Neutrino Mass Ordering from Discrete Flavor Symmetry

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Outline

- 🔥 **Motivation behind the Model**
- 🔥 **Basic concepts (review)**
- 🔥 **Elements & Properties of the Model**
- 🔥 **Phenomenology**
- 🔥 **Conclusions**

Going BSM

Three reasons for going BSM

Neutrino Masses
(Majorana)

Going BSM

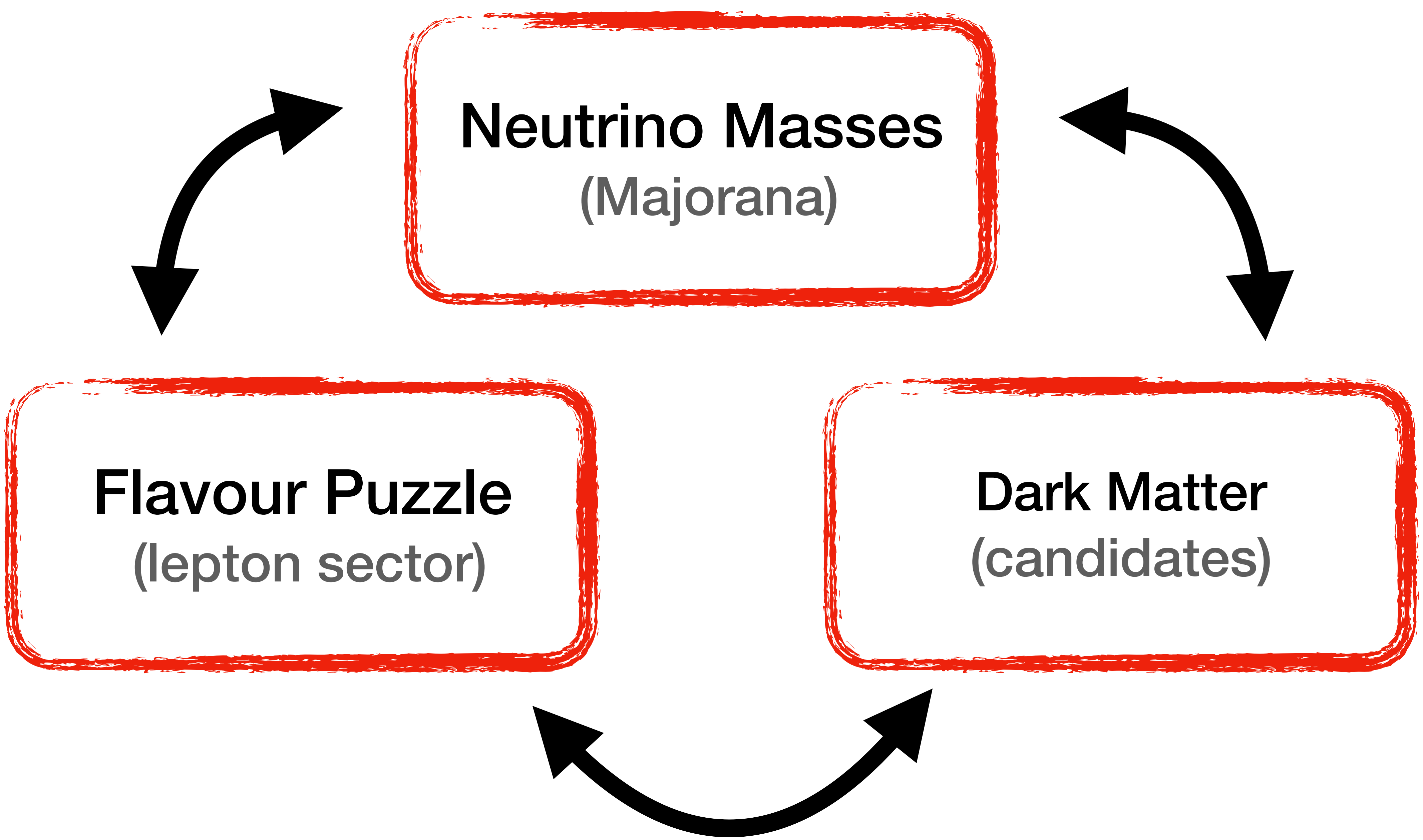
Three reasons for going BSM

Neutrino Masses
(Majorana)

Flavour Puzzle
(lepton sector)

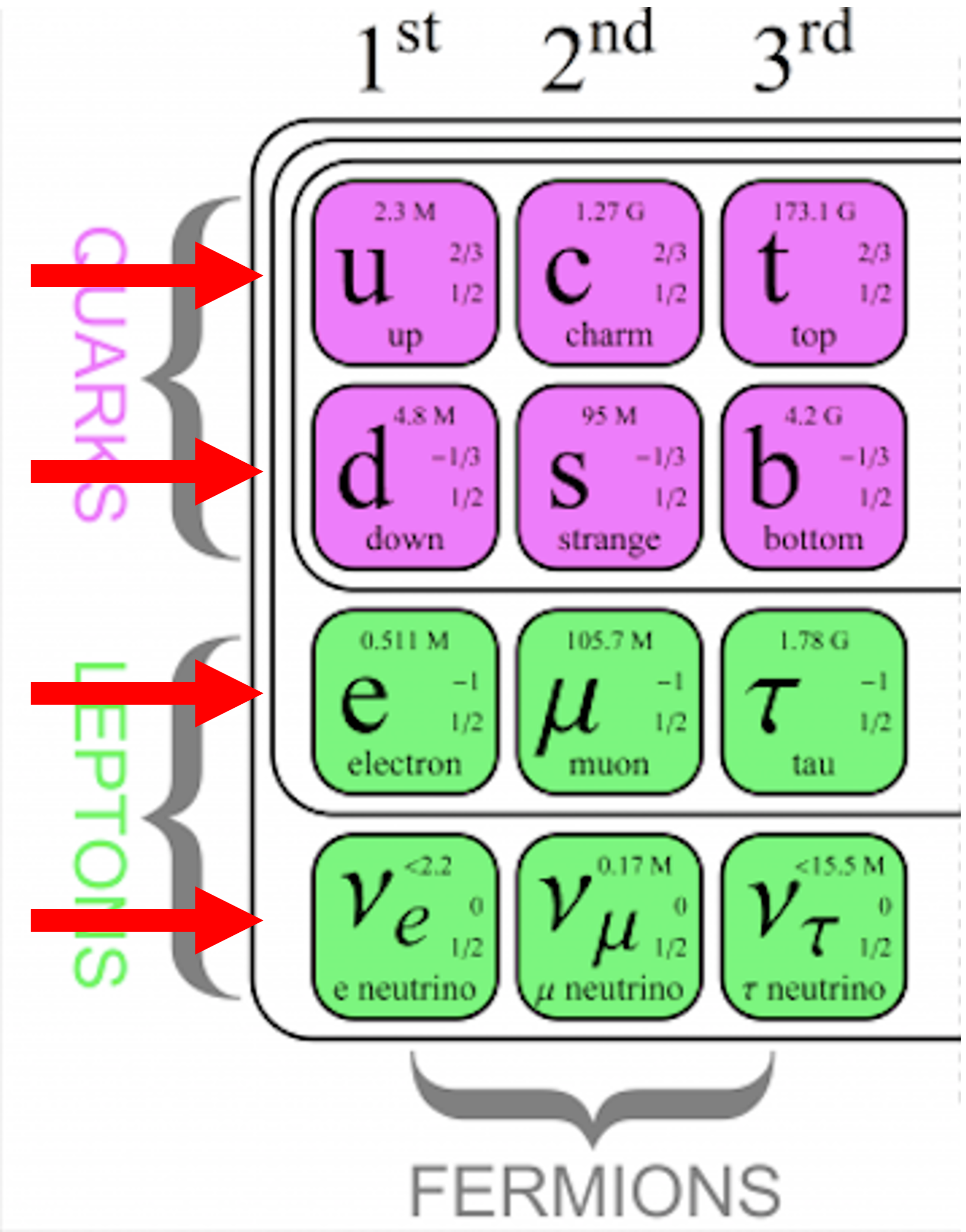
Going BSM

Three reasons for going BSM



Basic Concepts Review

The Flavour Puzzle



- The $\mathscr{L}_{SM}$ is **built** to be invariant under

$$SU(3)_c \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{\text{Electroweak Sector}}.$$

- The SM gauge group is **generation blind**, preserves a $U(3)^5$ **flavor symmetry**

The Flavour Puzzle

- **Yukawa interaction**
    - is **not** based on the gauge principle.

The Flavour Puzzle

- **Yukawa interaction**

  - is **not** based on the gauge principle.

  - In the SM **breaks** the flavour symmetry

Lots of input parameters!

$$-\underline{Y_e^{ij}}\overline{L}_{iL}^{I}\Phi e_{jR}^{I}, \qquad Y_e = \begin{pmatrix} Y_e^{ee} & Y_e^{e\mu} & Y_e^{e\tau} \\ Y_e^{\mu e} & Y_e^{\mu\mu} & Y_e^{\mu\tau} \\ Y_e^{\tau e} & Y_e^{\tau\mu} & Y_e^{\tau\tau} \end{pmatrix}$$

The Flavour Puzzle

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- The CKM matrix and the PMNS matrix **translate flavor symmetry breaking** to the gauge sector

$$U_{CKM}, \quad V_{LMM}$$

The Flavour Puzzle

- 5 of the SM are from gauge interaction

$$\{g_e,\ \theta_W,\ g_s,\ v_h,\ m_h\}$$

The Flavour Puzzle

- 5 of the SM are from gauge interaction

$$\{g_e,\ \theta_W,\ g_s,\ v_h,\ m_h\}$$

- 22 out of the 27 parameter come from the Yukawa sector

$$\{m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3},\ m_d,\ m_s,\ m_b,\ m_u,\ m_c,\ m_b\}$$

$$\{\theta^l_{12},\ \theta^l_{13},\ \theta^l_{23},\ \delta^l,\ \phi_{12},\ \phi_{13},\ \theta^q_{12},\ \theta^q_{13},\ \theta^q_{23},\ \delta^q\}$$

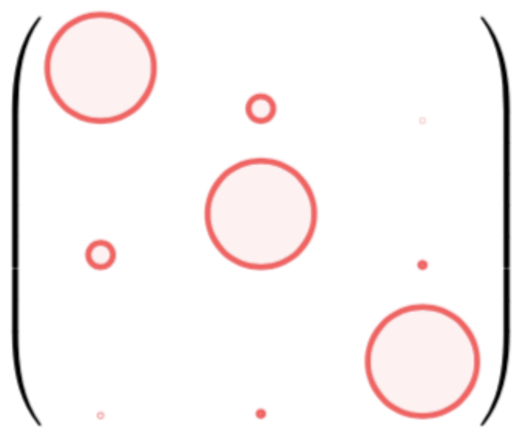
Huge hint of the existence of a more fundamental theory.

The Flavour Puzzle

- 22 out of the 27 parameters of the SM are in the Yukawa sector. Not constrained by **symmetry**

CKM

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \sim$$



,

PMNS (Normal Ordering)

$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} \sim$$

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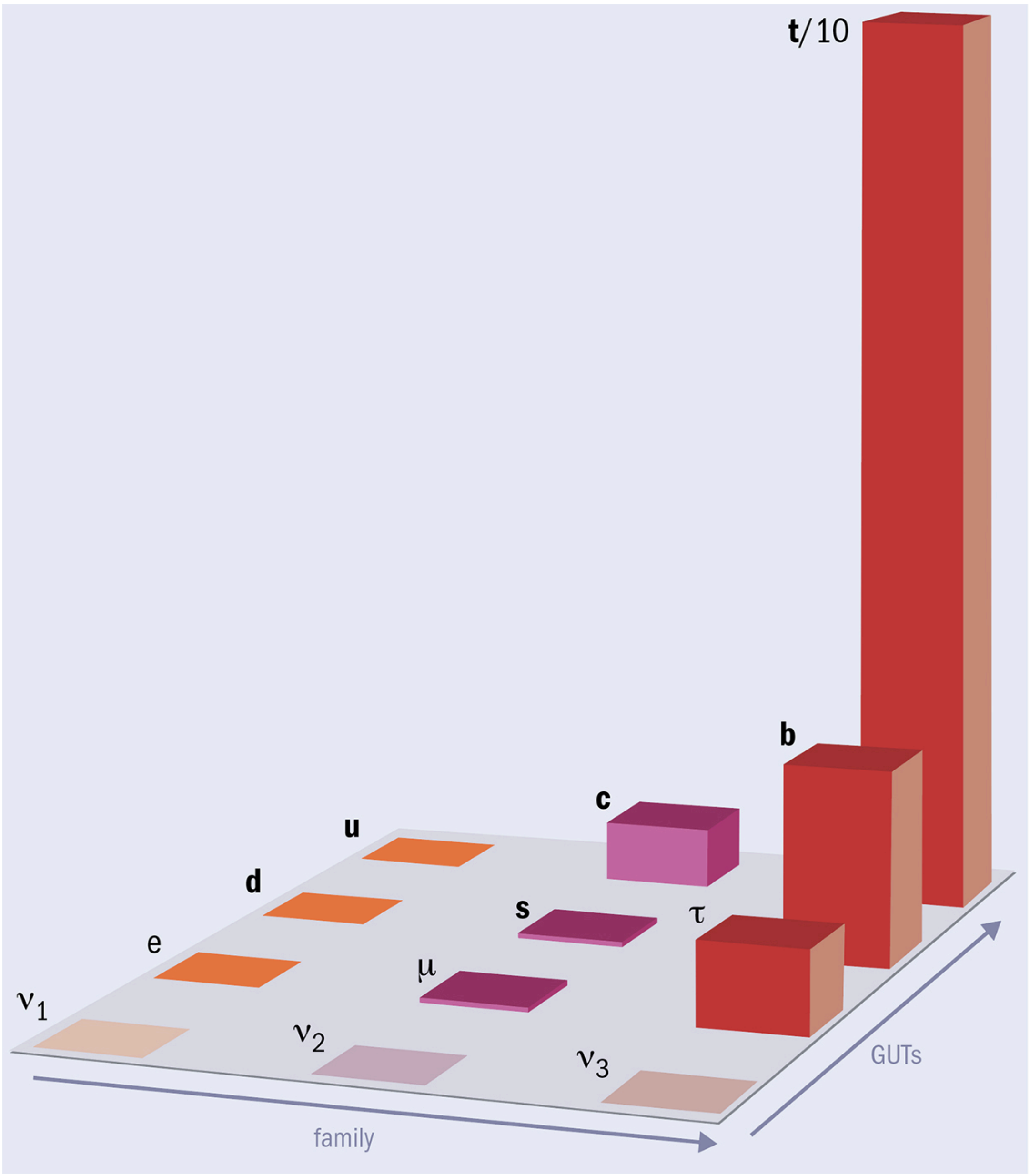
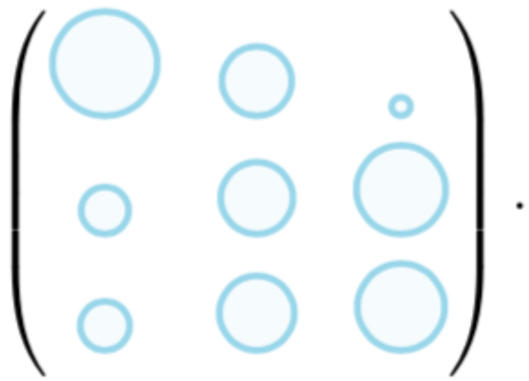


The Flavour Puzzle

- In the lepton sector: Neutrino Oscillation Parameters

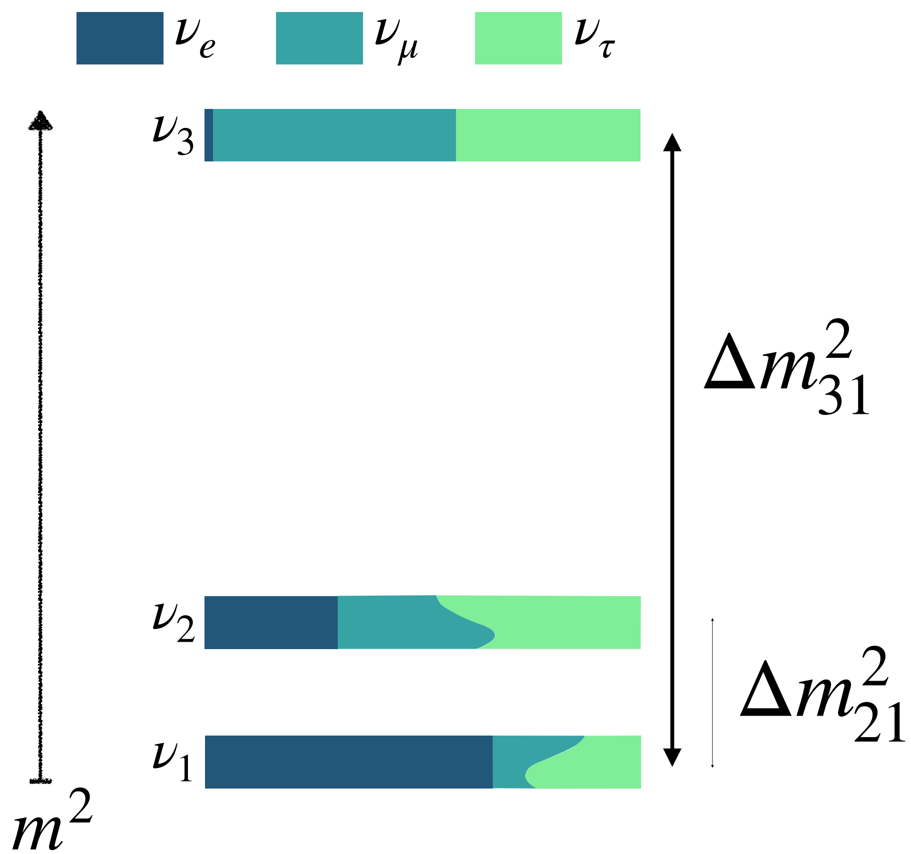
$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} \sim$$



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

$$\delta^{CP} \quad \Delta m^2_{21} \quad \Delta m^2_{31}$$

Neutrino Masses (NO)



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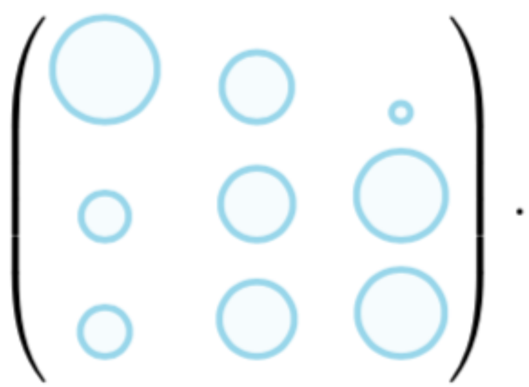

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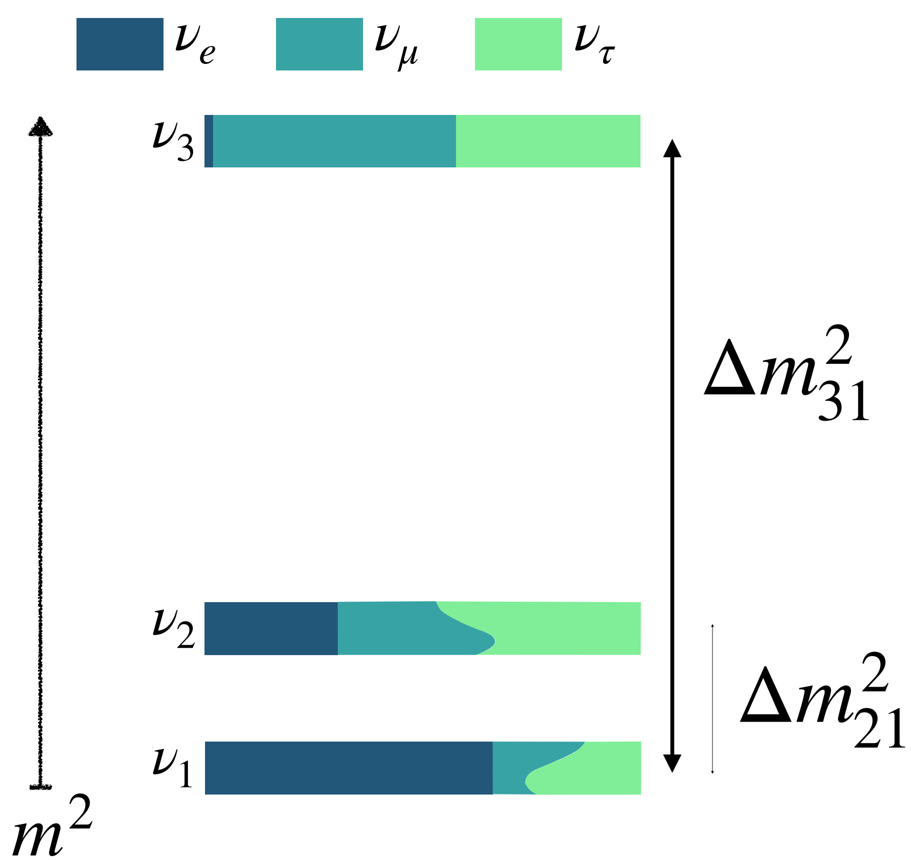


- Two orders of magnitude hierarchy

$$\Delta m^2_{31} \gg \Delta m^2_{21}$$

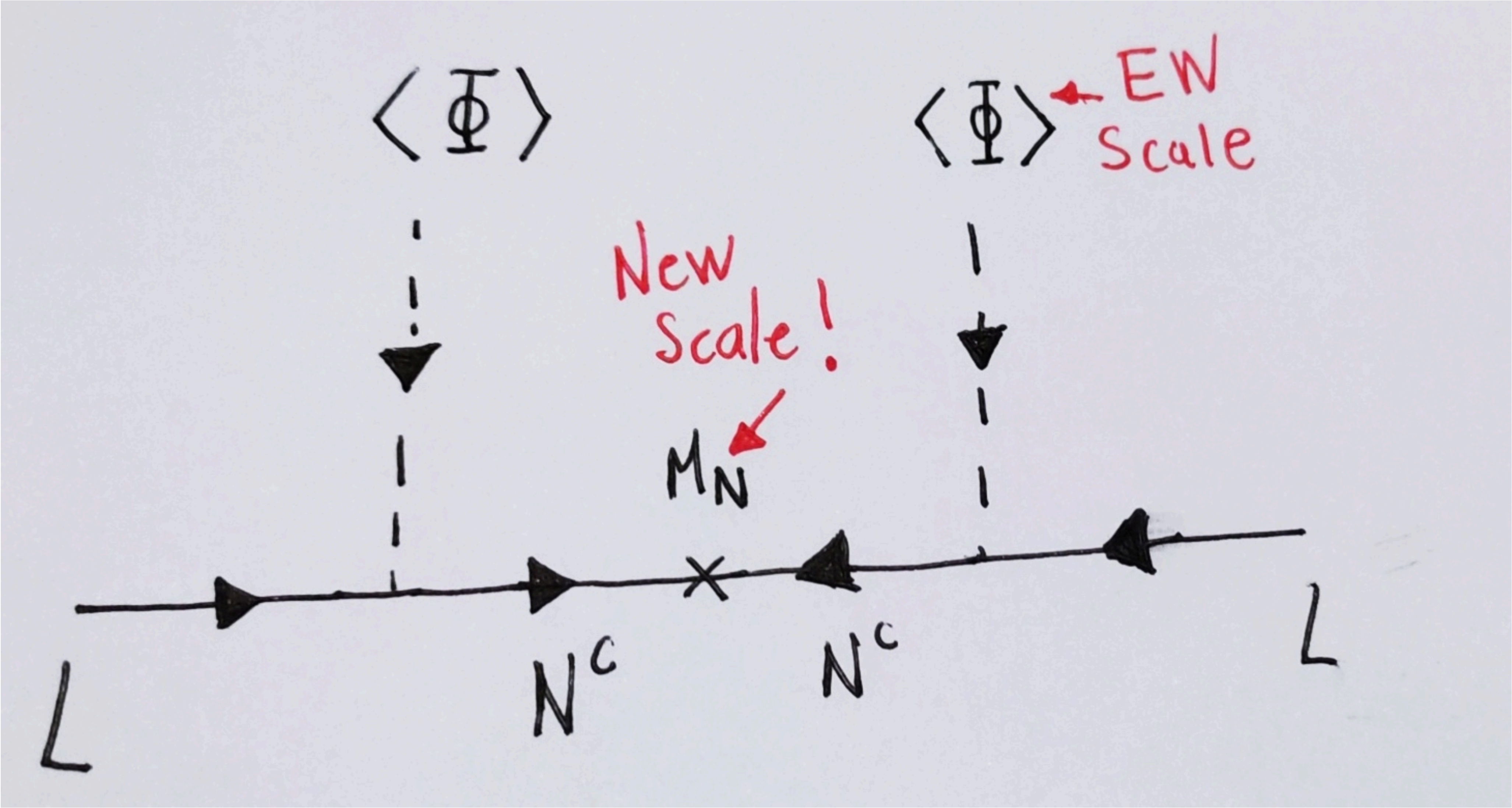
Neutrino Global Fit (Valencia)

Neutrino mass mechanisms

The seesaw mechanism

[Minkowski,77]
[Yanaguida,80]
[Mahopatra and Senjanović ,80]
[Schechter and Valle ,80]

- Explains the lightness of neutrinos
- Introduces Heavy Neutral Leptons N^c
- Introduces a **new physics scale**! (LNV)



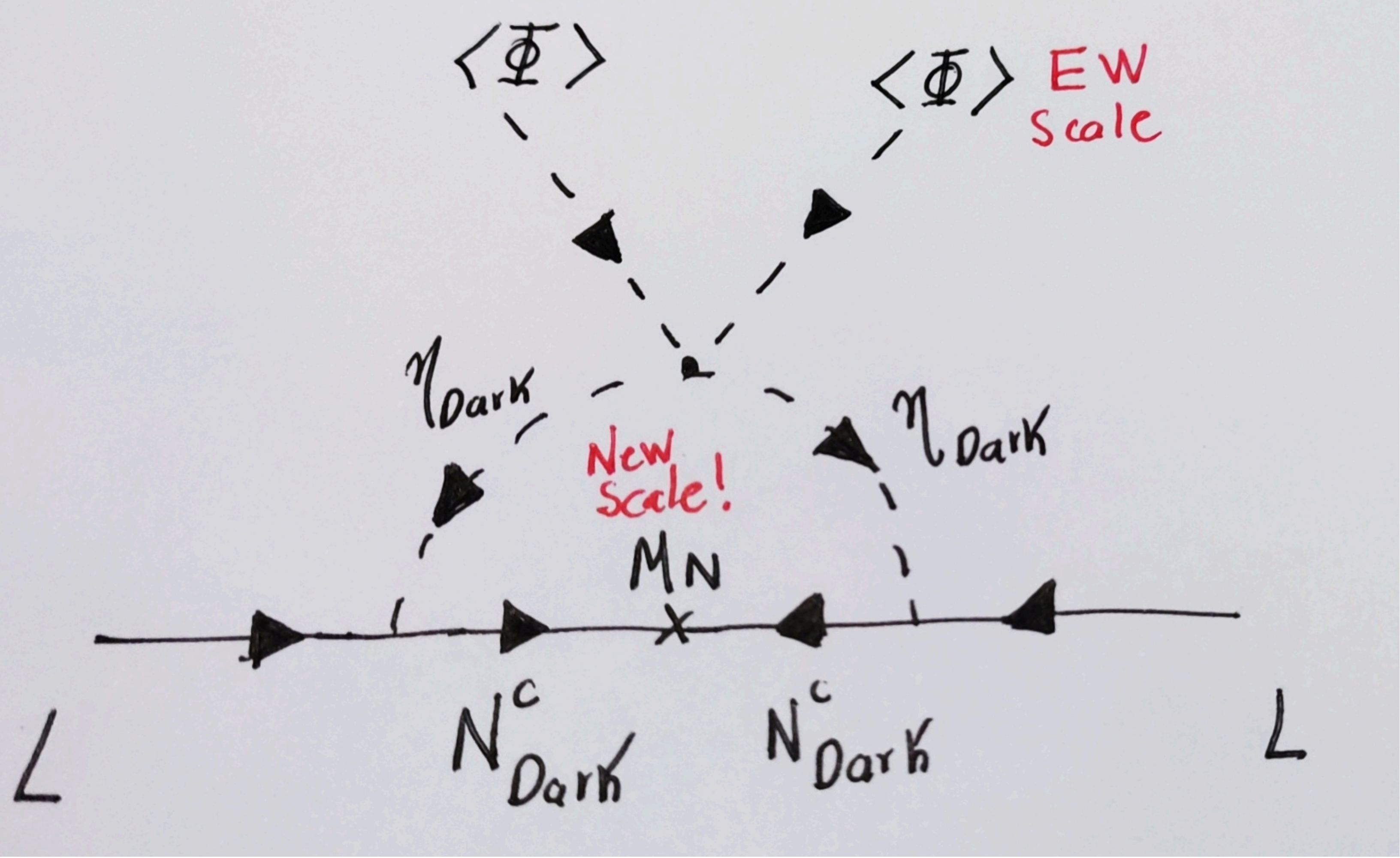
Neutrino mass mechanisms

The Scotogenic Mechanism

[Ma,2006]

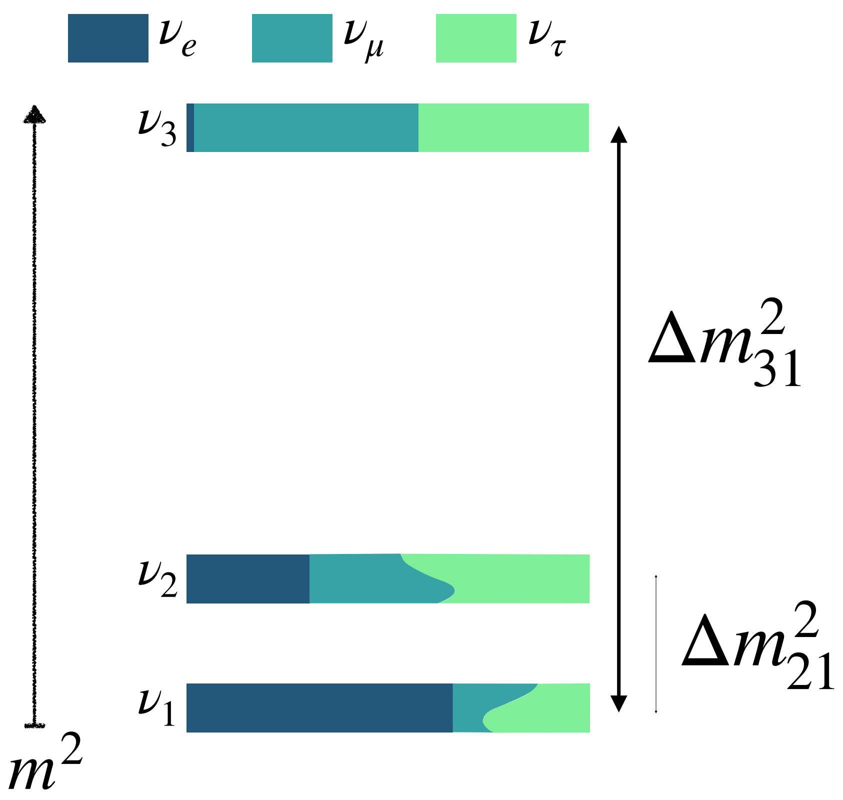
- Additional $\mathbb{Z}_2$ symmetry and new Higgs-doublet
- **Dark Matter** generates neutrino mass.

$$N^c \sim -1, \quad \eta \sim -1 \quad \textbf{under} \quad \mathbb{Z}_2$$



Scoto-seesaw Mechanism

Neutrino Masses (NO)



$$\Delta m^2_{\rm ATM} \sim \left(\frac{v^2}{M_N}\mathbb{Y}^2_{(N)}\right)^2 ,$$

$$\Delta m^2_{\rm SOL} \sim \left(\frac{1}{32\pi^2}\right)^2 \left(\frac{\lambda_5 v^2}{M_f^2 - m_\eta^{(R)2}} M_f \mathbb{Y}^2_{(f)}\right)^2 .$$

$$\frac{\Delta m^2_{\rm SOL}}{\Delta m^2_{\rm ATM}} \sim \left(\frac{1}{32\pi^2}\right)^2 \lambda_5^2 \left(\frac{M_N M_f}{M_f^2 - m_\eta^{(R)2}}\right)^2 \left(\frac{\mathbb{Y}^2_{(f)}}{\mathbb{Y}^2_{(N)}}\right)^2$$

Flavour Symmetry

- **Flavour symmetry** at high-energy regime.

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \underbrace{\otimes\, G}_{\text{Flavour}} .$$

- Constraining, or relating the Yukawa coupling structure

$$\underbrace{G}_{\text{Symmetry}} \xrightarrow{\text{SSB}} \underbrace{V_{\text{CKM}},\ U,\ \text{Mass Hierarchy}}_{\text{Flavour Observables}}.$$

- An appealling option are Discrete and Non-Abelian Groups

Forbids and Relates couplings

$$-Y_e^{ij} \overline{L}_{i\,L}^{\,I} \Phi e_{j\,R}^{\,I}, \qquad Y_e = \begin{pmatrix} Y_e^{ee} & Y_e^{e\mu} & Y_e^{e\tau} \\ Y_e^{\mu e} & Y_e^{\mu\mu} & Y_e^{\mu\tau} \\ Y_e^{\tau e} & Y_e^{\tau\mu} & Y_e^{\tau\tau} \end{pmatrix}$$

Flavour Symmetry

- The A_4 group

$$A_4 \simeq \left\{ S, T \mid S^2 = T^3 = (ST)^2 = \mathbf{1} \right\},$$

Four Irreps.

$$\mathbf{1}\,,\ \mathbf{1}'\,,\ \mathbf{1}''\,,\ \mathbf{3}.$$

$$\omega \equiv e^{\frac{2\pi i}{3}}.$$

$$\mathbf{1}: \quad S = 1, \quad T = 1,$$

$$\mathbf{1}': \quad S = 1, \quad T = \omega,$$

$$\mathbf{1}'': \quad S = 1, \quad T = \omega^2,$$

$$\mathbf{3}: \quad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix},$$

Flavour Symmetry

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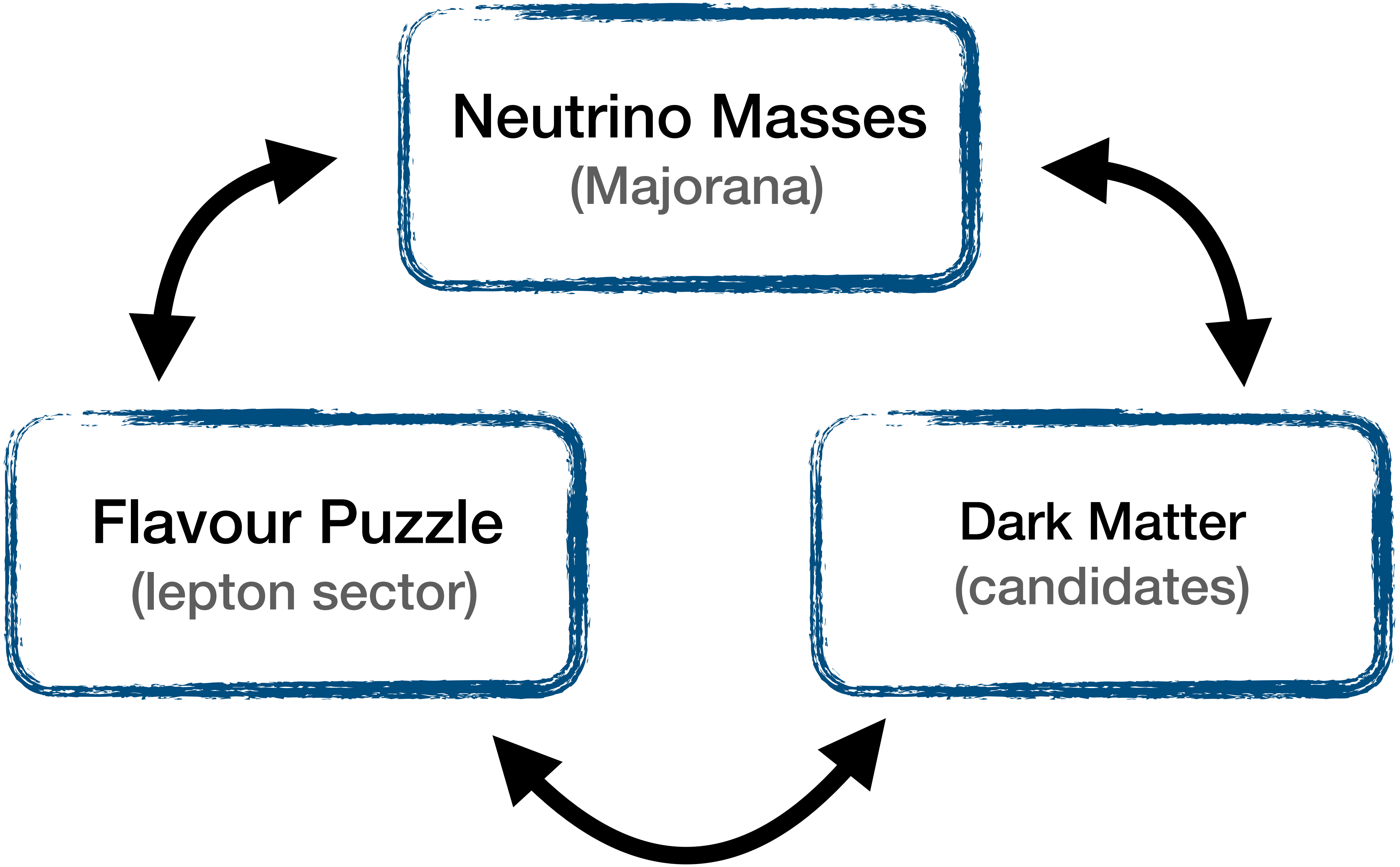
Generates a $\mathbb{Z}_2$ symmetry

The Discrete Dark Matter Model



The Discrete Dark Matter Model

- Fields and Symmetries (Lepton sector only)

[Hirsch,2010]
[Boucenna,2011]

	L_e	L_μ	L_τ	l_e	l_μ	l_τ	N_T	H	η
$SU(2)$	2	2	2	1	1	1	1	2	2
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	0	$\frac{1}{2}$	$\frac{1}{2}$
A_4	$1'$	1	$1''$	$1'$	1	$1''$	3	1	3

RH-Neutrinos

$$N_T = (N_1, N_2, N_3)$$

Mass degenerate m_N

Scalar iso-doublets

$$\eta = (\eta_1, \eta_2, \eta_3)$$

The Discrete Dark Matter Model

- Yukawa Lagrangian invariant under A_4

$$Y^{\eta_1} = \begin{pmatrix} y_1^\nu & 0 & 0 \\ y_2^\nu & 0 & 0 \\ y_3^\nu & 0 & 0 \end{pmatrix}, \quad Y^{\eta_2} = \begin{pmatrix} 0 & y_1^\nu \omega^2 & 0 \\ 0 & y_2^\nu & 0 \\ 0 & y_3^\nu \omega & 0 \end{pmatrix}, \quad Y^{\eta_3} = \begin{pmatrix} 0 & 0 & y_1^\nu \omega \\ 0 & 0 & y_2^\nu \\ 0 & 0 & y_3^\nu \omega^2 \end{pmatrix}, \quad \text{with} \quad \omega = e^{i\frac{2\pi}{3}}.$$

- Electroweak and Flavour symmetry breakdown

$$\langle H^0 \rangle = v_H \neq 0, \qquad \langle \eta_1^0 \rangle = v_{\eta_1} \neq 0, \qquad \langle \eta_{2,3}^0 \rangle = 0,$$

SM Higgs couple to charged leptons

$$\frac{v_H}{\sqrt{2}} Y_l^H = \frac{v_H}{\sqrt{2}} \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}.$$

$$\langle \eta^0 \rangle = \begin{pmatrix} v_{\eta_1} \\ 0 \\ 0 \end{pmatrix}$$

The Discrete Dark Matter Model

- Remnant $\mathbb{Z}_2$ symmetry from A_4

A_4	$\mathbb{Z}_2$
$\mathbf{1}$	$\mathbf{1}_+$
$\mathbf{1}'$	$\mathbf{1}_+$
$\mathbf{1}''$	$\mathbf{1}_+$
$\mathbf{3}$	$\mathbf{1}_+ \oplus \mathbf{1}_- \oplus \mathbf{1}_-$

$$\langle \eta^0 \rangle = \begin{pmatrix} v_{\eta_1} \\ 0 \\ 0 \end{pmatrix}$$

↓

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

The Discrete Dark Matter Model

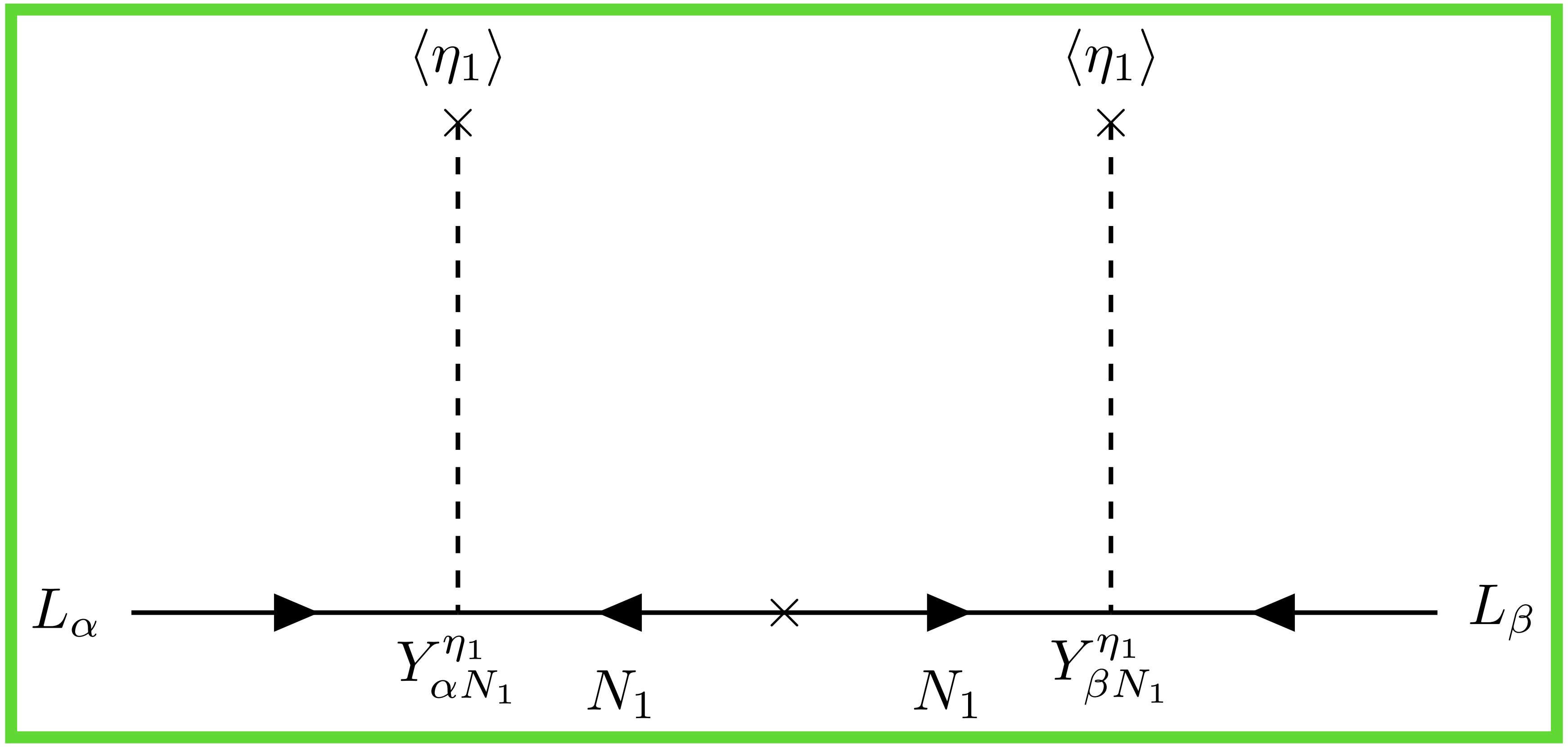
- Remnant $\mathbb{Z}_2$ symmetry from A_4

$$\mathbb{Z}_2$$

$+1$	-1
Active Sector	**Dark Sector**
SM; $N_1, \quad H, \quad \eta_1$	$N_2, \quad N_3, \quad \eta_2 \quad \eta_3$

The Discrete Dark Matter Model

- **Active fields (Tree level)** $H, \quad N_1, \quad \eta_1$



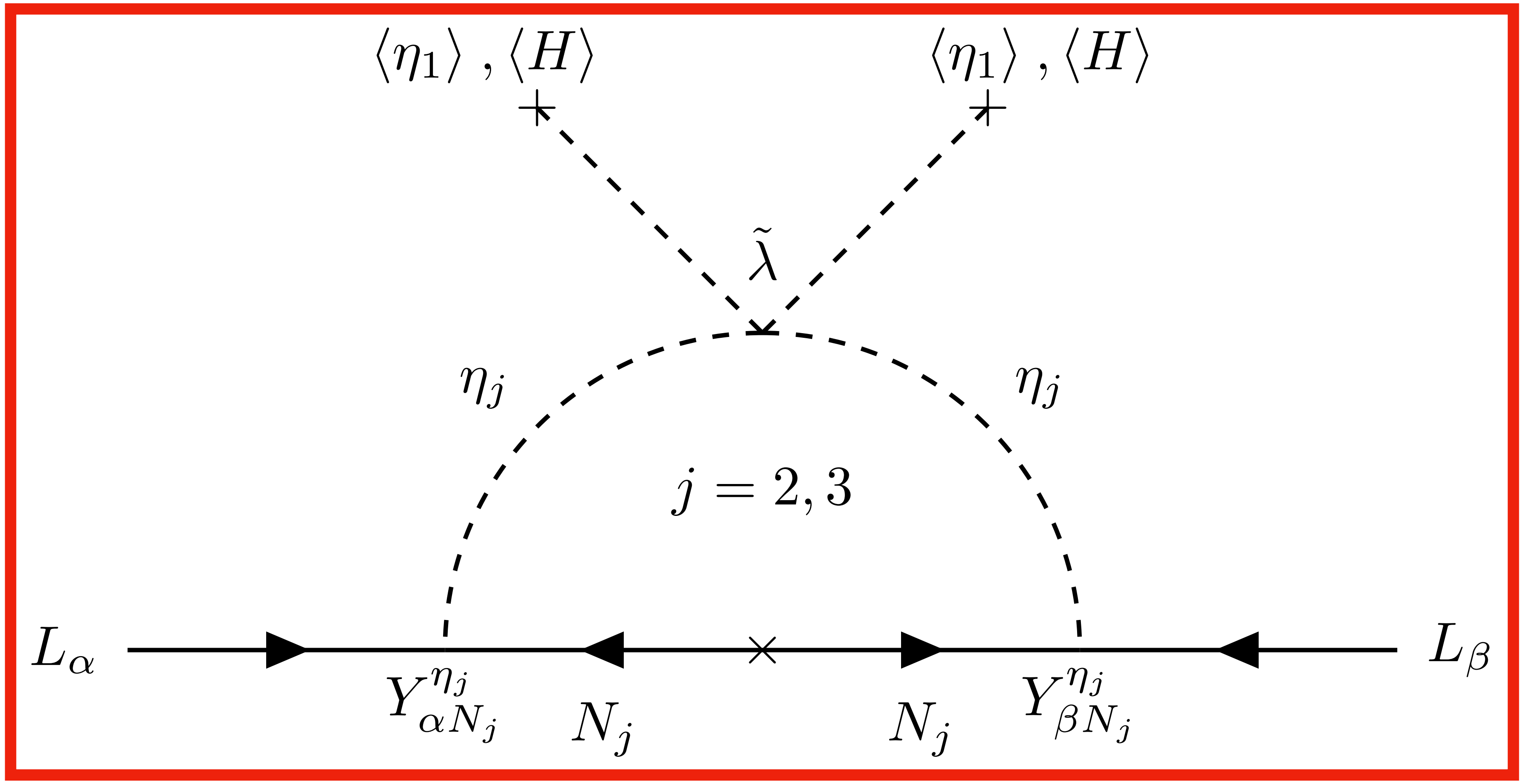
- Main contribution to: (Plus one-loop corrections)

$$\Delta m^2_{31}$$ (Normal Ordering)

The Discrete Dark Matter Model

- **Dark fields (one-loop)**

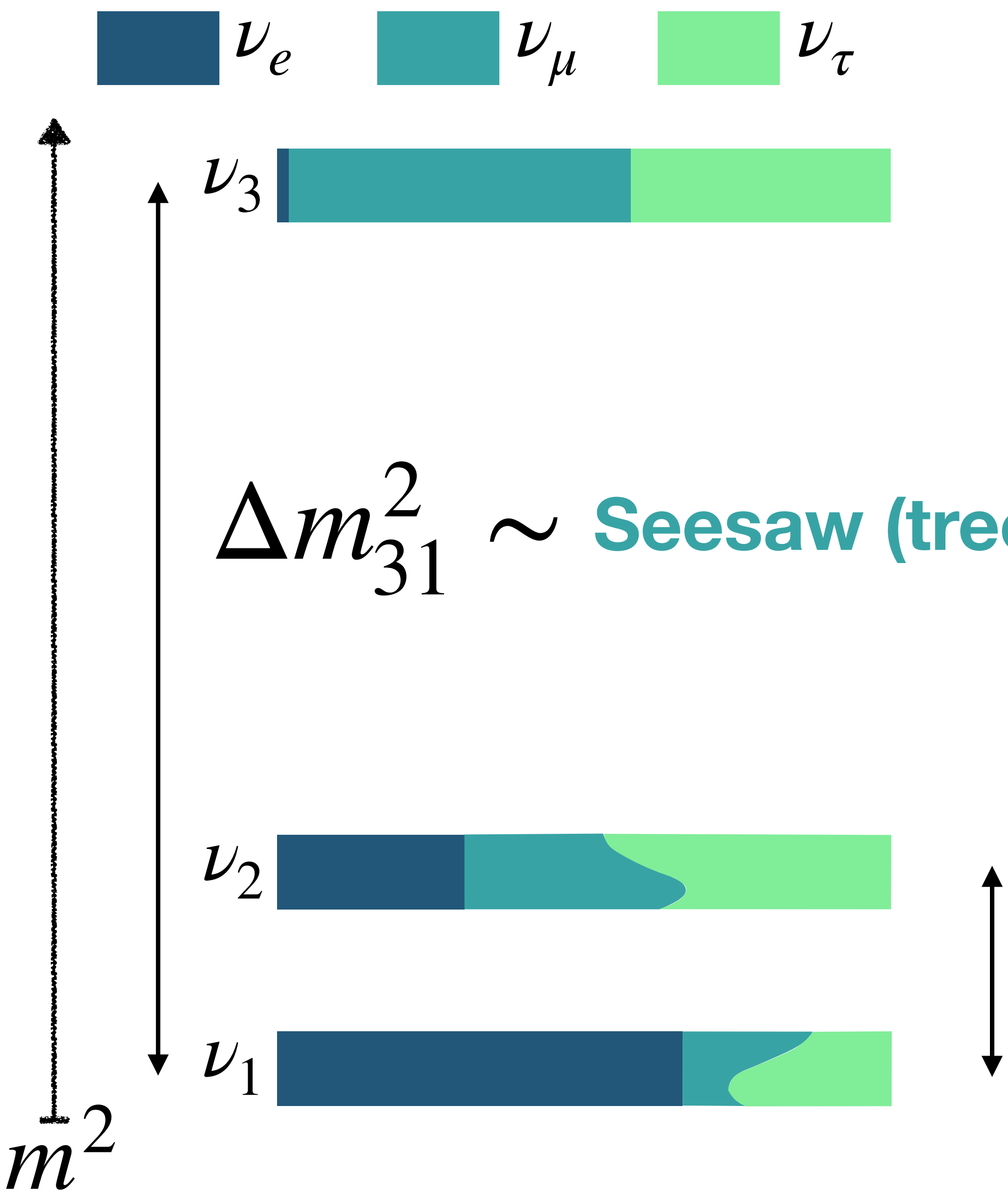
$$N_2, \quad N_3, \quad \eta_2 \quad \eta_3$$



- Main contribution to: Δm^2_{21} (Normal Ordering)

A Special Scotoseesaw

Both mechanism share the same Yukawa couplings



Neutrino Masses (NO)

$\Delta m^2_{31} \sim$ Seesaw (tree-level)

$H, \quad N_1, \quad \eta_1$

$\Delta m^2_{21} \sim$ Scotogenic (one-loop)

$N_2, \quad N_3, \quad \eta_2 \quad \eta_3$

A Special Scotoseesaw

Both mechanism share the same Yukawa couplings

[N. Rojas, R. Srivastava, J.W.F. Valle, 2019]

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$$\Delta m^2_{\text{SOL}} \sim \left(\frac{1}{32\pi^2}\right)^2\left(\frac{\lambda_5 v^2}{M_f^2 - m_\eta^{(R)2}}M_f\mathbb{Y}^2_{(f)}\right)^2.$$

$y_1^\nu, \quad y_2^\nu, \quad y_3^\nu$

m_N

Natural Hierarchy from Flavor Symmetry

Explicit CP violation

- **CP-violation** for the dark sector is **necessary** to fit **lepton mixing**

$$M^2_{\text{neutral}} = \begin{pmatrix} M^2_{H'_0 H'_1} & 0 & 0 & 0 \\ 0 & M^2_{A'_0 A'_1} & 0 & 0 \\ 0 & 0 & M^2_{H'_2 H'_3} & M^2_{\text{CPV}} \\ 0 & 0 & M^2_{\text{CPV}} & M^2_{A'_2 A'_3} \end{pmatrix}$$

$\sin^2\theta^l_{13}$ $\sin^2\theta^l_{12}$ $\sin^2\theta^l_{23}$ δ^{CP}

Δm^2_{21} Δm^2_{31}

Neutrino Global Fit (Valencia)

Parameter	Value
y_e	3.96×10^{-6}
y_μ	8.35×10^{-4}
y_τ	1.42×10^{-2}
y_1^ν	-1.41×10^{-5}
y_2^ν	8.05×10^{-5}
y_3^ν	-1.47×10^{-4}
$v_{\eta 1}$/GeV	173.94
v_H/GeV	173.95
m_N/GeV	9.59×10^6
λ_1	0.732
λ_2	3.5
λ_3	-2.532
λ_4	-1.205
λ_5	1.16
λ_6	3.492
λ_7	3.489
λ_8	-1.017
λ_9	-1.118
λ_{10}	-0.7
φ_5	0.524
φ_9	0.562
φ_{10}	2.134

Observable	Data		Best fit
	Central value	1σ range	
$\sin^2\theta_{12}/10^{-1}$	3.18	$3.02 \to 3.34$	2.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	2.200	$2.138 \to 2.269$	2.222
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74	$5.60 \to 5.88$	5.82
δ^ℓ $/\pi$ (NO)	1.08	$0.96 \to 1.21$	1.00
$\Delta m_{21}^2/(10^{-5}\,\mathrm{eV}^2)$	7.50	$7.30 \to 7.72$	7.43
$\Delta m_{31}^2/(10^{-3}\,\mathrm{eV}^2)$ (NO)	2.55	$2.52 \to 2.57$	2.55
$m_{\mathrm{lightest}}^\nu$ /meV (NO)			5.45
m_2^ν /meV			10.20
m_3^ν /meV			50.81
ϕ_{12}/π			0.5
ϕ_{13}/π			0.5
ϕ_{23}/π			1.0
$\langle m_{\beta\beta}\rangle$/eV			3.66×10^{-4}
m_e /MeV	0.486	$0.486 \to 0.486$	0.486
m_μ /GeV	0.102	$0.102 \to 0.102$	0.102
m_τ /GeV	1.746	$1.743 \to 1.747$	1.746
v/GeV	246	$246 \to 246$	246
M_H/GeV (Higgs boson)	125.25	$125.08 \to 125.42$	125.30
M_{DM}/GeV (scalar DM)			59
M_N/GeV			9.59×10^6
M_{H_0}/GeV (Heavy Higgs)			295
M_{A_0}/GeV (Pseudoscalar)			701
$M_{H_0}^+$/GeV (Active)			375
$M_{\chi_1^+}$/GeV (Dark)			469
$M_{\chi_2^+}$/GeV (Dark)			388
$M_{\chi_1}^0$/GeV (Dark)			618
$M_{\chi_2}^0$/GeV (Dark)			547
$M_{\chi_3}^0$/GeV (Dark)			440
$\lambda_{\chi h}$			1.0×10^{-3}

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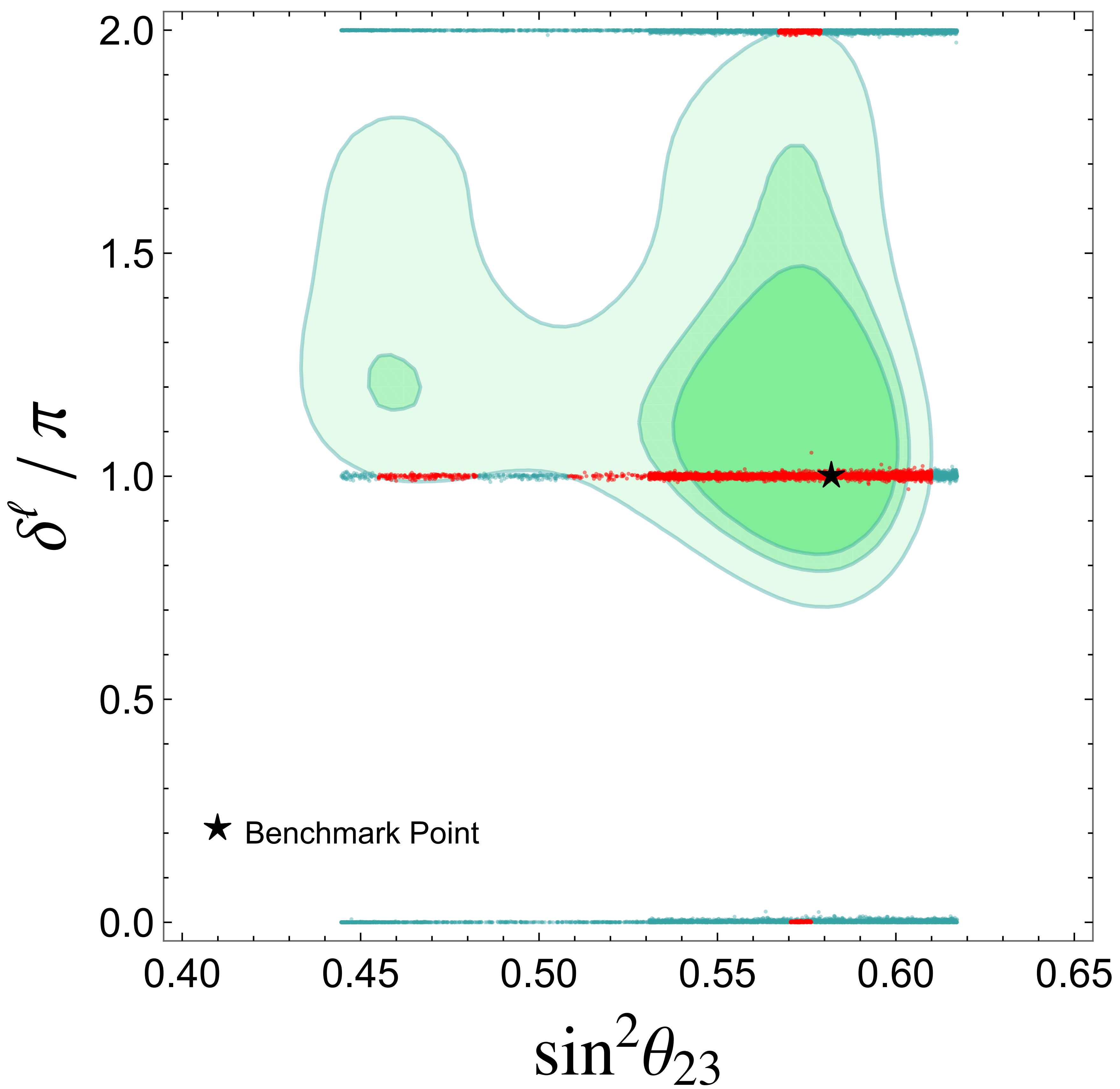
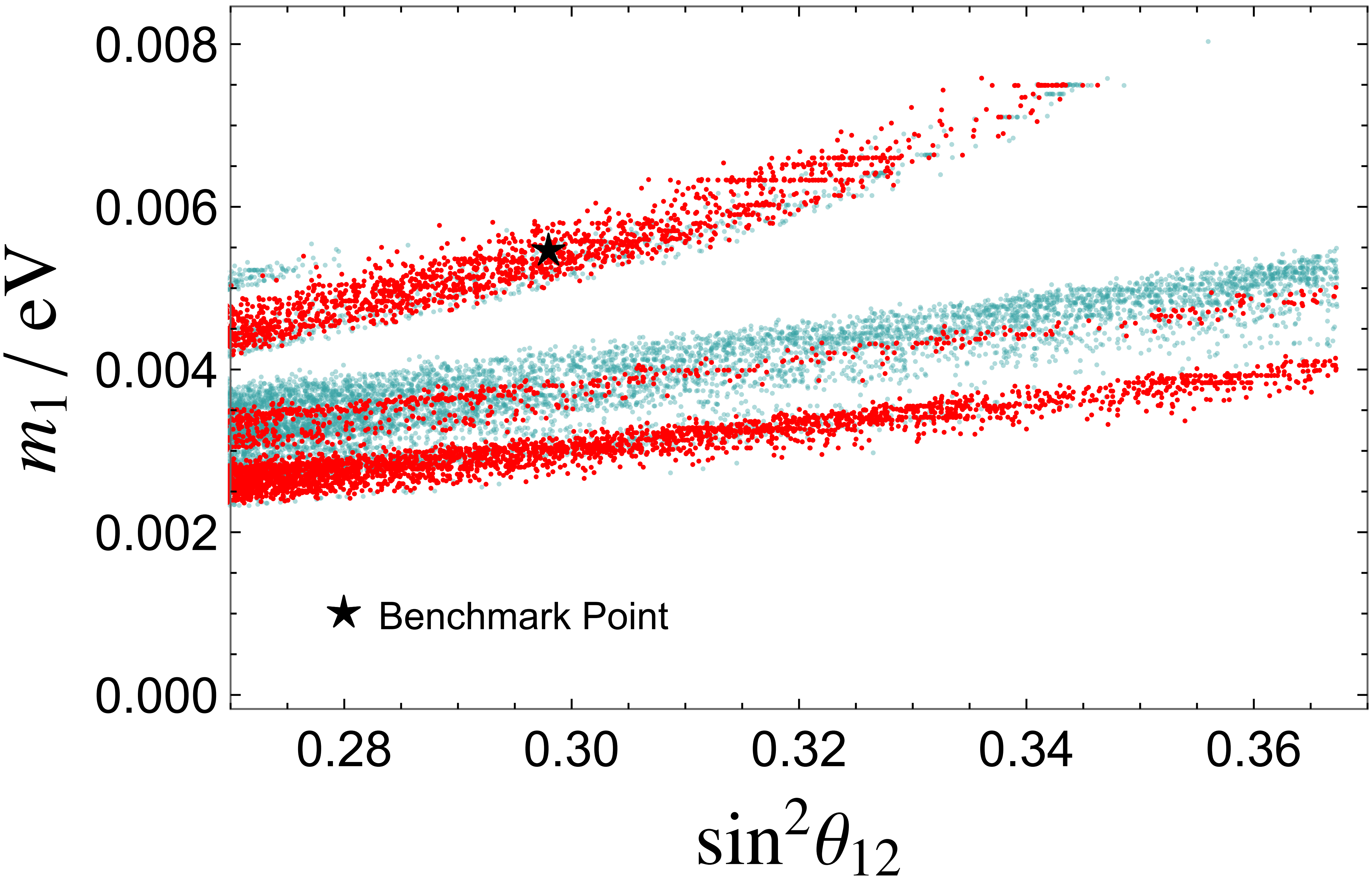
Scalar DM particle

Neutrino Global Fit (Valencia)

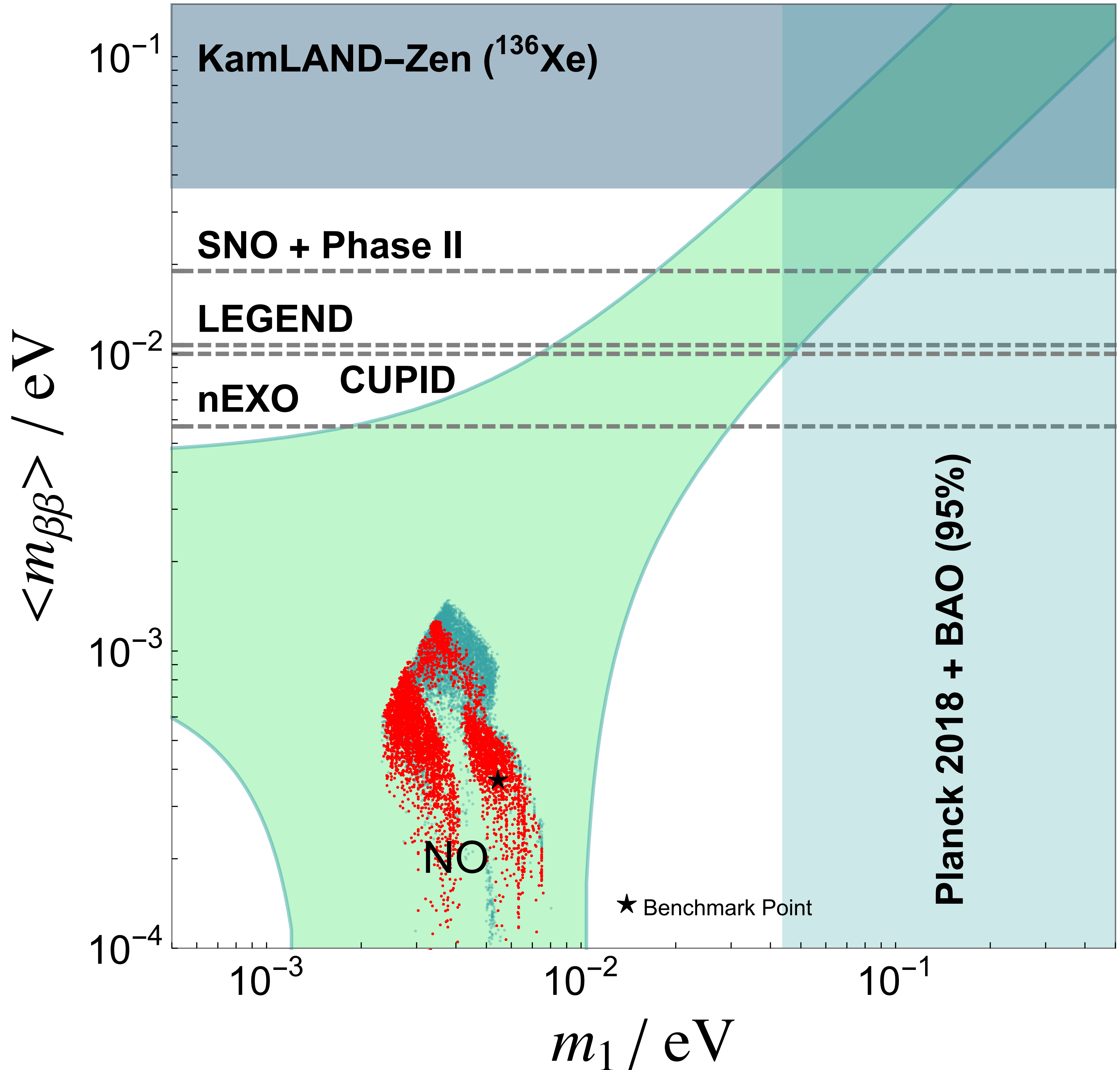
CP-violation



Lightest Neutrino



Neutrinoless double beta decay



Conclusions

The Discrete Dark Matter Model

From a $A_4 \longrightarrow \mathbb{Z}_2$ a special scoto-seesaw emerges

- Predicts Normal Ordering, and reproduces lepton **masses** and **mixings**.

$$\sin^2\theta_{12}, \quad \sin^2\theta_{12}, \quad \sin^2\theta_{23} \qquad \delta_l^{CP} \sim \pi \qquad \text{(Normal Ordering)}$$

- **Scotogenic-Seesaw** mass mechanism for neutrinos.

$$2 \lessapprox m_1^\nu \lessapprox 8\,[meV] \qquad \langle m_{\beta\beta}\rangle \sim 0.2\,[meV]$$

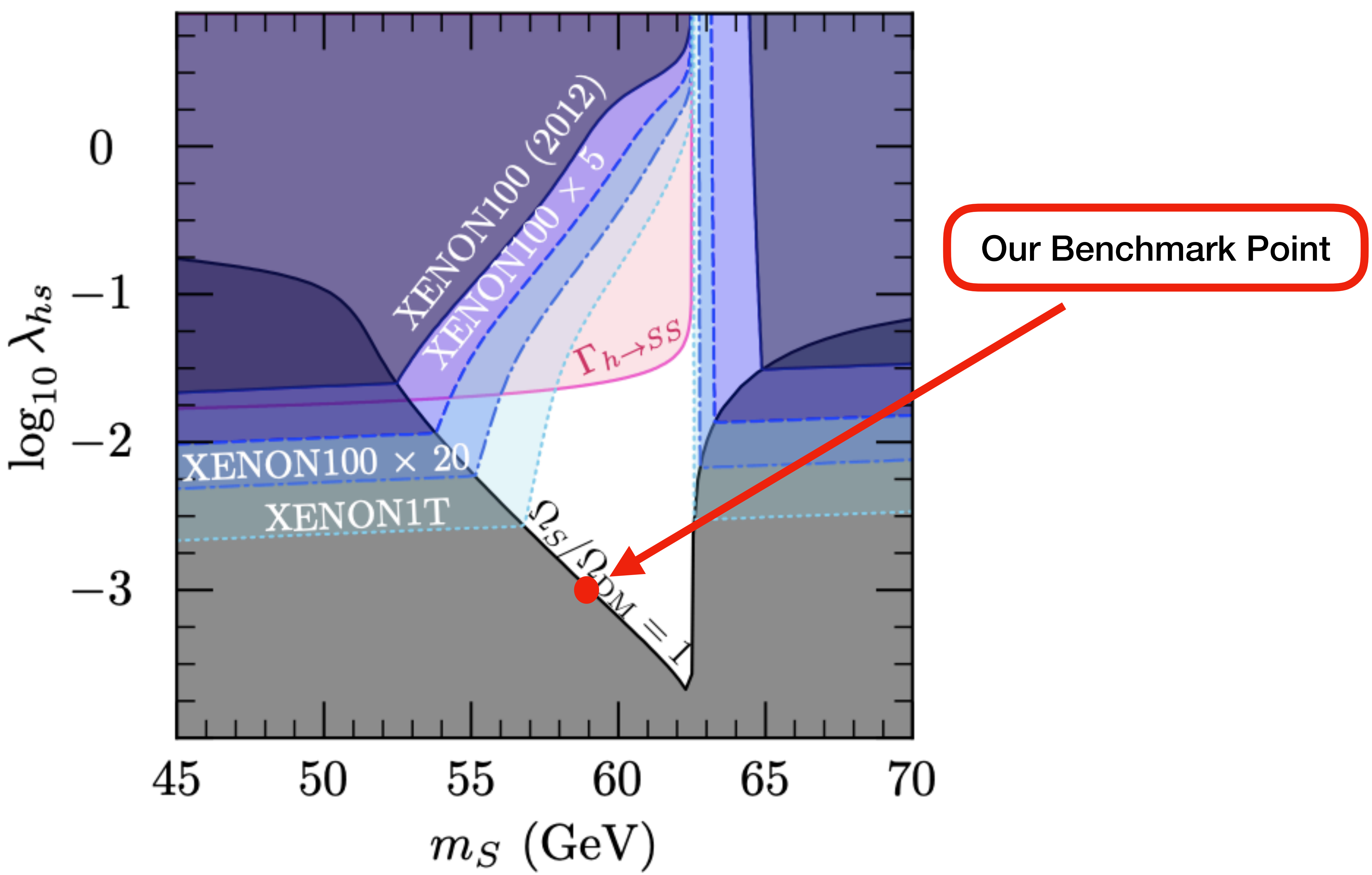
- **Naturally explains the hierarchy** (seesaw dominates over scotogenic):

$$\Delta m_{31}^2 \gg \Delta m_{21}^2$$

- Rich scalar sector: with CP-violation which Includes a Scalar Dark Matter candidate stabilized by a remnant symmetry

Scalar DM in the Model

- **The model has a scalar DM particle**



Seesaw One-loop corrections