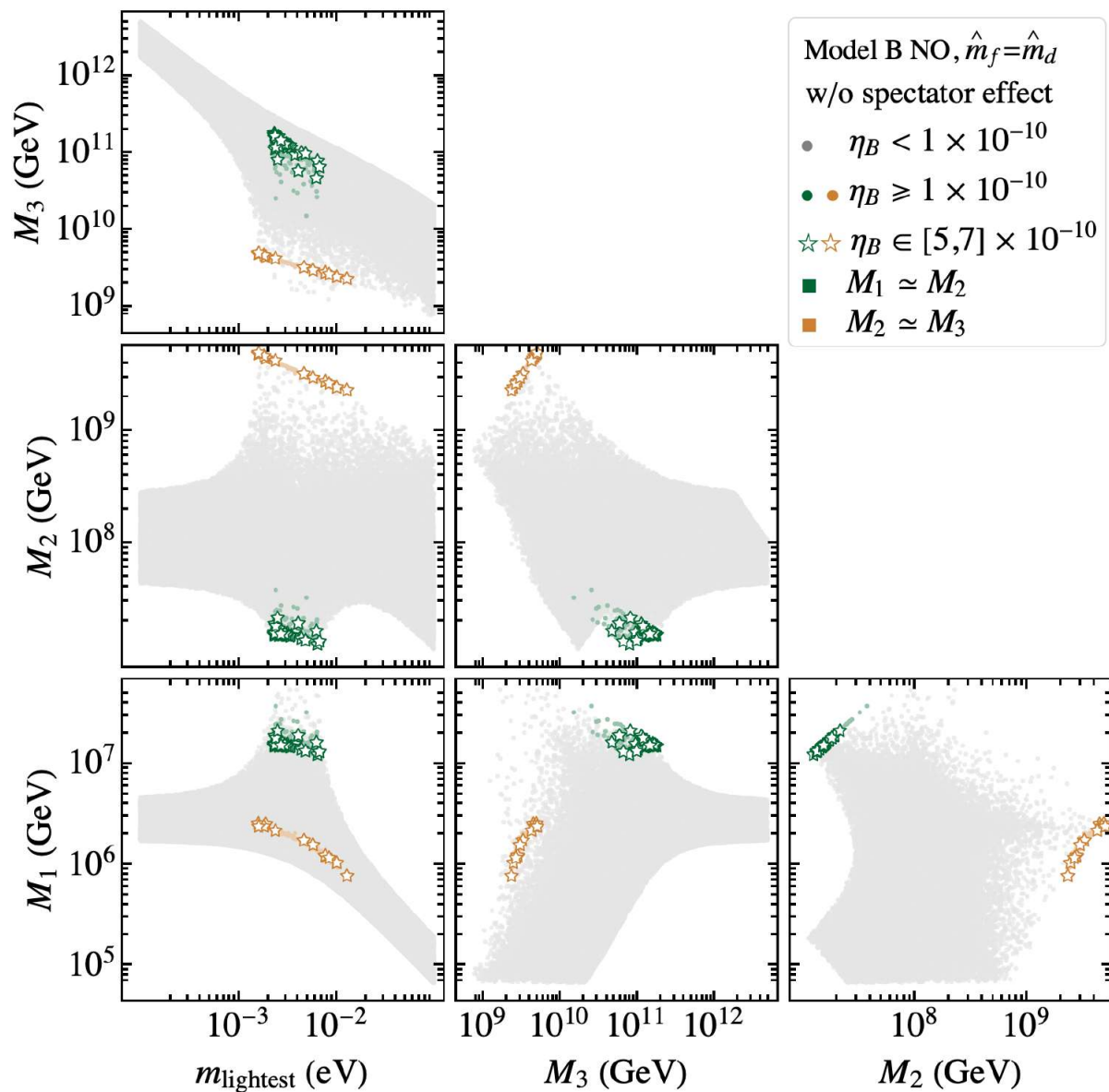
$$\frac{dN_{B-L}^{\alpha\beta}}{dz} = \sum_{i=1,2,3} \left[\epsilon_{\alpha\beta}^{(i)} \frac{M_i}{M_1} D_i(z) (N_{N_i} - N_{N_i}^{\text{eq}}) - \frac{1}{2} \frac{M_i}{M_1} W_i(z) \{P^{0(i)}, N_{B-L}^{\text{spec}}\}_{\alpha\beta} \right]$$

— decoherence terms

Processes can change Higgs and lepton doublet density

Numerical Results

- Scan over more than 10^7 points for each model
- **Normal ordering (NO) works**
- **Model A ($f = u$) fails**
CP asymmetry is too small while washout remains sizable.
- **Models B ($f = d$), C ($f = e$) success**
12+33 points, and **10** points
- Successful points require $|M_i - M_j|/M_i < 10^{-3}$



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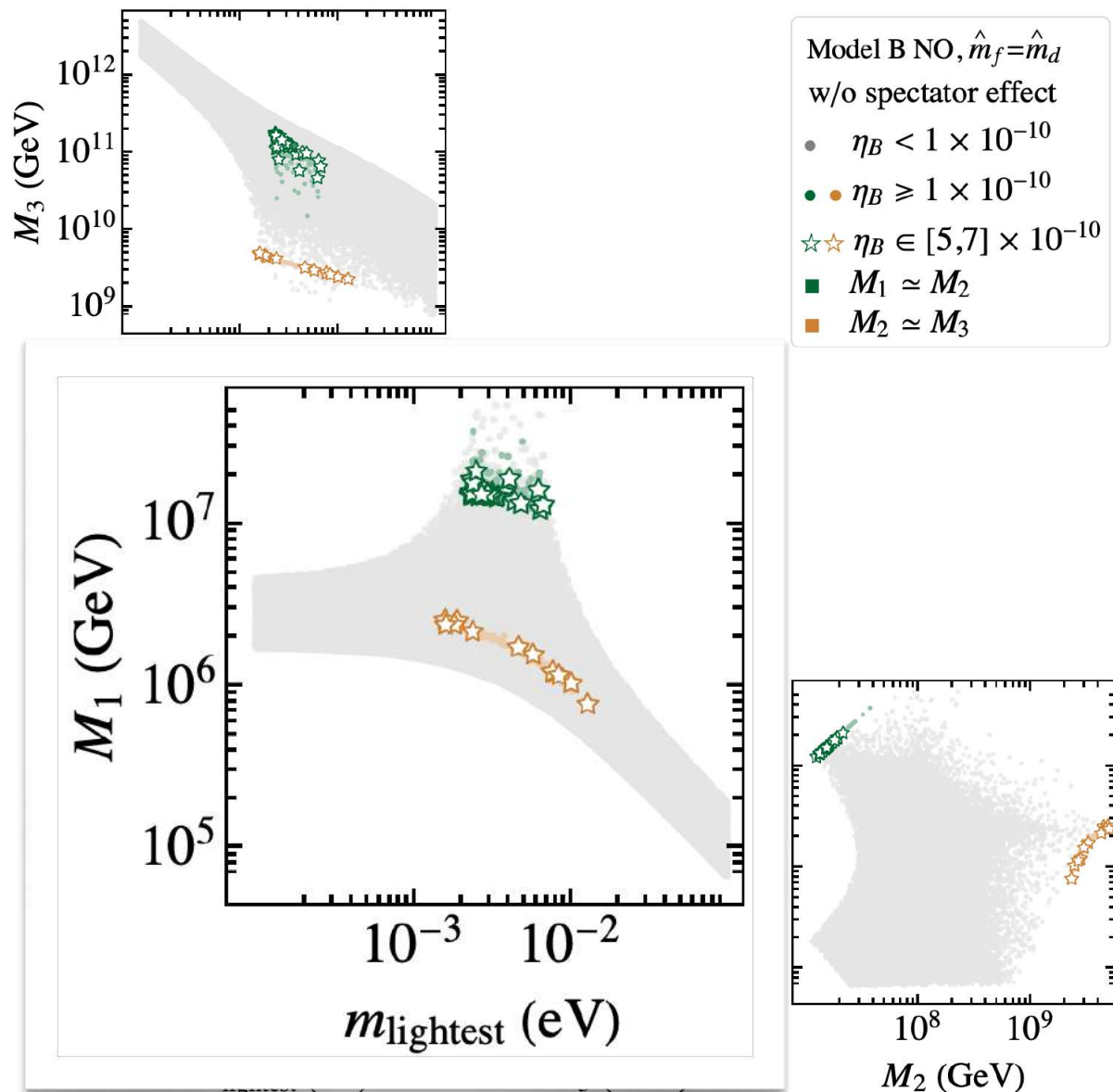
Successful leptogenesis is found only in a limited part of the parameter space, especially for the range

$$m_{\text{lightest}} \in [10^{-3}, 10^{-2}] \text{ eV}$$

model B: $M_1 \simeq M_2 \simeq O(10^{7-8}) \text{ GeV}$

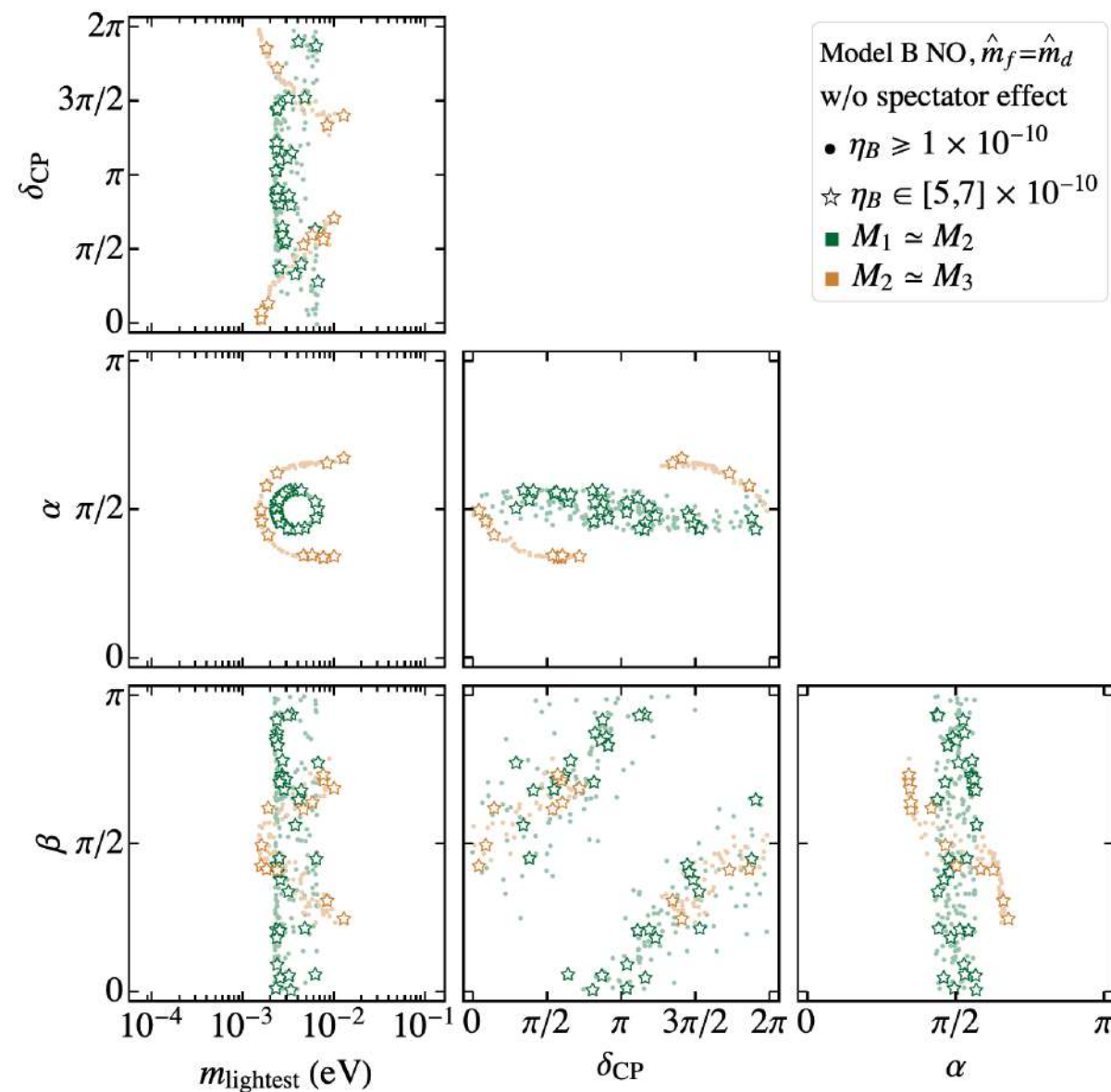
and $M_2 \simeq M_3 \simeq O(10^{9-10}) \text{ GeV}$

model C: $M_2 \simeq M_3 \simeq O(10^{9-10}) \text{ GeV}$



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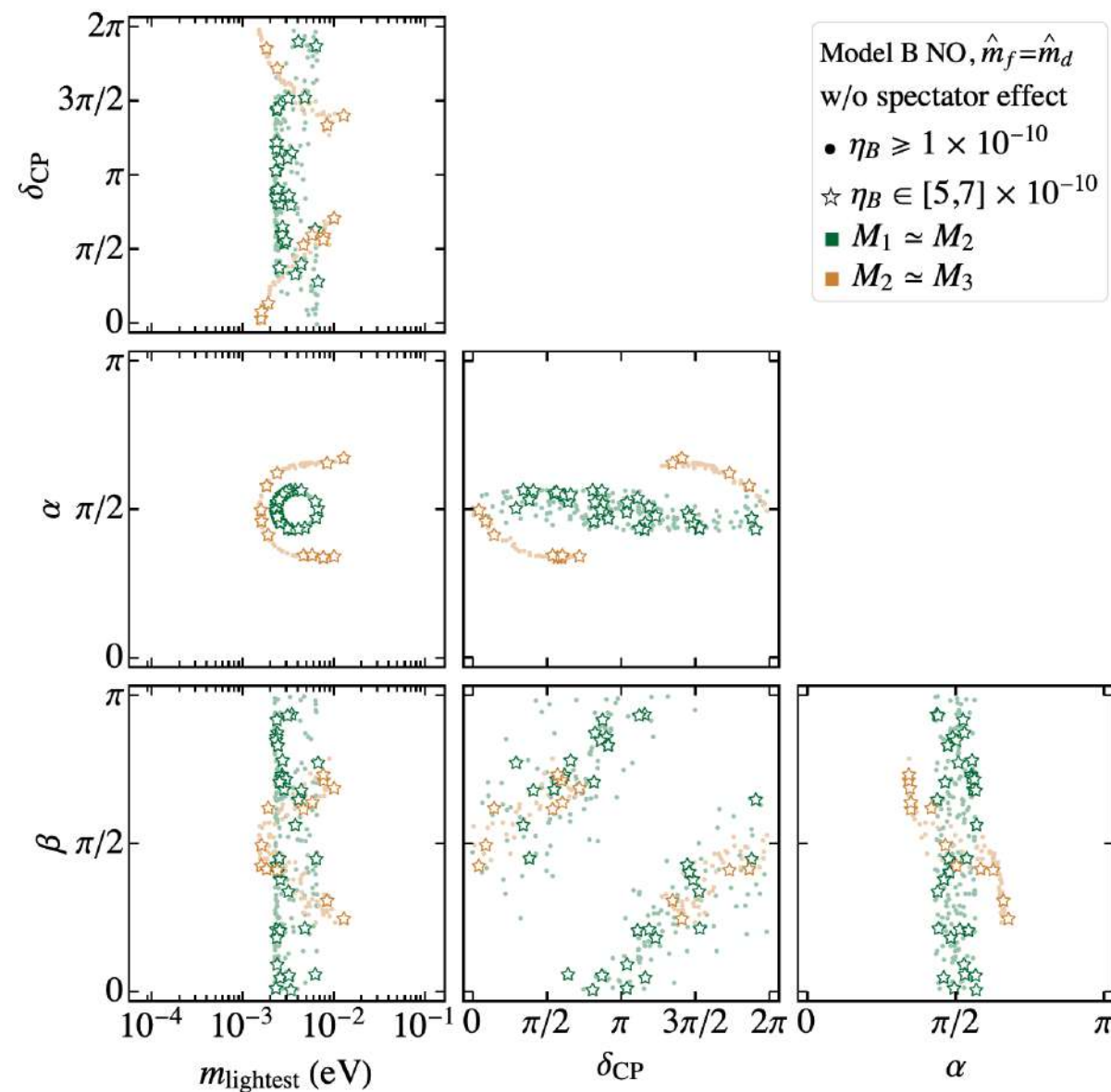
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Successful leptogenesis is only found for **non-zero Majorana phases α**

model B:

α around $\pi/2$, $\beta \in [\pi/4, 3\pi/4]$, δ_{CP} no around $\pi/4$

α more tightly around $\pi/2$, β and δ_{CP} have much broader range



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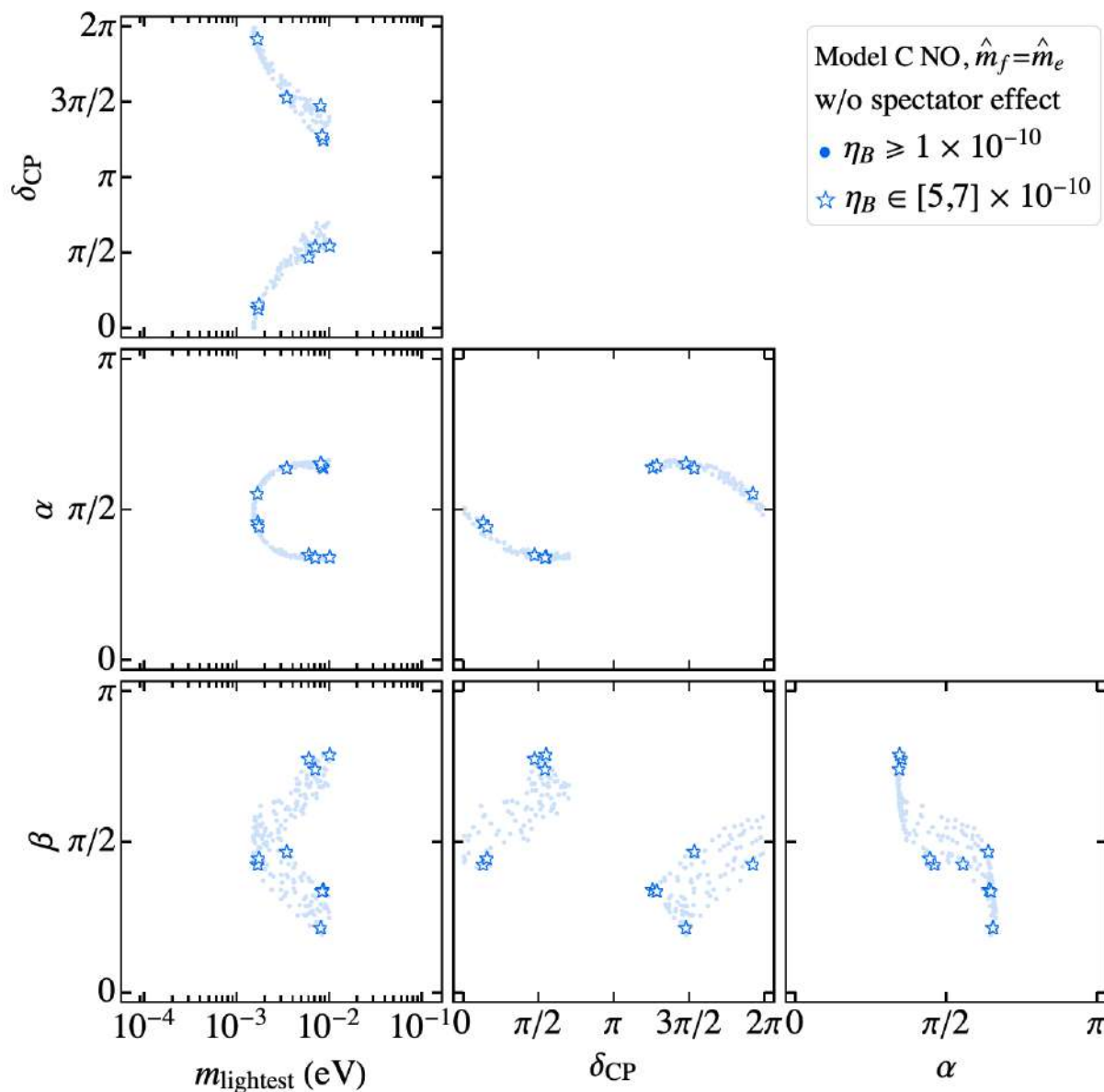
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12+33 points, and **10** points
- Successful points require $|M_i - M_j|/M_i < 10^{-3}$

Successful leptogenesis is only found for **non-zero Majorana phases α**

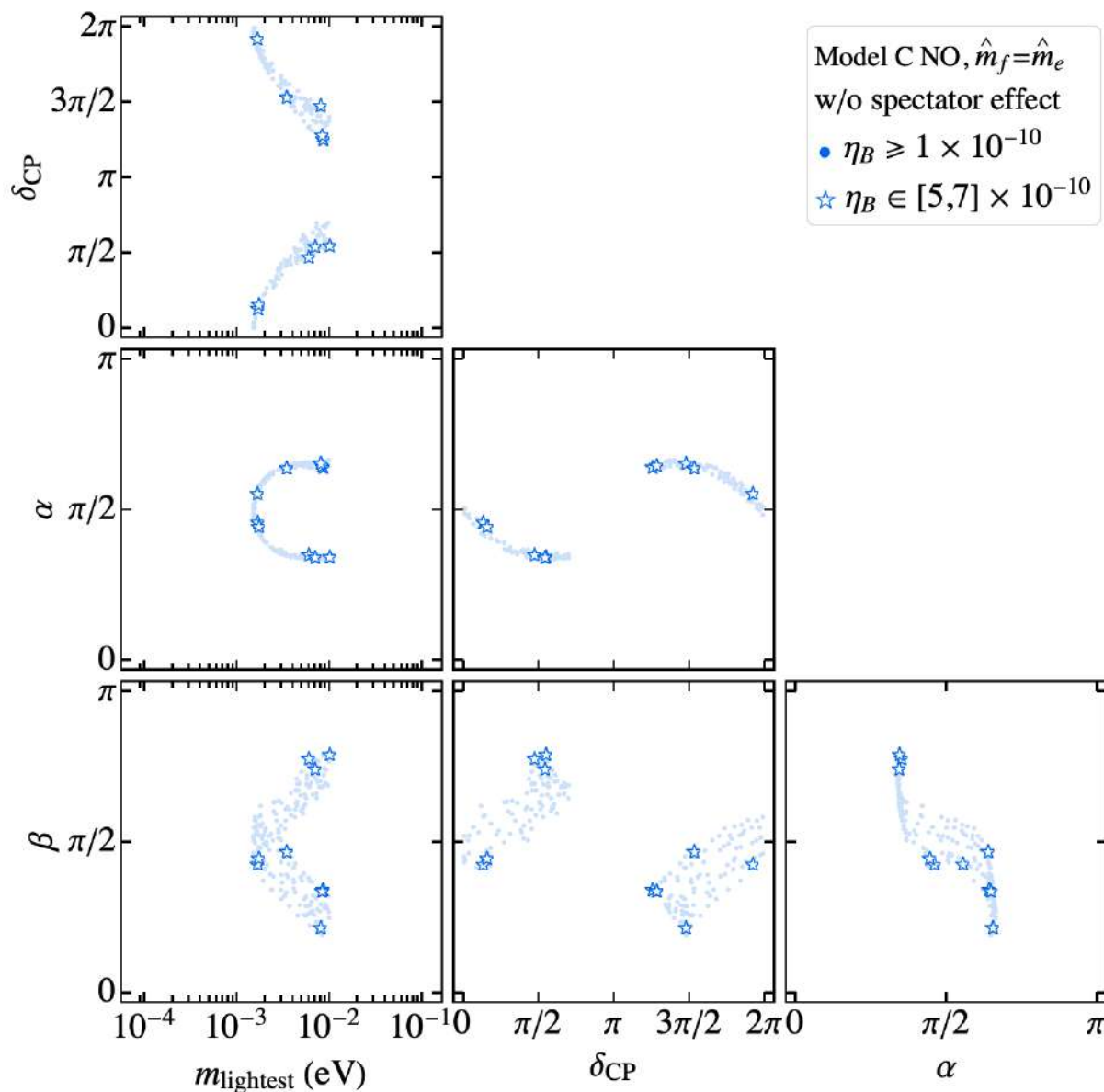
model B:

α around $\pi/2$, $\beta \in [\pi/4, 3\pi/4]$, δ_{CP} no around $\pi/4$

α more tightly around $\pi/2$, β and δ_{CP} have much broader range

model C:

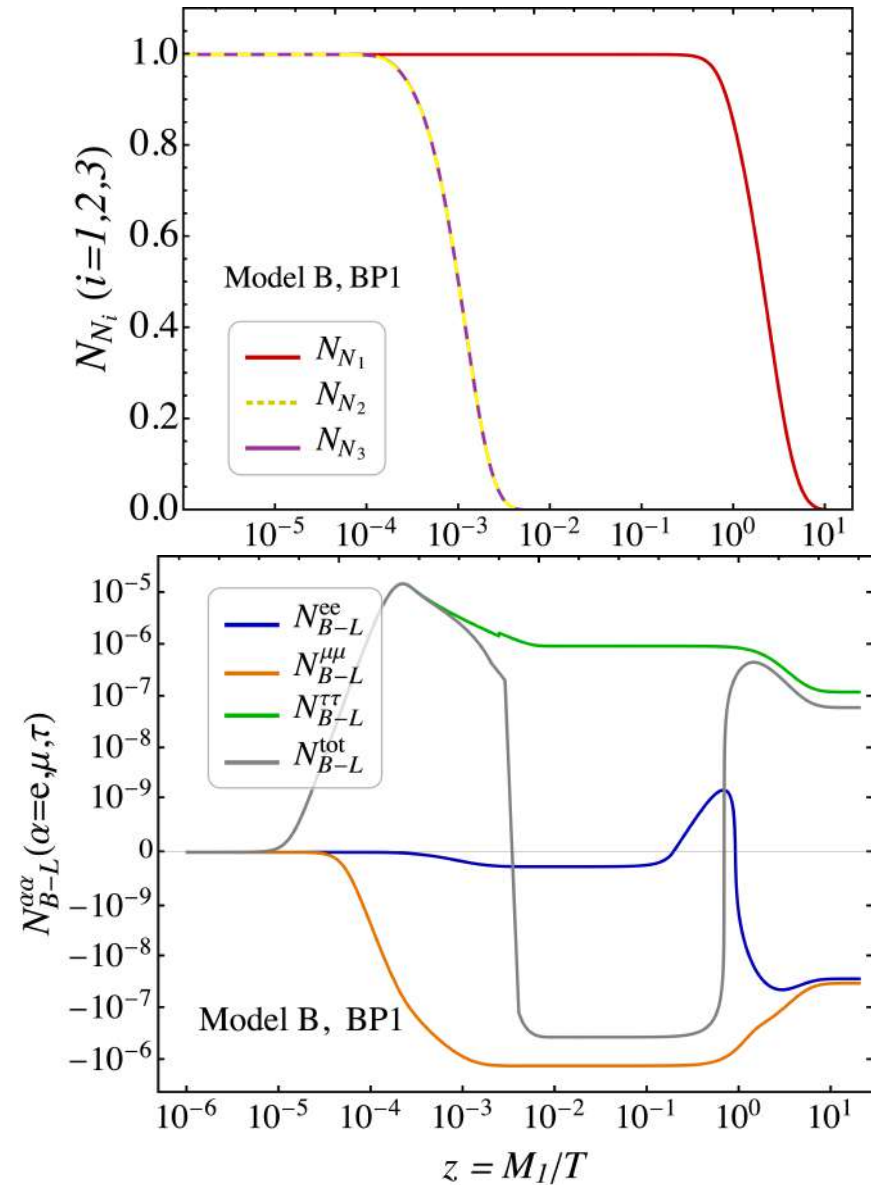
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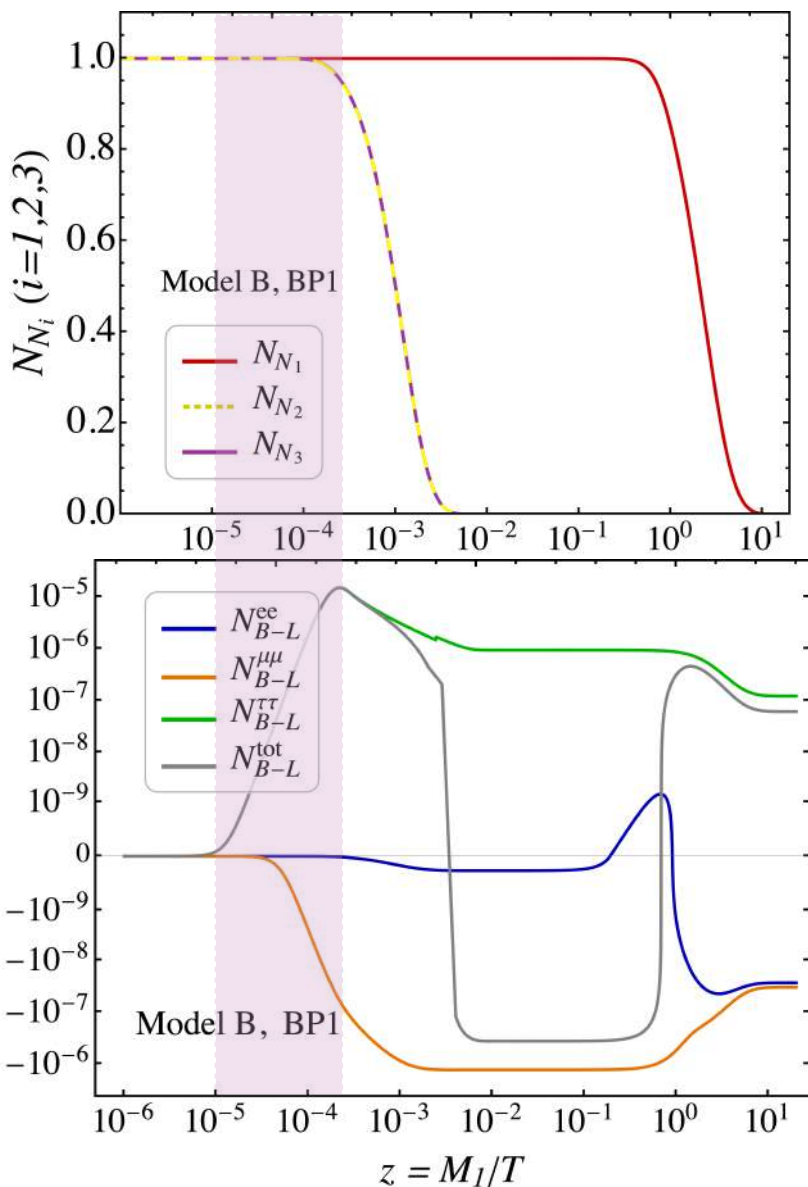
Numerical Results

BP: $m_{\text{lightest}} = 1.56 \text{ meV}$ $M_2 = 4.9651 \times 10^9 \text{ GeV}$
 $M_1 = 2.4181 \times 10^6 \text{ GeV}$ $M_3 = 4.9656 \times 10^9 \text{ GeV}$

Although masses are close, but not resonant: $R_{\text{reson}}^{i,j} \equiv \frac{|M_i - M_j|}{\Gamma_{i,j}^{\text{tot}}} \simeq 60 \gg 1$



Numerical Results



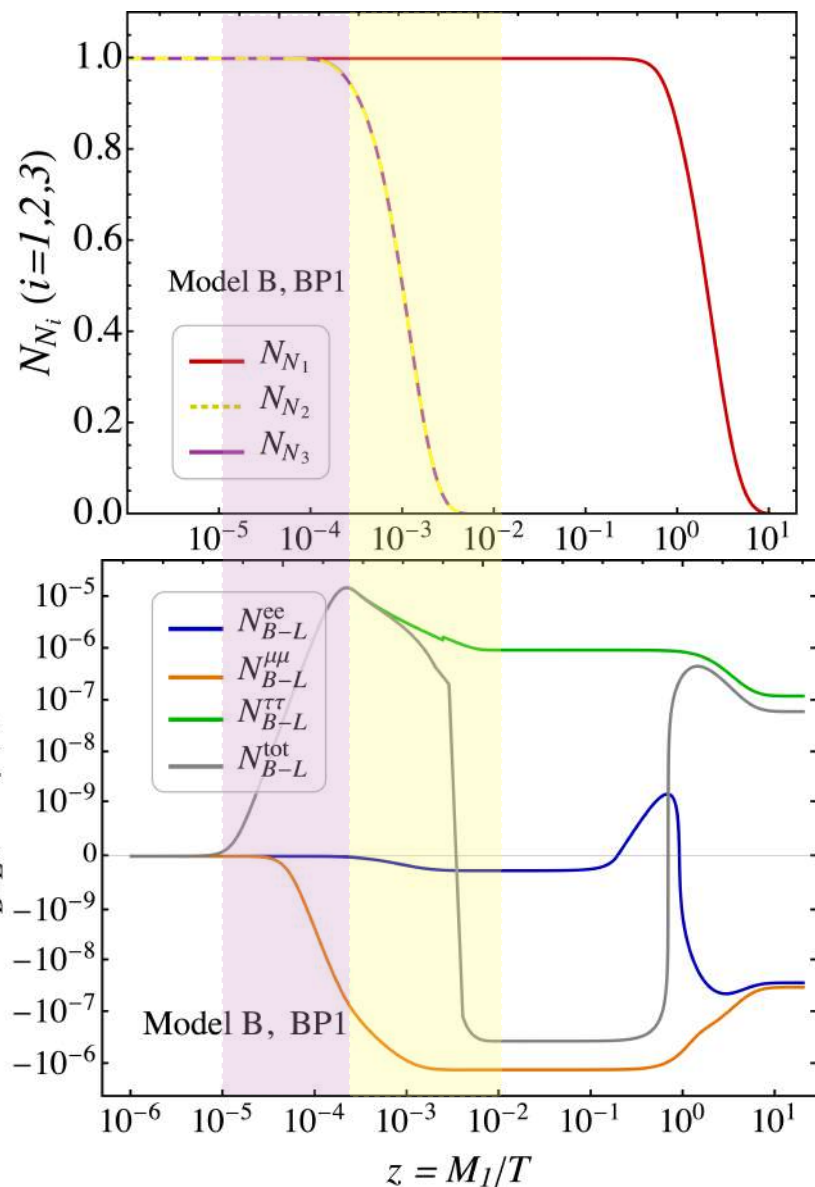
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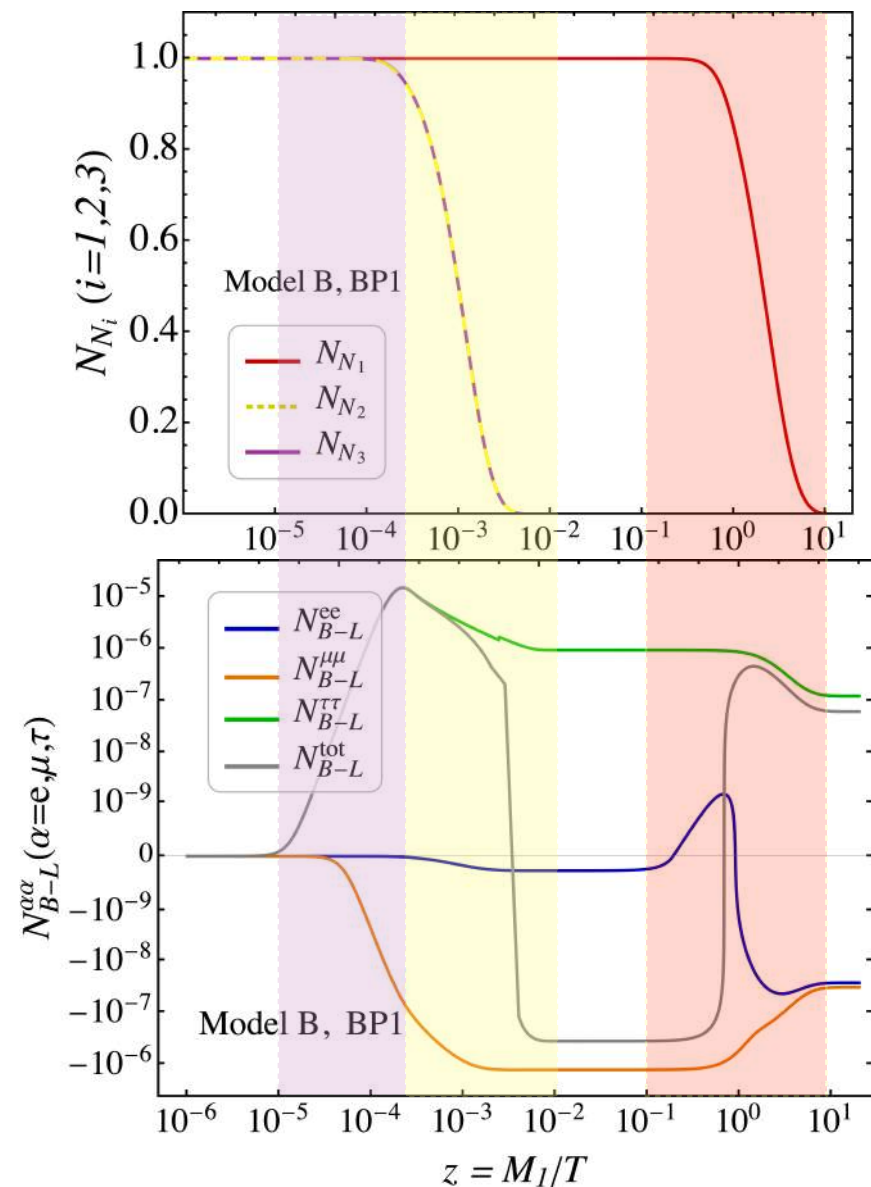
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- Middle Stage:**

- $N_{2,3}$ inverse decay **strongly** erase part of τ asymmetry ($K_{2,3\tau} \simeq 200$)
- But no obvious erase of μ asymmetry ($K_{2,3\mu} < 1$)
- Total asymmetry flips to the negative sign

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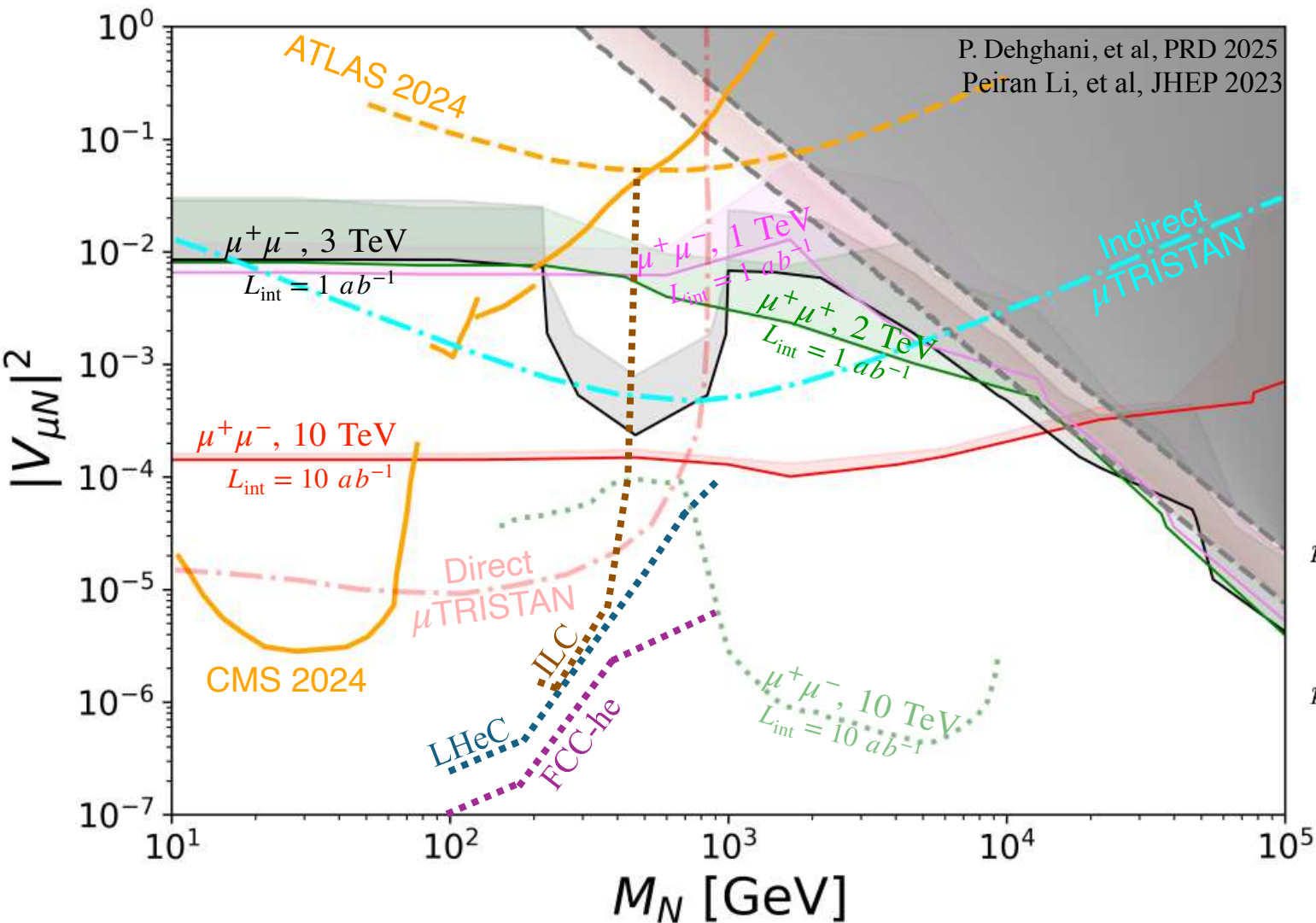
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• Late Stage:

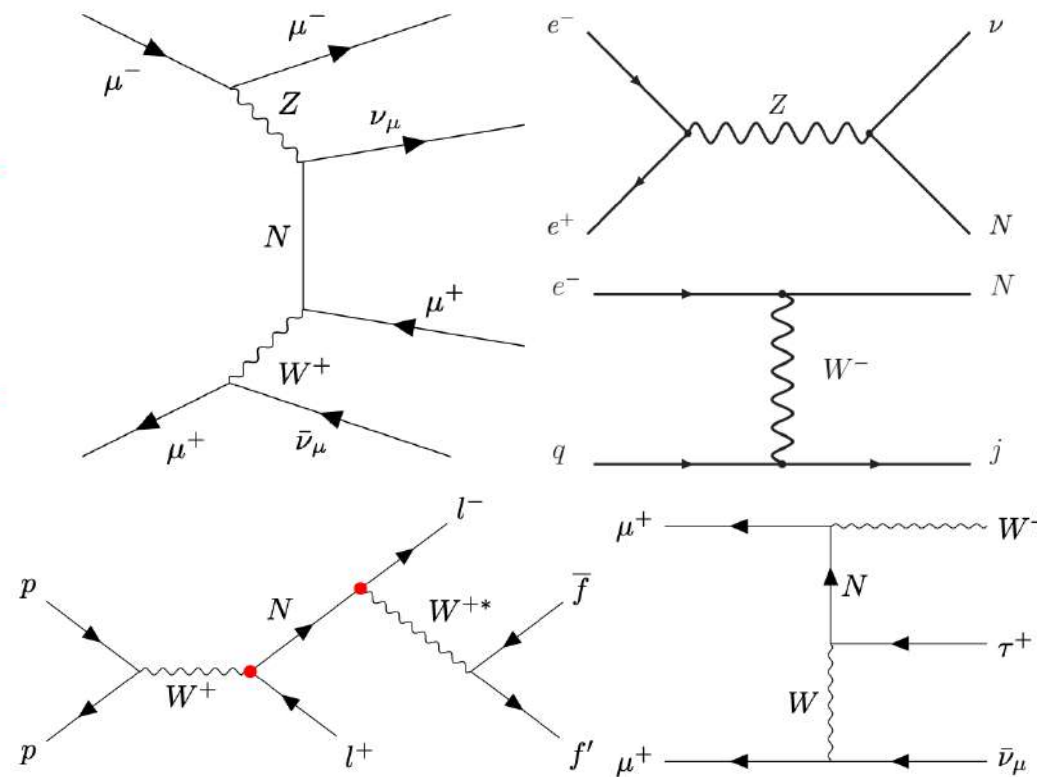
- N_1 is weak at generating any flavor lepton asymmetry
- Inverse decay is **strong** at μ asymmetry ($K_{1\mu} \simeq 20$)
But gives **weak** washout of τ asymmetry ($K_{1\tau} \simeq 2$)
- negative μ asymmetry cannot compatible with τ asymmetry
total asymmetry **survives** to have the correct order and sign

$$\eta_B \simeq 6 \times 10^{-10}$$

Search for heavy neutral lepton

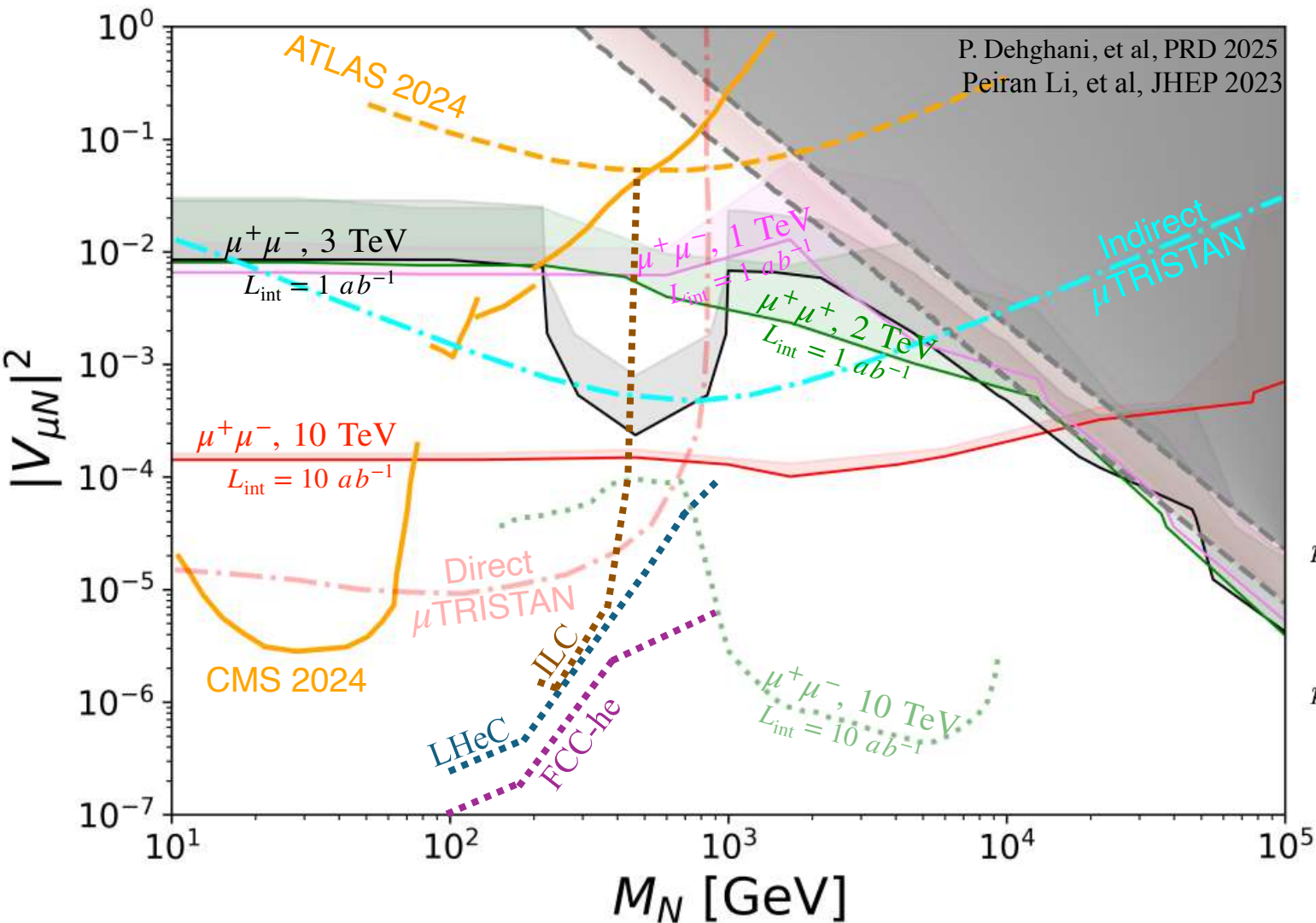


$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} V_{\ell N} \bar{\ell} \gamma^\mu P_L N W_\mu + \text{h.c.},$$

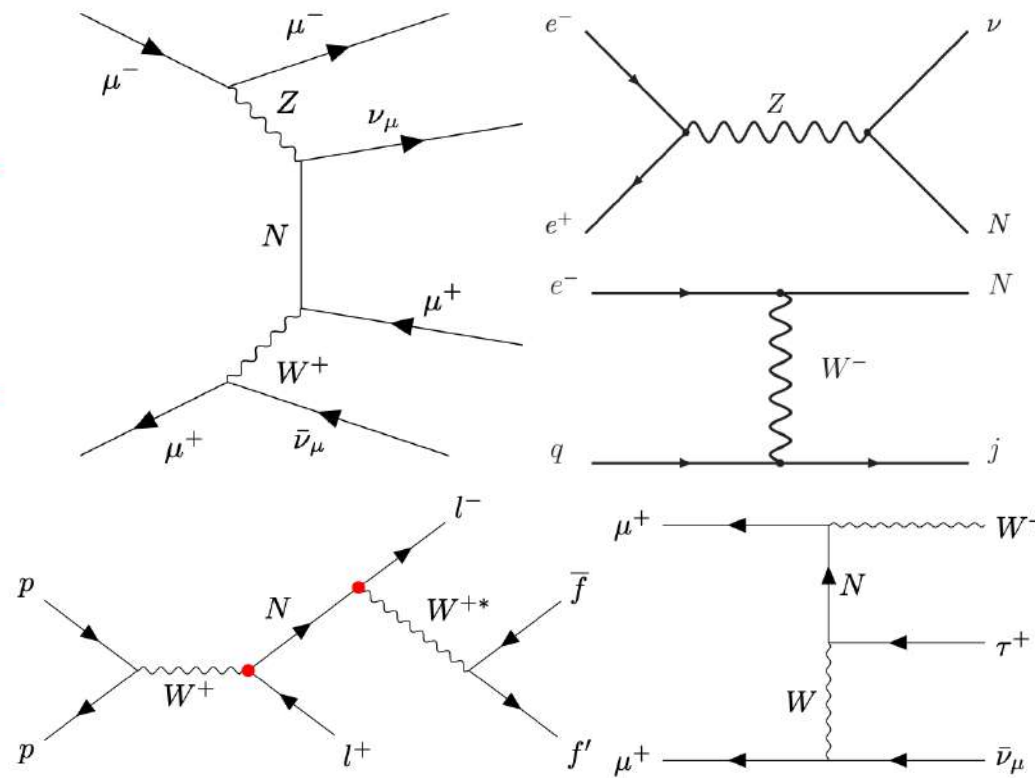


Other Pheno.

Search for heavy neutral lepton



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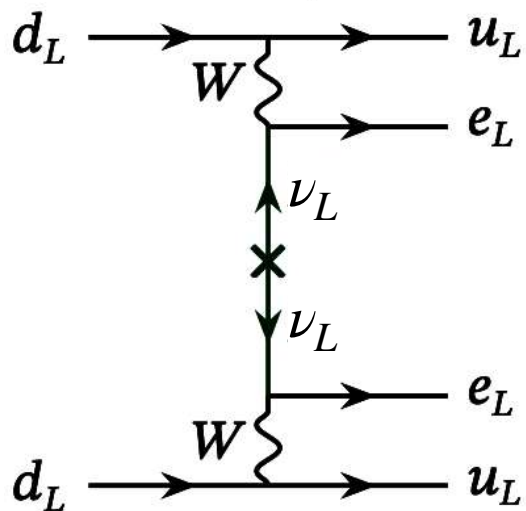
All the successful leptogenesis points have

$$|V_{\mu N}|^2 < O(10^{-12}) \text{ for } M_N > 10^6 \text{ GeV}$$

Really hard to detect on collider

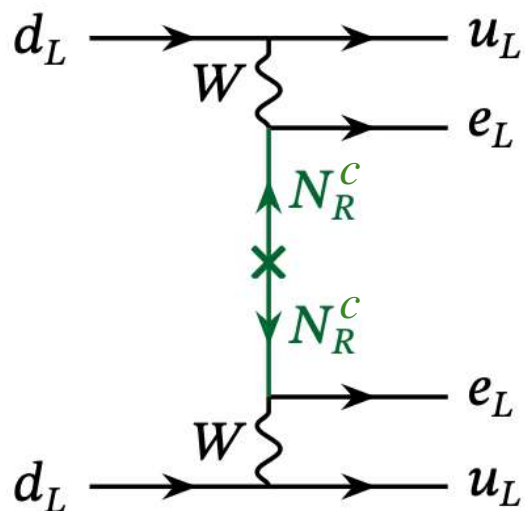
Neutrinoless double beta decay

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} V_{\ell N} \bar{\ell} \gamma^\mu P_L N W_\mu + \text{h.c.} ,$$



$$\langle m_{ee} \rangle = \sum_i U_{ei}^2 m_i$$

Standard contribution



$$\epsilon_N = \sum_i V_{ei}^2 m_p / m_{N_i}$$

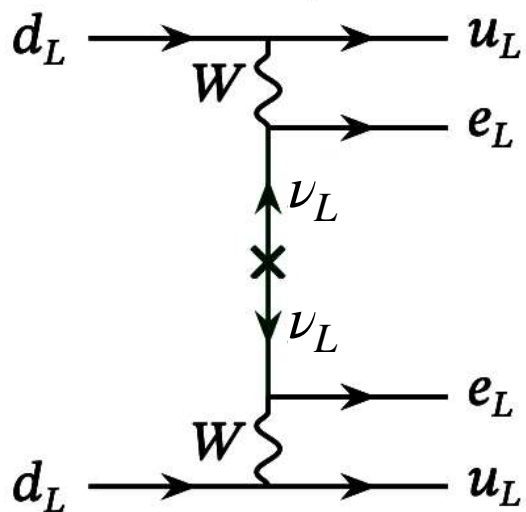
Extremely small,
can be neglected

$$\langle m_{ee} \rangle = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2i\alpha} + s_{13}^2 m_3 e^{2i(\beta - \delta_{\text{CP}})} \right|$$

Other Pheno.

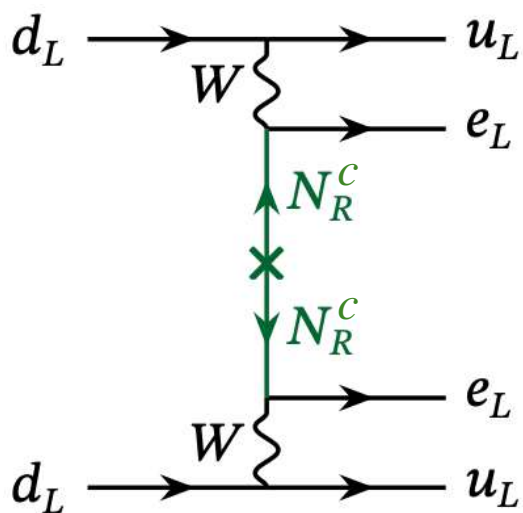
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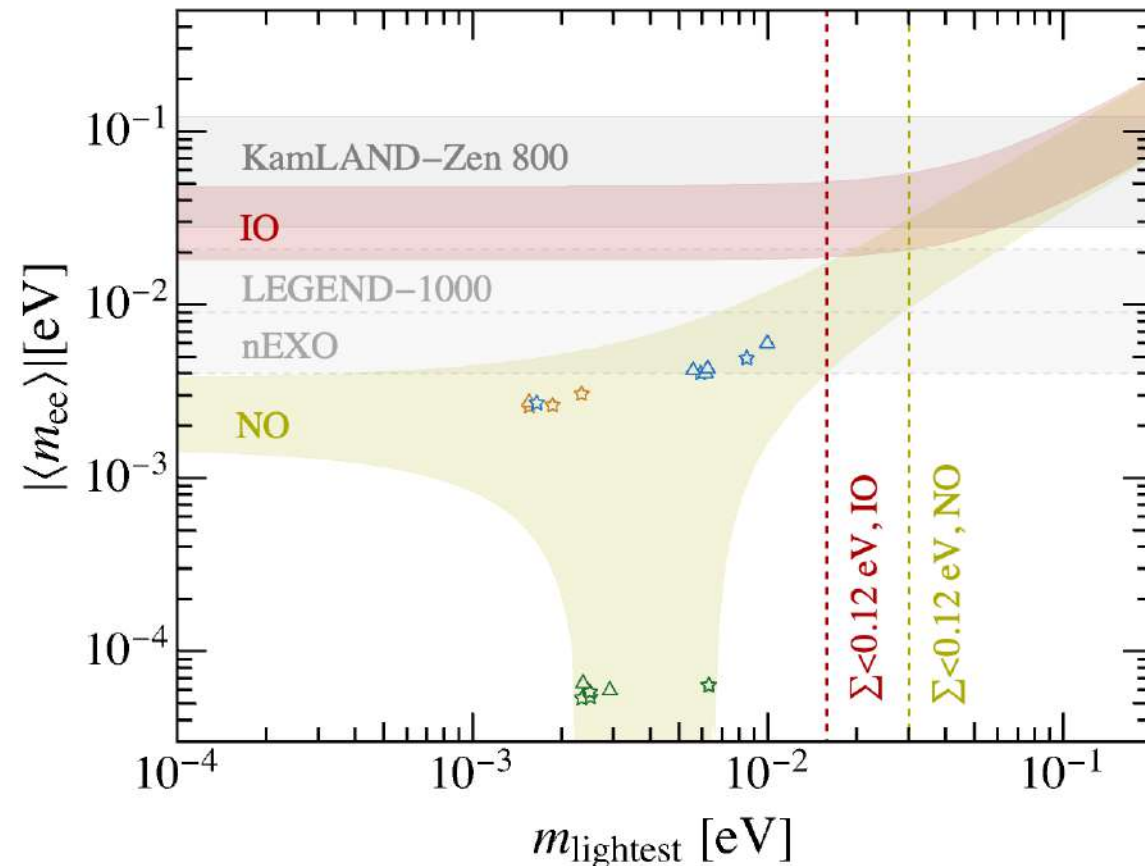


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The successful points in model B ($f = d, M_2 \simeq M_3$) and model C ($f = e$) can be probed by next-generation experiments



$\triangle / \star$: with / without spectators
BAU selection: $(6.12 \pm 0.20) \times 10^{-10}$

Summary

$$\{m_{\text{lightest}}, \delta_{\text{CP}}, \alpha, \beta\} \xrightarrow[\text{symmetry-fixed } m_D]{\text{reconstruct } M_R} \{M_i, \tilde{h}\} \longrightarrow \{\eta_B, m_{\beta\beta}\}$$

- **Certain UV complete model to give predictive seesaw**

Introduce symmetry to reduce the degrees of freedom $m_D = \Omega \hat{m}_f$

Induce special structure $M_R \simeq \hat{m}_f U_{\text{PMNS}}^* \hat{m}_\nu^{-1} U_{\text{PMNS}}^\dagger \hat{m}_f$

- **Leptogenesis fully determined by low energy parameters**

NO solutions are found in Models B ($f = d$) and C ($f = e$)

heavy neutrinos have similar masses, but not resonant

- **Neutrinoless double beta decay gives a complementary test**

Certain viable solutions can be examined in next-generation experiments

Thank you