Neutrino mass hierarchy from the **Discrete Dark Matter** model

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Outline

- 🔥 **Motivation**
- 🔥 **Aim of this Model**
- 🔥 **Elements & Properties**
- 🔥 **Phenomenology**
- 🔥 **Conclusions**

Going BSM

Three drawbacks of the SM that we tackled with this model

Neutrino Masses
(Majorana)

Going BSM

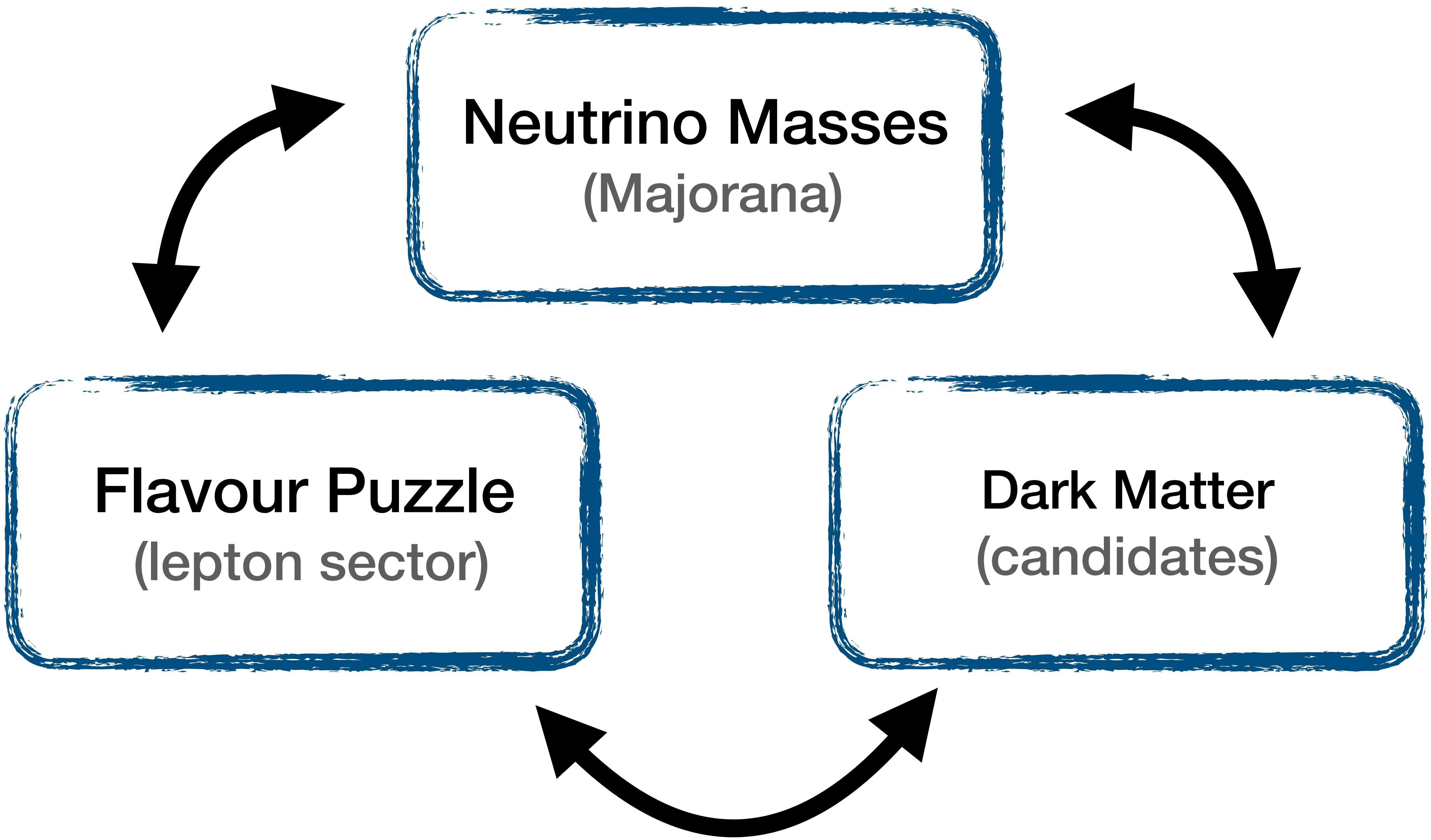
Three drawbacks of the SM that we tackled with this model

Neutrino Masses
(Majorana)

Flavour Puzzle
(lepton sector)

Going BSM

Three drawbacks of the SM that we tackled with this model

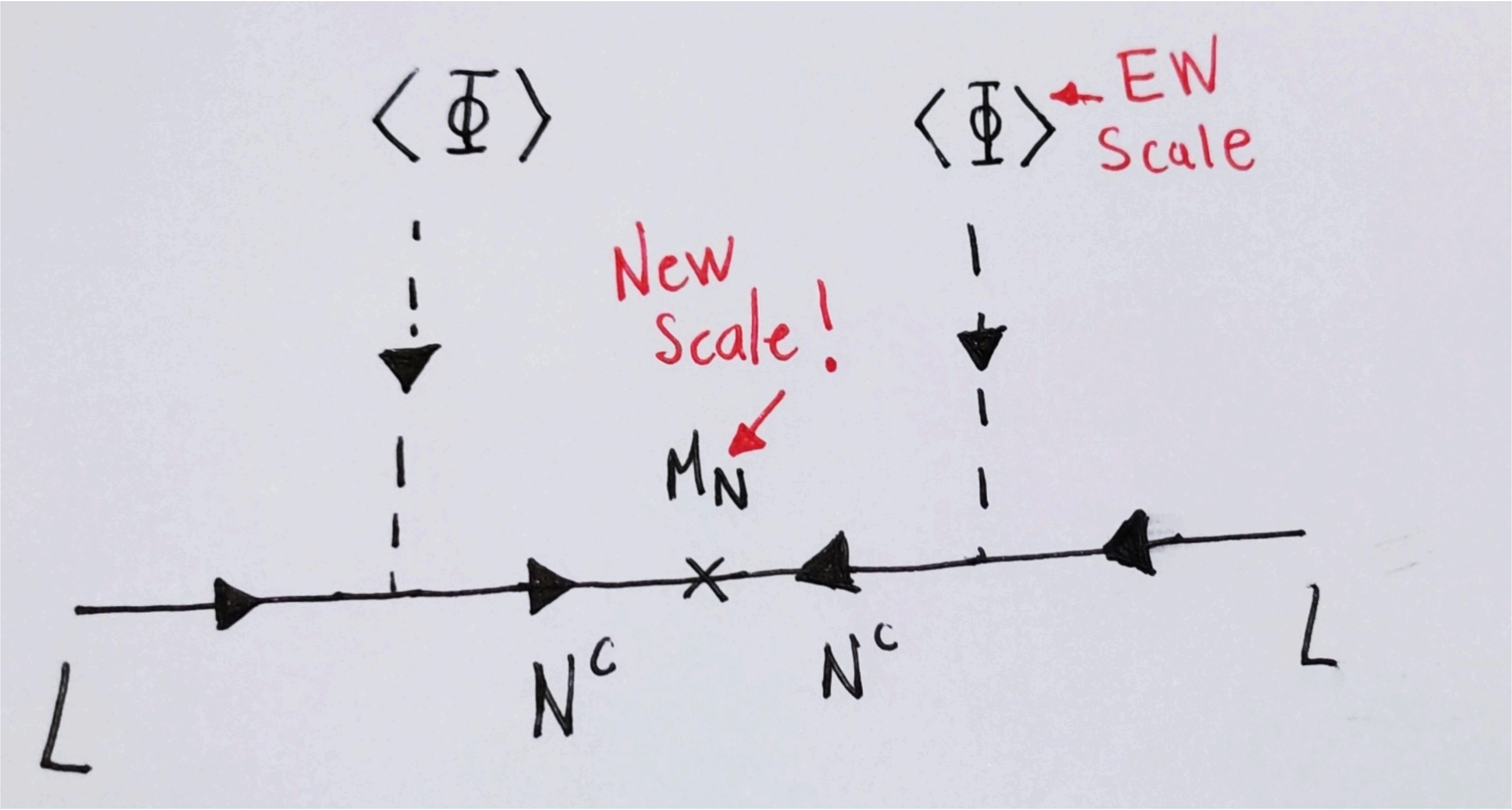


Neutrino mass mechanisms

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)



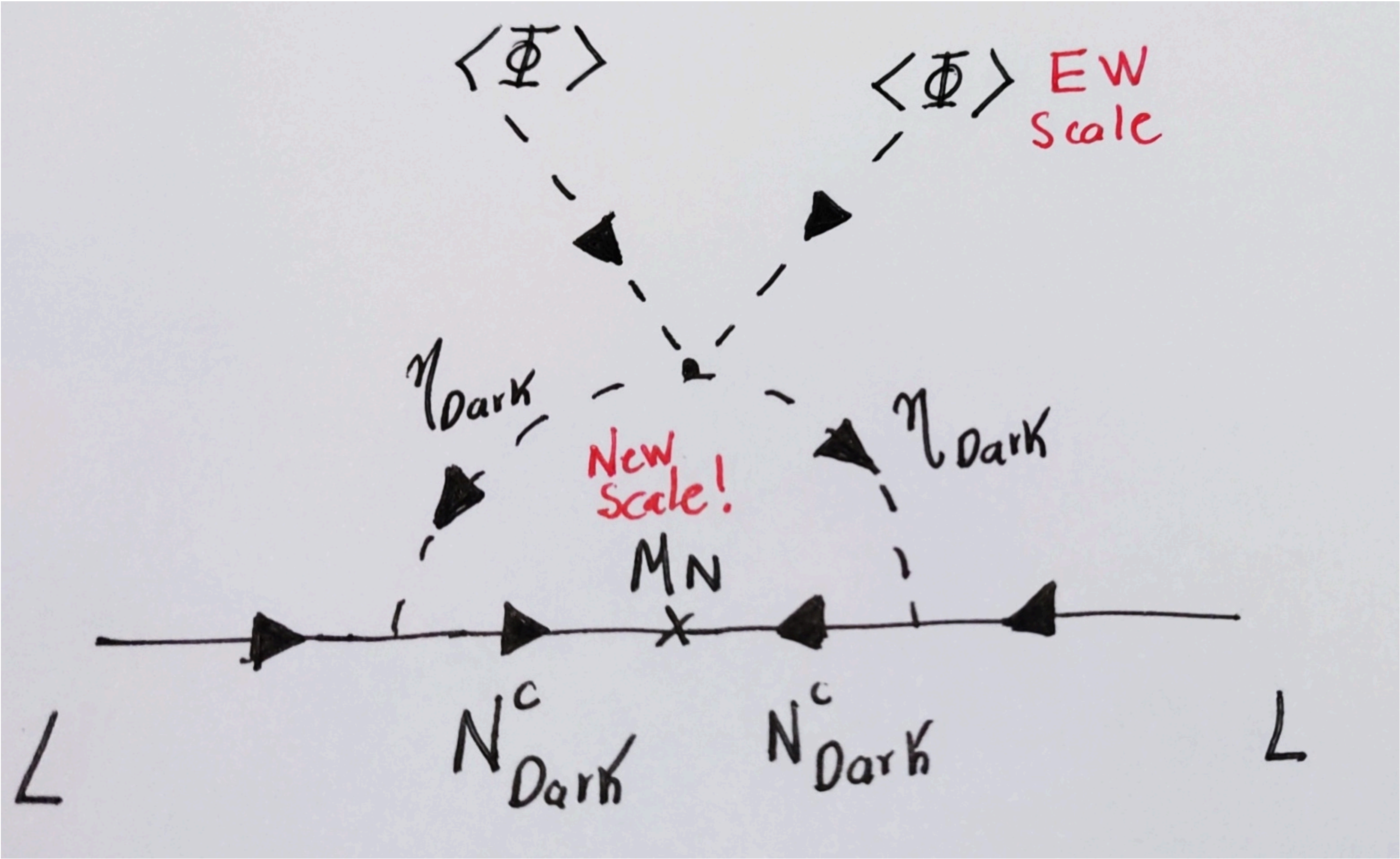
Neutrino mass mechanisms

The scotogenic mechanism

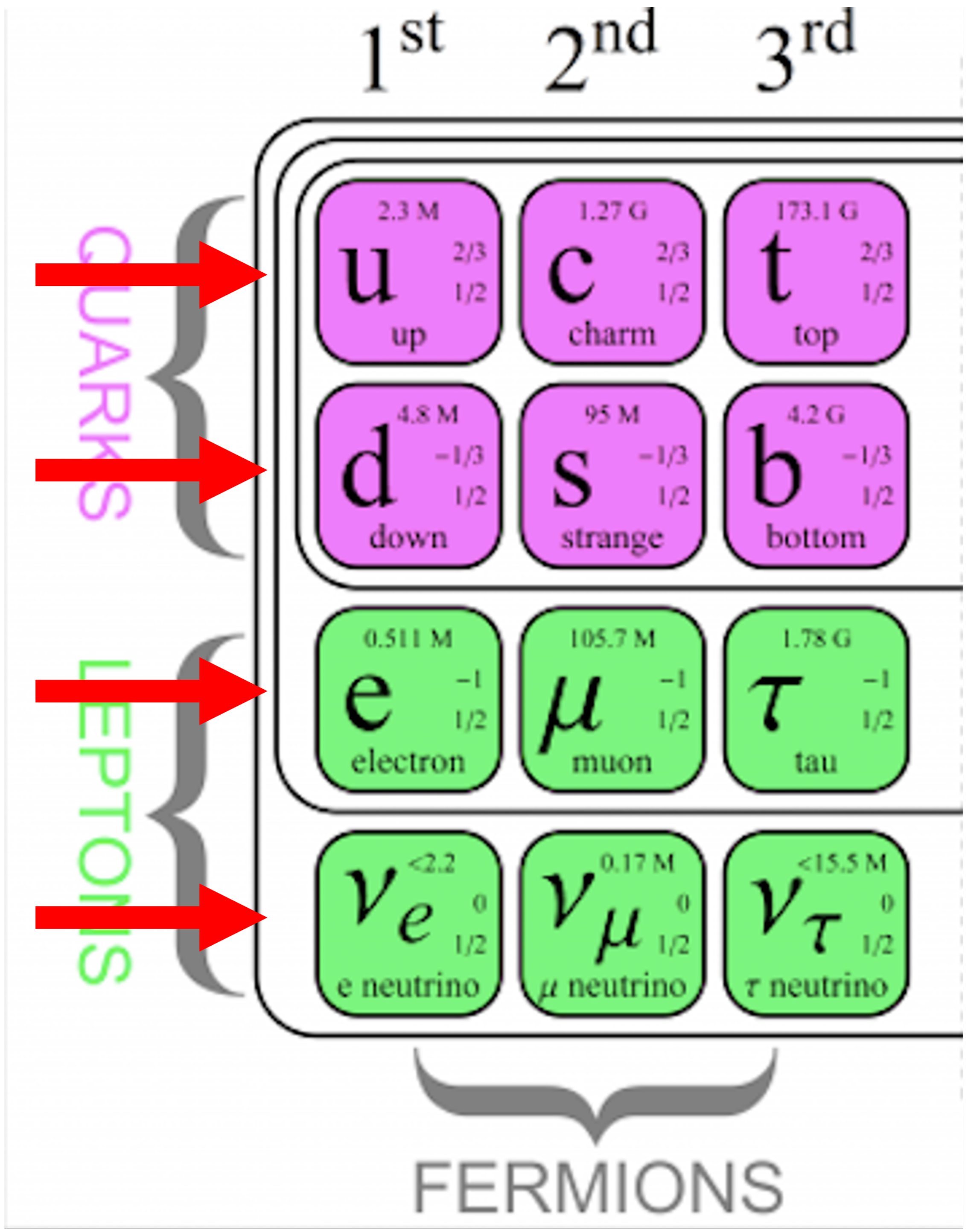
[Ma,2006]

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

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



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 **full flavour symmetry**

The Flavour Puzzle

- **Yukawa interaction** is **not** based on the gauge principle, and in the SM **breaks** flavour symmetry

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

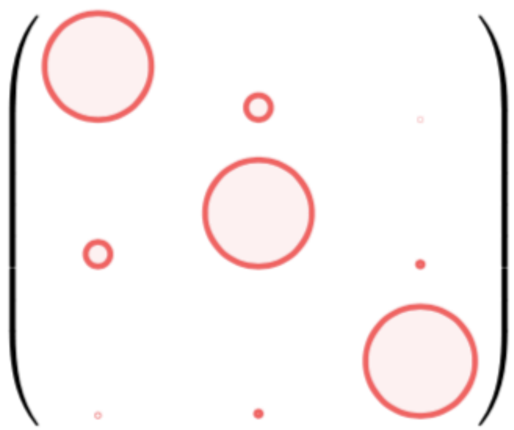
- The CKM matrix and the PMNS matrix **translate flavour symmetry breaking** to the gauge sector

$$U_{CKM}, \quad \boxed{V_{PMNS}}$$

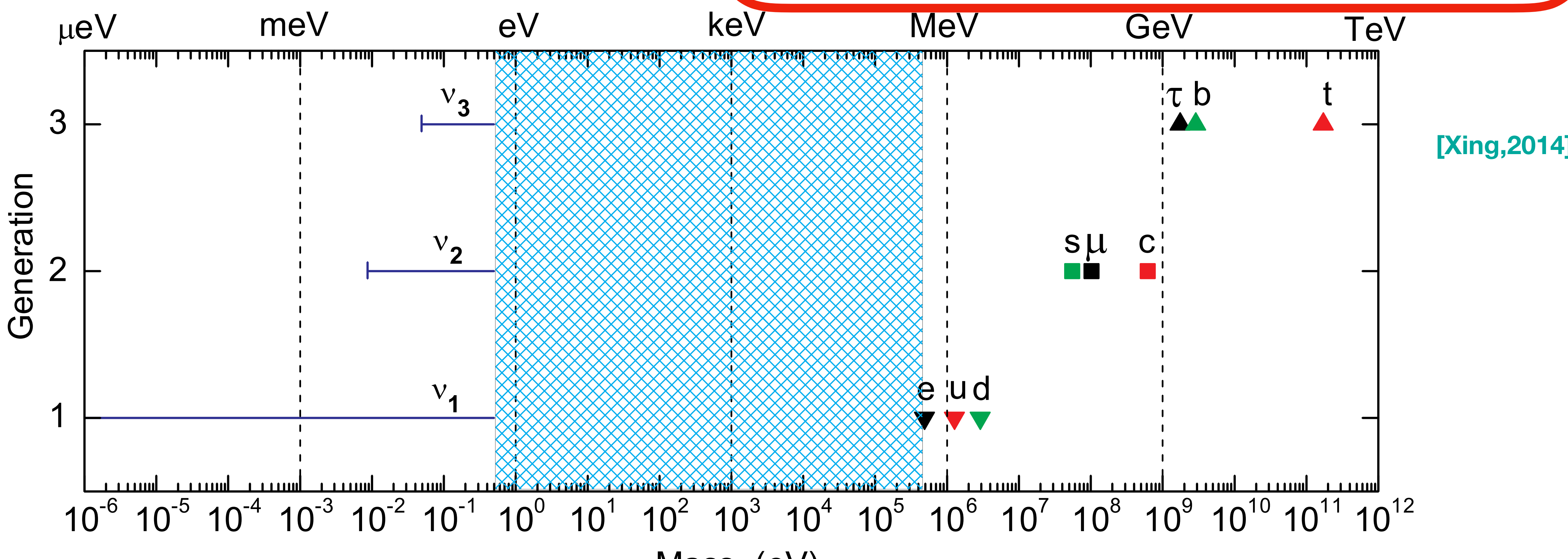
The Flavour Puzzle

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

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

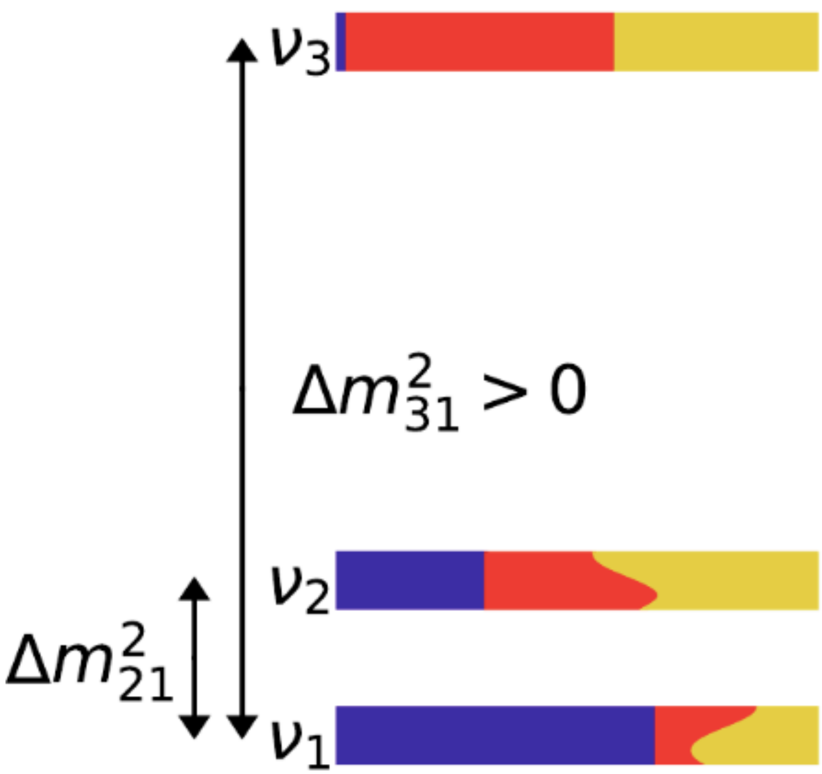


$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} \sim$$



The Flavour Puzzle

- In the lepton sector: Neutrino Oscillation Parameters



NO

Neutrino Global Fit (Valencia)

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

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

$$\delta^{CP}$$

- Two orders of magnitude hierarchy $\Delta m^2_{31} \gg \Delta m^2_{21}$

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

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

- The A_4 group

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

Four Irreps.

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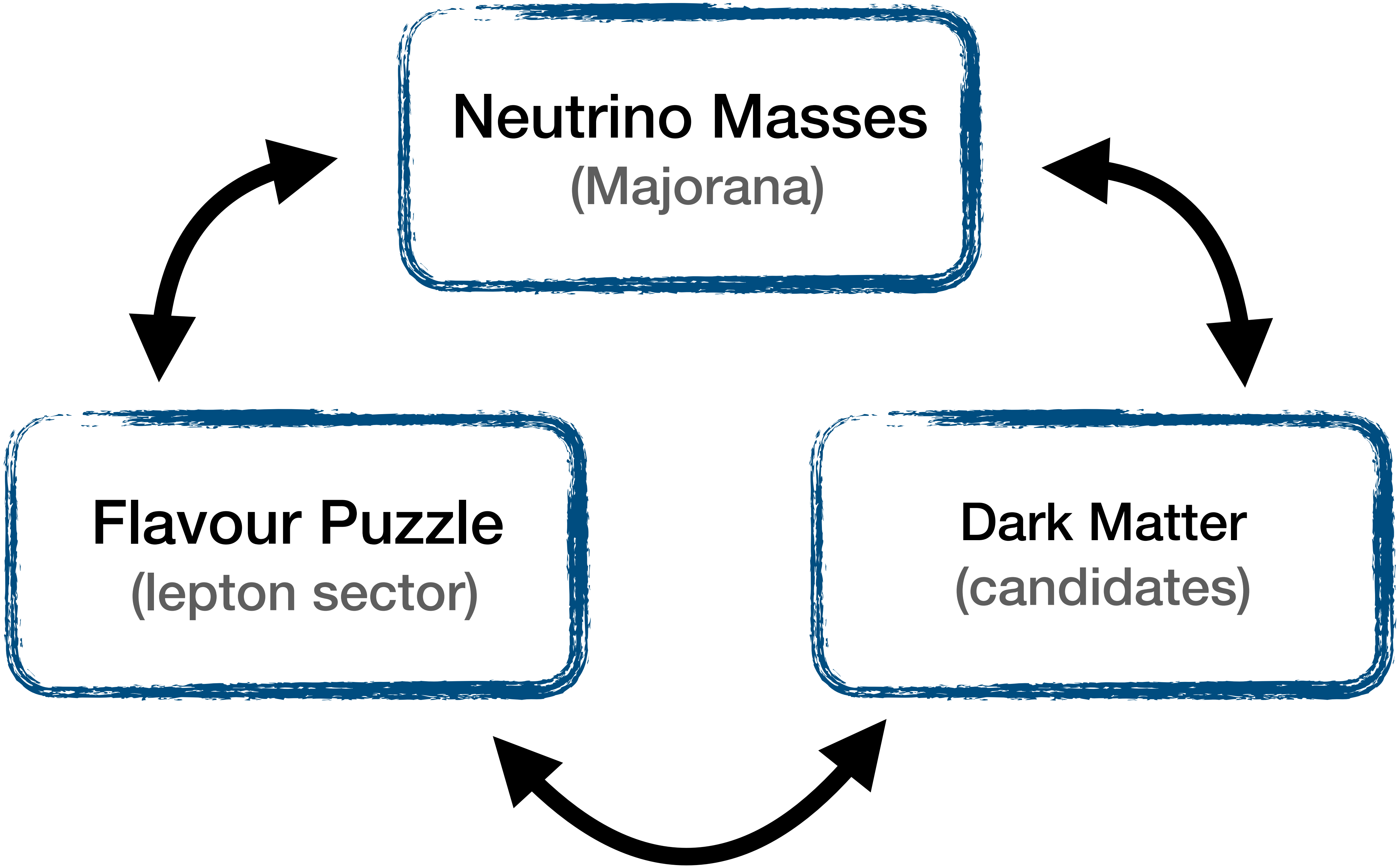
Generates a $\mathbb{Z}_2$ symmetry

See Ivo's talk

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

Scalar iso-doublets

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

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

Mass degenerate m_N

The Discrete Dark Matter Model

- Yukawa Lagrangian invariant under A_4

$$\mathcal{L}^{H}_{\text{Yukawa}} = y_e \overline{L}_e l_e H + y_\mu \overline{L}_\mu l_\mu H + y_\tau \overline{L}_\tau l_\tau H + H.c.$$

$$\mathcal{L}^{\eta}_{\text{Yukawa}} = y_1^\nu \overline{L}_e [N_T\,\eta]_{\mathbf{1}} + y_2^\nu \overline{L}_\mu [N_T\,\eta]_{\mathbf{1}''} + y_3^\nu \overline{L}_\tau [N_T\,\eta]_{\mathbf{1}'} + M_N\,[\overline{N_T^c} N_T]_{\mathbf{1}} + H.c.$$

The Discrete Dark Matter Model

- Yukawa Lagrangian invariant under A_4

$$\mathcal{L}^H_{\text{Yukawa}} = y_e \overline{L}_e l_e H + y_\mu \overline{L}_\mu l_\mu H + y_\tau \overline{L}_\tau l_\tau H + H.c.$$

$$\mathcal{L}^\eta_{\text{Yukawa}} = y_1^\nu \overline{L}_e [N_T\, \eta]_{\mathbf{1}} + y_2^\nu \overline{L}_\mu [N_T\, \eta]_{\mathbf{1}''} + y_3^\nu \overline{L}_\tau [N_T\, \eta]_{\mathbf{1}'} + M_N\, [\overline{N^c_T} N_T]_{\mathbf{1}} + H.c.$$

- 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

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

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

The Discrete Dark Matter Model

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

$$\langle \eta^0 \rangle = \begin{pmatrix} v_{\eta_1} \\ 0 \\ 0 \end{pmatrix} \longrightarrow S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\mathbb{Z}_2$$

$+1$ ↙ ↘ -1

Active Sector **Dark Sector**

The Discrete Dark Matter Model

- The **Active** Sector

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

$$\hat{H} = \begin{pmatrix} H_0'^{+} \\ (v_H + H_0' + iA_0')/\sqrt{2} \end{pmatrix}, \quad \eta_1 = \begin{pmatrix} H_1'^{+} \\ (v_{\eta_1} + H_1' + iA_1')/\sqrt{2} \end{pmatrix},$$

- **Seesaw mechanism** (rank 1 matrix)

$$m_{\rm D} = \begin{pmatrix} y_1^\nu v_{\eta_1} & 0 & 0 \\ y_2^\nu v_{\eta_1} & 0 & 0 \\ y_3^\nu v_{\eta_1} & 0 & 0 \end{pmatrix} \qquad m_\nu^{\rm Tree} = -\frac{v_{\eta_1}^2}{M} \begin{pmatrix} y_1^\nu y_1^\nu & y_1^\nu y_2^\nu & y_1^\nu y_3^\nu \\ y_1^\nu y_2^\nu & y_2^\nu y_2^\nu & y_2^\nu y_3^\nu \\ y_1^\nu y_3^\nu & y_2^\nu y_3^\nu & y_3^\nu y_3^\nu \end{pmatrix}$$

The Discrete Dark Matter Model

- The **Dark** Sector

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

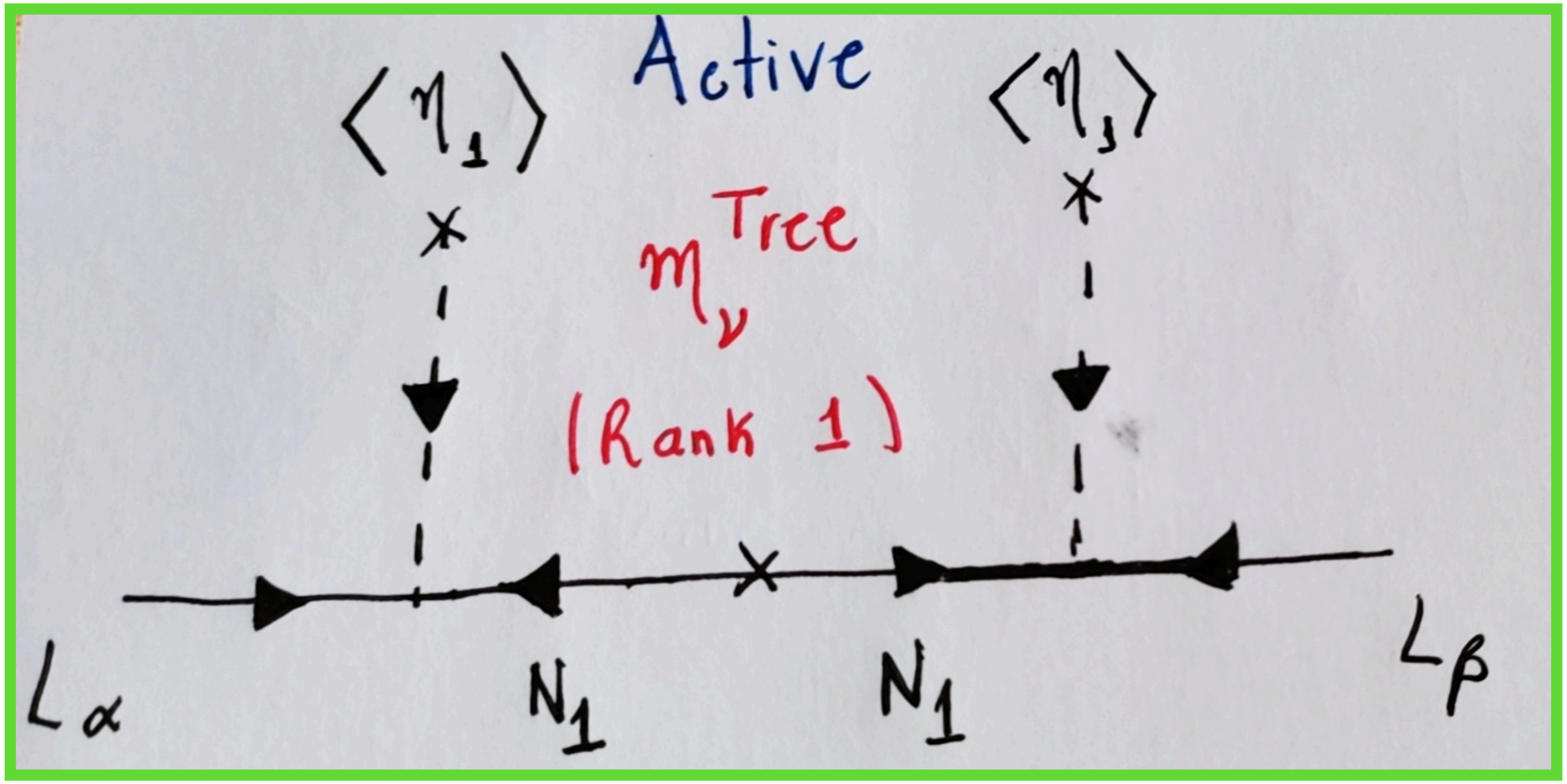
$$\eta_2 = \begin{pmatrix} H_2'^+ \\ (H_2' + iA_2')/\sqrt{2} \end{pmatrix}, \qquad \eta_3 = \begin{pmatrix} H_3'^+ \\ (H_3' + iA_3')/\sqrt{2} \end{pmatrix}$$

- **Scotogenic mechanism** (rank 2 matrix)

$$Y^{\eta_2} = \begin{pmatrix} 0 & y_1^\nu \omega^2 & 0 \\ 0 & y_2^\nu & 0 \\ 0 & y_3^\nu \omega & 0 \end{pmatrix}, \quad Y^{\eta_3} = \begin{pmatrix} 0 & 0 & y_1^\nu \omega \\ 0 & 0 & y_2^\nu \\ 0 & 0 & y_3^\nu \omega^2 \end{pmatrix}$$

The Discrete Dark Matter Model

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



- Main contribution to:

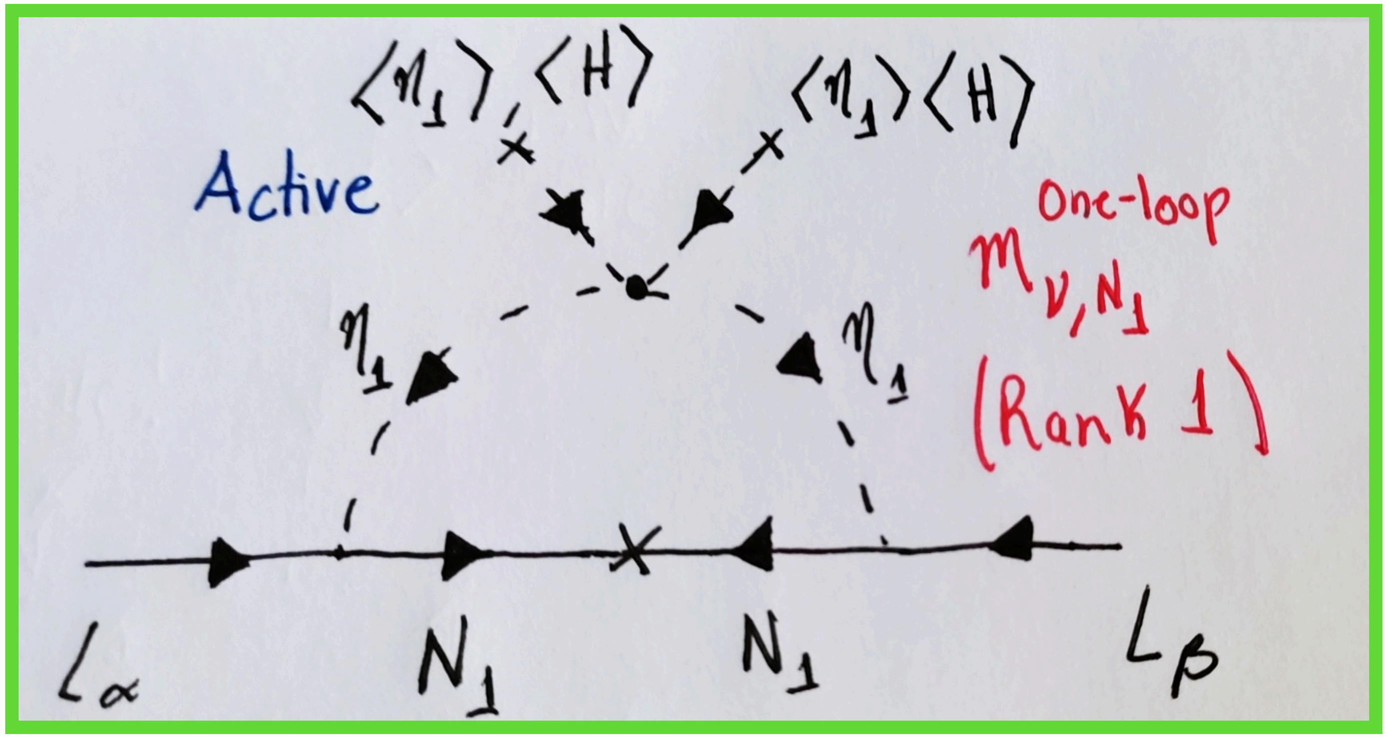
$$\Delta m^2_{31}$$

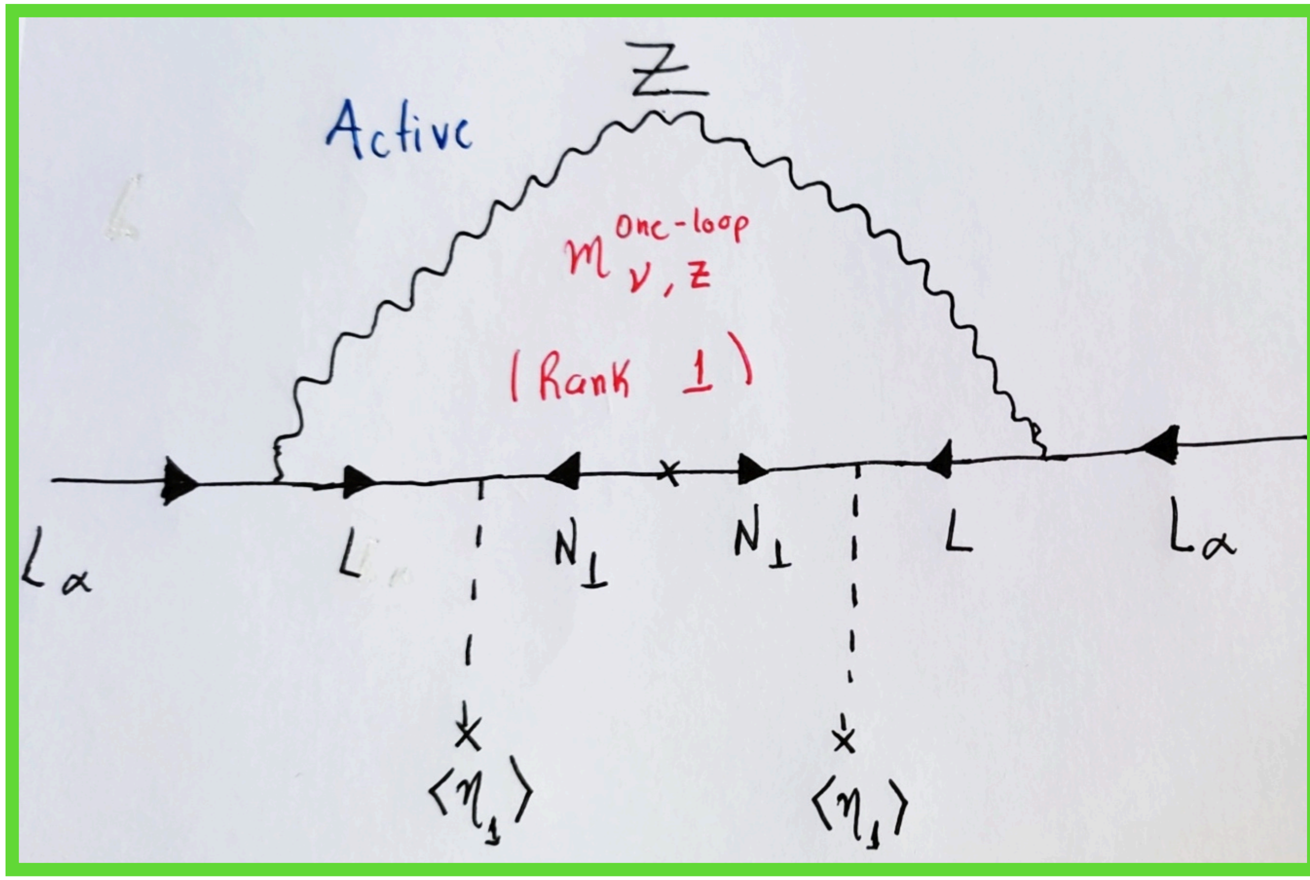
(Normal Ordering)

The Discrete Dark Matter Model

- **Active fields (one-loop)**

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





- Main contribution to:

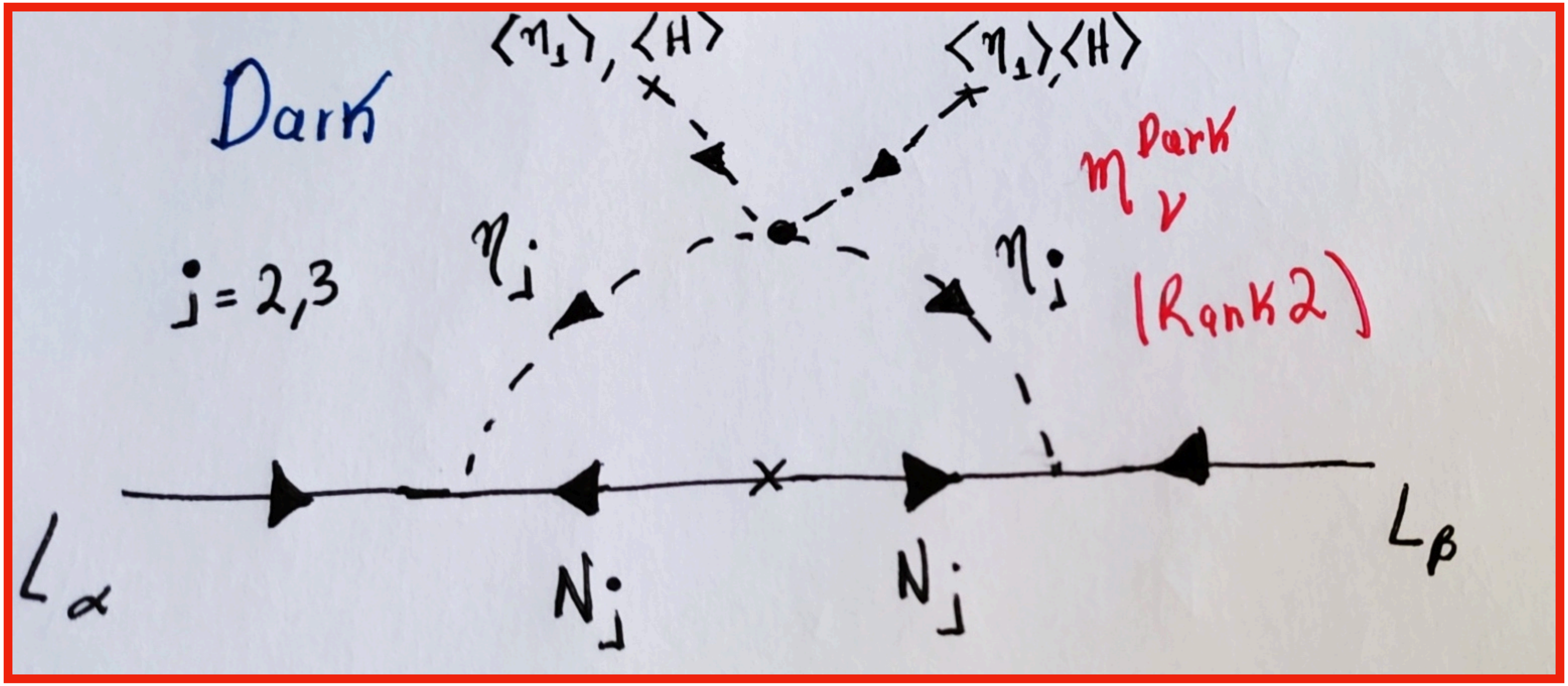
$$\Delta m^2_{31}$$

(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)

The Discrete Dark Matter Model

- **Scalar Sector A_4 invariant** (plays crucial role)

$$V(H,\eta) = \mu_H H^\dagger H + \mu_\eta \left(\eta^\dagger\eta\right)_{\mathbf{1}} + \lambda_1 \left(H^\dagger H\right)^2 + \lambda_2 \left(\eta^\dagger\eta\right)_{\mathbf{1}} \left(\eta^\dagger\eta\right)_{\mathbf{1}} + \lambda_3 \left(\eta^\dagger\eta\right)_{\mathbf{1}'} \left(\eta^\dagger\eta\right)_{\mathbf{1}''}$$
$$+ \lambda_4 \left(\eta^\dagger\eta\right)_{(\mathbf{3}_1} \left(\eta^\dagger\eta\right)_{\mathbf{3}_2)_{\mathbf{1}}} + \left[\lambda_5 e^{i\varphi_5} \left(\eta^\dagger\eta\right)_{(\mathbf{3}_1} \left(\eta^\dagger\eta\right)_{\mathbf{3}_1)_{\mathbf{1}}} + \text{ H.c.}\right]$$
$$+ \lambda_6 \left(H^\dagger H\right) \left(\eta^\dagger\eta\right)_{\mathbf{1}} + \lambda_7 \left(H^\dagger\eta\right)_{(\mathbf{3}} \left(\eta^\dagger H\right)_{\mathbf{3})_{\mathbf{1}}} + \left[\lambda_8 e^{i\varphi_8} \left(H^\dagger\eta\right)_{(\mathbf{3}} \left(H^\dagger\eta\right)_{\mathbf{3})_{\mathbf{1}}} + \text{ H.c.}\right]$$
$$+ \left[\lambda_9 e^{i\varphi_9} \left(\eta^\dagger\eta\right)_{(\mathbf{3}_1} \left(H^\dagger\eta\right)_{\mathbf{3})_{\mathbf{1}}} + \text{ H.c.}\right] + \left[\lambda_{10} e^{i\varphi_{10}} \left(\eta^\dagger\eta\right)_{(\mathbf{3}_2} \left(H^\dagger\eta\right)_{\mathbf{3})_{\mathbf{1}}} + \text{ H.c.}\right]$$

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

$$M^2_{\text{neutral}} = \begin{pmatrix} M^2_{H_0' H_1'} & 0 & 0 & 0 \\ 0 & M^2_{A_0' A_1'} & 0 & 0 \\ 0 & 0 & M^2_{H_2' H_3'} & M^2_{\text{CPV}} \\ 0 & 0 & M^2_{\text{CPV}} & M^2_{A_2' A_3'} \end{pmatrix}$$

$\sin^2\theta^l_{12}$

$\sin^2\theta^l_{13}$

$\sin^2\theta^l_{23}$

Δm^2_{21} Δm^2_{31}

The Discrete Dark Matter Model

The neutrino mass matrix

$$(m_\nu)_{\alpha\beta} = (m_\nu^{\text{Active}})_{\alpha\beta} + (m_\nu^{\text{Dark}})_{\alpha\beta},$$

Active contribution

$$m_\nu^{\text{Active}} = m_\nu^{\text{Tree}} + m_{\nu,N_1}^{\text{One-loop}} + m_{\nu,Z}^{\text{One-loop}}.$$

$$m_\nu^{\text{Tree}} = -\frac{v_{\eta_1}^2}{M}\begin{pmatrix} y_1^\nu y_1^\nu & y_1^\nu y_2^\nu & y_1^\nu y_3^\nu \\ y_1^\nu y_2^\nu & y_2^\nu y_2^\nu & y_2^\nu y_3^\nu \\ y_1^\nu y_3^\nu & y_2^\nu y_3^\nu & y_3^\nu y_3^\nu \end{pmatrix}$$

$$(m_{\nu,Z}^{\text{One-loop}})_{\alpha\beta} = \frac{3}{16\pi^2}\frac{m_Z^2}{v^2}\log\left(\frac{m_Z^2}{m_N^2}\right)(m_\nu^{\text{Tree}})_{\alpha\beta},$$

$$(m_{\nu,N_1}^{\text{One-loop}})_{\alpha\beta} = -\frac{1}{32\pi^2}\sum m_N Y_{\alpha N_1}^a Y_{N_1\beta}^a B_0(0, m_a^2, m_N), \qquad a = h, H_0, G, A_0,$$

[Escribano,2020]

Passarino-Veltman reduction

Mass-eigenstates

The Discrete Dark Matter Model

The neutrino mass matrix

$$(m_\nu)_{\alpha\beta} = (m_\nu^{\text{Active}})_{\alpha\beta} + (m_\nu^{\text{Dark}})_{\alpha\beta},$$

Dark contribution

$$(m_\nu^{\text{Dark}})_{\alpha\beta} = -\frac{1}{32\pi^2}\sum_{n,a} m_N Y^a_{\alpha n} Y^a_{n\beta} B_0(0, m_a^2, m_N), \qquad a = \chi_1^D, \ldots, \chi_4^D,$$

DM candidate

$$\chi_4^D$$

Scalar mixing plays

Mass-eigenstates

Numerical Result

With the **CP-symmetry conservation** in the scalar potential

Parameter	Value
y_e	-2.420×10^{-6}
y_μ	5.108×10^{-4}
y_τ	8.684×10^{-3}
y_1^ν	2.127×10^{-6}
y_2^ν	-1.046×10^{-5}
y_3^ν	-1.172×10^{-5}
v_{η_1}/GeV	142.243
v_H/GeV	201.079
M_N/GeV	9.997×10^4
λ_1	2.0
λ_2	2.0
λ_3	−0.42
λ_4	0.578
λ_5	−0.486
λ_6	2.0
λ_7	−1.984
λ_8	−0.369
λ_9	1.198
λ_{10}	−1.191
φ_5	0
φ_9	0
φ_{10}	0

Observable	Data		Model best fit
	Central value	1σ range	
$\sin^2\theta_{12}/10^{-1}$	3.18	$3.02 \to 3.34$	1.46
$\sin^2\theta_{13}/10^{-2}$ (NO)	2.200	$2.138 \to 2.269$	2.314
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74	$5.60 \to 5.88$	6.2
$\delta^\ell\ /\pi$ (NO)	1.08	$0.96 \to 1.21$	1.0
$\Delta m_{21}^2/(10^{-5}\,\mathrm{eV}^2)$	7.50	$7.30 \to 7.72$	7.49
$\Delta m_{31}^2/(10^{-3}\,\mathrm{eV}^2)$ (NO)	2.55	$2.52 \to 2.57$	2.55
m^ν_{lightest} /meV (NO)			2.03
m_2^ν /meV			8.89
m_3^ν /meV			50.54
ϕ_{12}/π			1.5
ϕ_{13}/π			1.5
ϕ_{23}/π			1.0
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
M_H/GeV (Higgs boson)	125.25	$125.08 \to 125.42$	125.25
M_{DM}/GeV (lightest dark scalar)			87.0
M_N/GeV			9.997×10^4
χ^2			128.99

$\sin^2\theta_{12}$ Excluded

All Other observables in global fit 3-sigma range

Numerical Result

With the **CP-symmetry breaking** in the scalar potential, all oscillation parameter and scalar sector observables are fitted without tensions.

Parameter	Value
y_e	-2.136×10^{-6}
y_μ	4.509×10^{-4}
y_τ	7.665×10^{-3}
y_1^ν	5.193×10^{-6}
y_2^ν	-3.404×10^{-5}
y_3^ν	-7.540×10^{-5}
v_{η_1}/GeV	93.447
v_H/GeV	227.799
M_N/GeV	1.088×10^6
λ_1	1.772
λ_2	2.0
λ_3	−0.057
λ_4	1.782
λ_5	−1.644
λ_6	2.0
λ_7	−1.466
λ_8	−0.392
λ_9	1.171
λ_{10}	−1.154
φ_5	1.764
φ_9	0.059
φ_{10}	6.228

Observable	Data		Model best fit
	Central value	1σ range	
$\sin^2\theta_{12}/10^{-1}$	3.18	$3.02 \to 3.34$	3.14
$\sin^2\theta_{13}/10^{-2}$ (NO)	2.200	$2.138 \to 2.269$	2.201
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74	$5.60 \to 5.88$	5.75
δ^ℓ/π (NO)	1.08	$0.96 \to 1.21$	1.0
$\Delta m_{21}^2/(10^{-5}\,\text{eV}^2)$	7.50	$7.30 \to 7.72$	7.48
$\Delta m_{31}^2/(10^{-3}\,\text{eV}^2)$ (NO)	2.55	$2.52 \to 2.57$	2.55
m^ν_{lightest} /meV (NO)			6.21
m_2^ν /meV			10.65
m_3^ν /meV			50.87
ϕ_{12}/π			0.5
ϕ_{13}/π			0.5
ϕ_{23}/π			1.0
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
M_H/GeV (Higgs boson)	125.25	$125.08 \to 125.42$	125.25
M_{DM}/GeV (lightest dark scalar)			87.6
M_N/GeV			1.09×10^6
M_{H_0}/GeV (Heavy Higgs)			449.57
M_{A_0}/GeV (Heavy Pseudoscalar)			435.98
$M^+_{H_0}$/GeV (Charged Active)			373.5
$M^+_{H_a}$/GeV (Charged Dark)			345.5
$M^+_{H_b}$/GeV (Charged Dark)			347.7
$M^0_{H_a}$/GeV (Neutral Dark)			109.47
$M^0_{H_b}$/GeV (Neutral Dark)			411.36
$M^0_{H_c}$/GeV (Neutral Dark)			413.1
χ^2			0.52

Δm_{31}^2

Δm_{21}^2

Both generated

Conclusions

The Discrete Dark Matter Model

From a A_4 symmetric origin:

arXiv:2-soon

- Reproduces lepton **masses** and **mixings**.

$$\sin^2\theta_{12}, \quad \sin^2\theta_{12}, \quad \sin^2\theta_{23} \qquad \delta_l^{CP} \sim \pi$$

(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

$$A_4 \longrightarrow \mathbb{Z}_2$$

Back-up Slides

Dark scalars mass matrices

$$M^2_{H_2'H_3'} = \begin{pmatrix} v_{\eta_1}^2\left(-\frac{3}{2}\lambda_3+\frac{1}{2}\lambda_4+\lambda_5\cos\varphi_5\right) & 6v_{\eta_1}v_s\left(\lambda_{10}\cos\varphi_{10}+\lambda_9\cos\varphi_9\right) \\ 6v_{\eta_1}v_s\left(\lambda_{10}\cos\varphi_{10}+\lambda_9\cos\varphi_9\right) & v_{\eta_1}^2\left(-\frac{3}{2}\lambda_3+\frac{1}{2}\lambda_4+\lambda_5\cos\varphi_5\right) \end{pmatrix},$$

$$M^2_{A_2'A_3'} = \begin{pmatrix} v_{\eta_1}^2\left(-\frac{3}{2}\lambda_3+\frac{1}{2}\lambda_4-\lambda_5\cos\varphi_5\right)-v_s^2\left(8\lambda_8\right) & 2v_{\eta_1}v_s\left(\lambda_9\cos\varphi_9+\lambda_{10}\cos\varphi_{10}\right) \\ 2v_{\eta_1}v_s\left(\lambda_9\cos\varphi_9+\lambda_{10}\cos\varphi_{10}\right) & v_{\eta_1}^2\left(-\frac{3}{2}\lambda_3+\frac{1}{2}\lambda_4-\lambda_5\cos\varphi_5\right)-v_s^2\left(8\lambda_8\right) \end{pmatrix},$$

$$M^2_{\mathrm{CPV}} = \begin{pmatrix} -v_{\eta_1}^2\left(\lambda_5\sin\varphi_5\right) & -2v_{\eta_1}v_s\left(\lambda_9\sin\varphi_9+\lambda_{10}\sin\varphi_{10}\right) \\ -2v_{\eta_1}v_s\left(\lambda_9\sin\varphi_9+\lambda_{10}\sin\varphi_{10}\right) & v_{\eta_1}^2\left(\lambda_5\sin\varphi_5\right) \end{pmatrix}$$

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Yukawa couplings under basis change

$$Y^{a}_{n\alpha} = \left(O^{T}_{hH_0}\right)^{a}{}_{k} Y^{k}_{n\alpha}, \qquad \text{for} \quad a = h, H_0 \quad \text{and} \quad k = H'_1,$$

$$Y^{a}_{n\alpha} = \left(O^{T}_{GA_0}\right)^{a}{}_{k} Y^{k}_{n\alpha}, \qquad \text{for} \quad a = G, A_0 \quad \text{and} \quad k = A'_1,$$

$$Y^{a}_{n\alpha} = \left(O^{T}_{\chi}\right)^{a}{}_{k} Y^{k}_{n\alpha}, \qquad \text{for} \quad a = \chi^{D}_{1}, ..., \chi^{D}_{4}, \quad \text{and} \quad k = H'_2, H'_3, A'_2, A'_3.$$