# Flavor symmetries and DM stability

**Eduardo Peinado**

Departamento de Física Teórica
Instituto de Física UNAM

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11TH WORKSHOP
Flavor Symmetries and Consequences in Accelerators and Cosmology

# Flavor Symmetries

## To explain quark masses and mixings

Wilczek and Zee (1977)
Weinberg (1977)

$$\lambda_C = \sqrt{\frac{m_d}{m_s}}$$

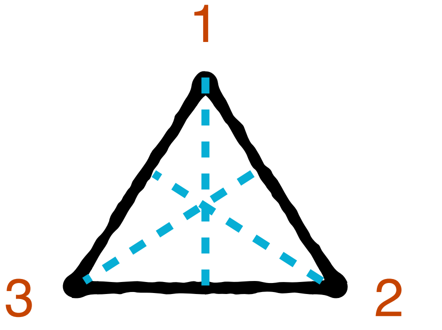
Cabibbo (1963)
Gatto Satori, Tonin (1968)

# Flavor Symmetries

## To explain quark masses and mixings

Wilczek and Zee (1977)
Weinberg (1977)

Pakvasa and Sugawara(1978)
Sartori(1979)
Wyler(1979)




$$\lambda_C = \sqrt{\frac{m_d}{m_s}}$$

Cabibbo (1963)
Gatto Satori, Tonin (1968)

Small mixing angle

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda_C & \lambda_C^3 \\ -\lambda_C & 1 & \lambda_C^2 \\ \lambda_C^3 & -\lambda_C^2 & 1 \end{pmatrix}$$

# Flavor Symmetries

## Massive neutrinos

E. Ma and G. Rajasekaran (2001)
E. Ma (2001)
Babu, Ma, Valle (2002)

Grimus and L. Lavour (2001)
Hirsch et. al. (2003)
Kubo, Mondragon et. al (2003)
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.....

S3, D4, A4, S4,…

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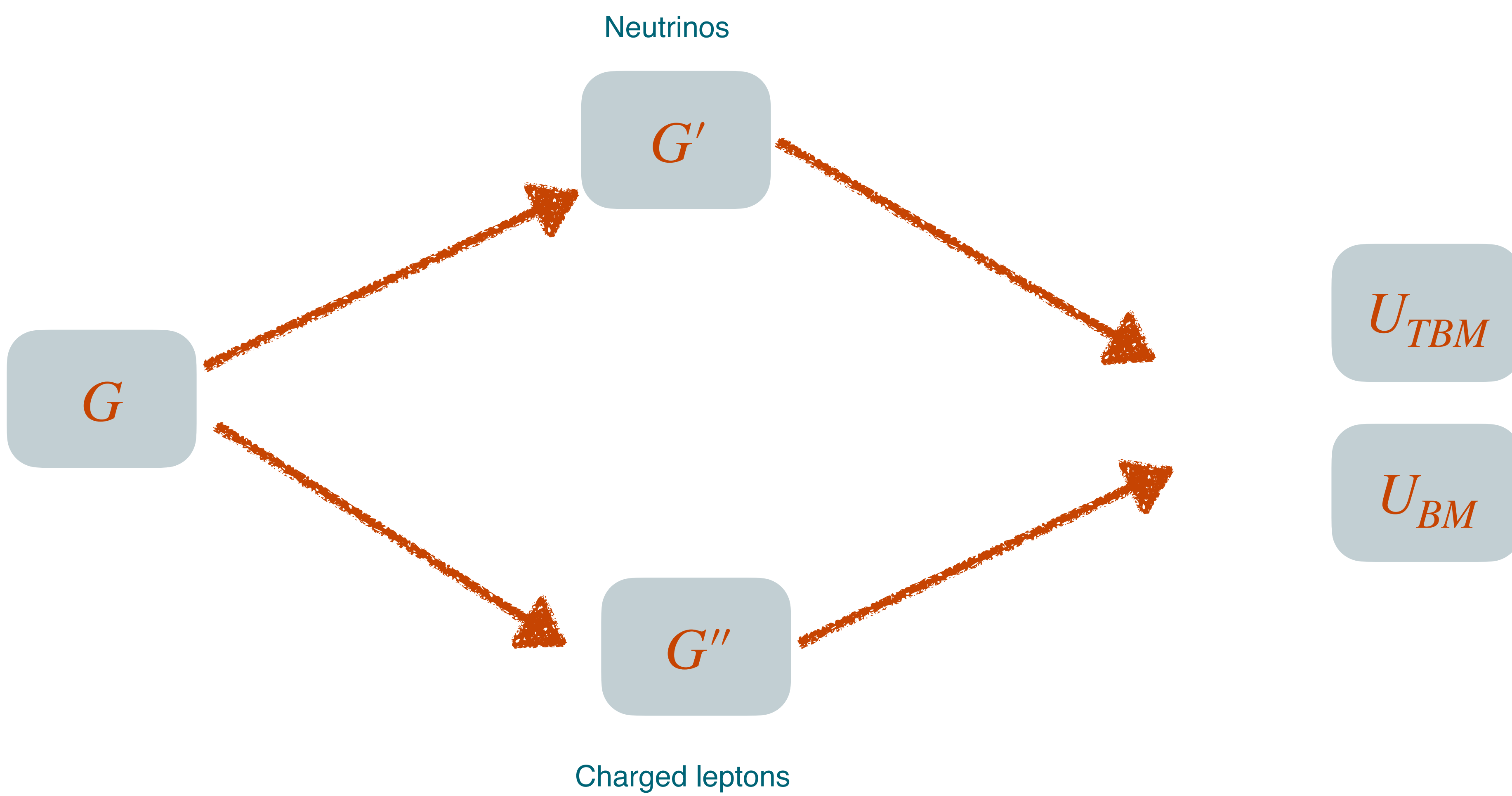
S3, D4, A4, S4,…

# Breaking FS

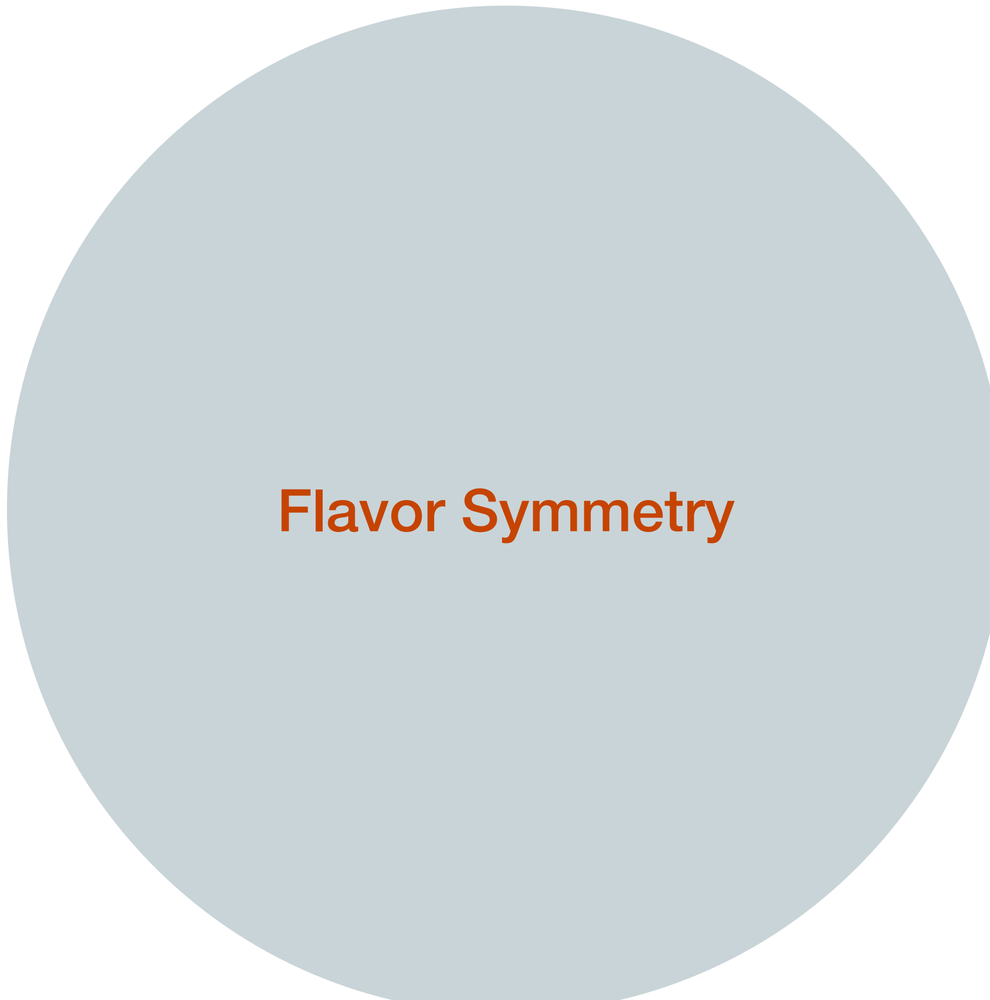



Large solar and atmospheric

Small reactor $\theta_{13} \sim 0$

Correlations $m_{\nu_i} - \theta_{ij}$

# What else?



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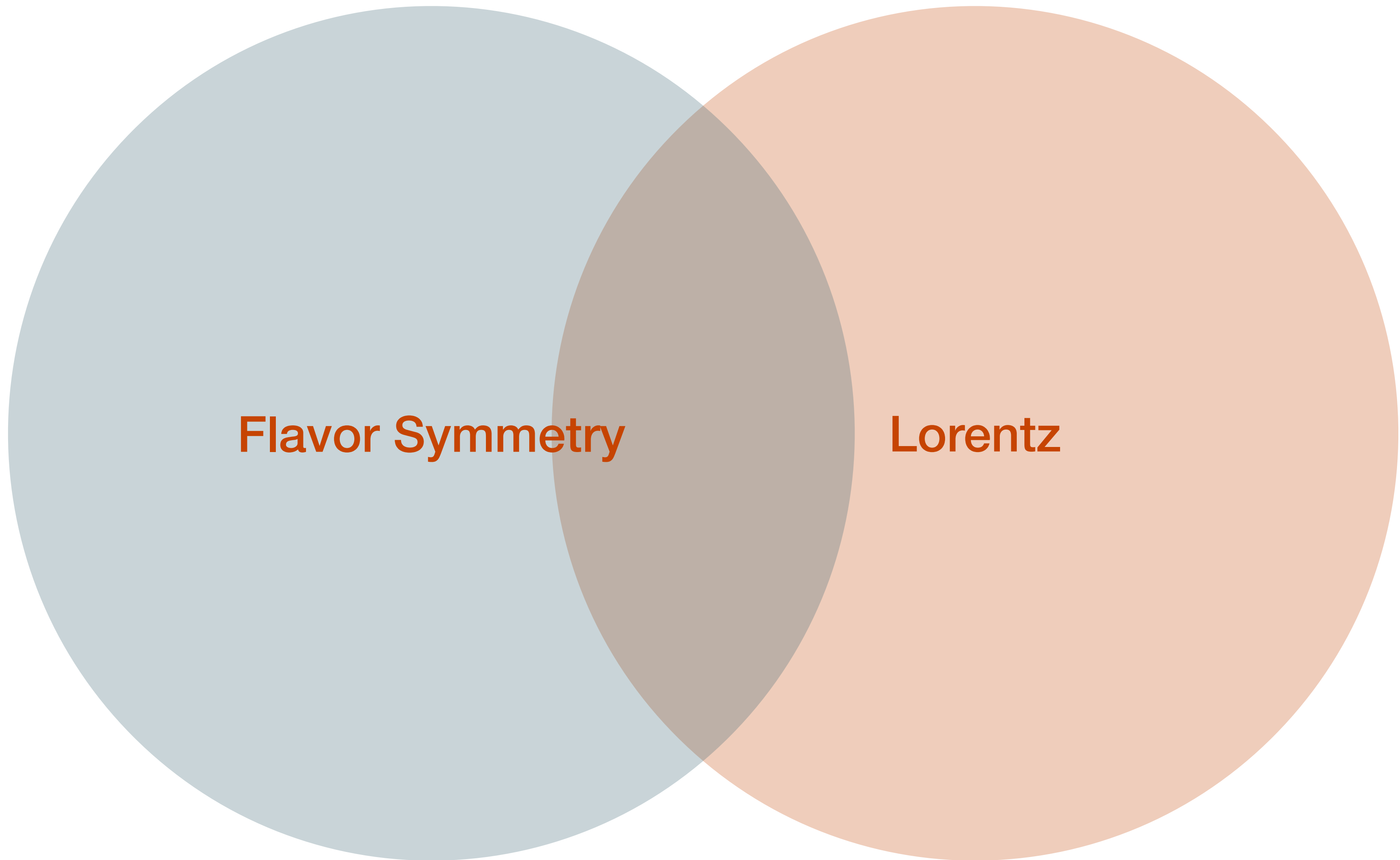

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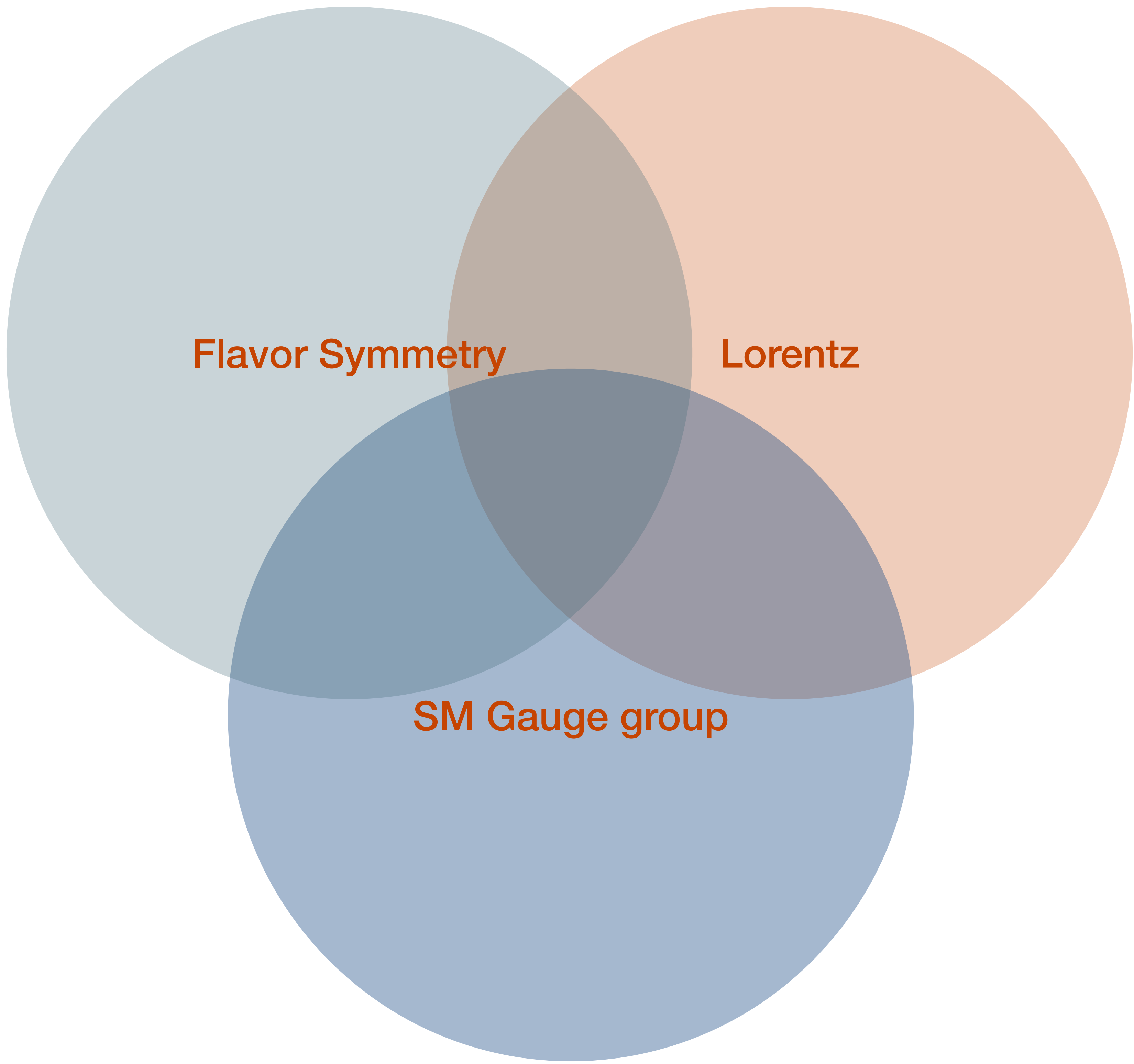

# What else?

## R parity and proton decay

$\Delta(27)$

EP, Vicente and Morisi (2013)

| | $\hat{L}$ | $\hat{e}$ | $\hat{H}_d$ | $\hat{H}_u$ | $\hat{Q}$ | $\hat{d}$ | $\hat{u}$ |
|---|---|---|---|---|---|---|---|
| $\Delta(27)$ | $\mathbf{3}$ | $\mathbf{1}_{1,2,3}$ | $\mathbf{3}^*$ | $\mathbf{3}$ | $\mathbf{3}$ | $\mathbf{1}_{1,2,3}$ | $\mathbf{3}$ |

$$[LH_u]_F\,, \quad [LLe]_F\,, \quad [LQd]_F\,, \quad [udd]_F$$

$$3\times 3\times 1_k \quad 3\times 3\times 1_k \quad 3\times 3\times 1_k \quad 3\times 1_l\times 1_k$$

# What else?

## R parity and proton decay

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$$[LH_u]_F\,,\quad [LLe]_F\,,\quad [LQd]_F\,,\quad [udd]_F$$

$3\times 3\times 1_k \quad 3\times 3\times 1_k \quad 3\times 3\times 1_k \quad 3\times 1_l\times 1_k$

Also Forbidden

$$\mathcal{O}_1^{(5)} = [QQQL]_F \qquad \mathcal{O}_2^{(5)} = [uude]_F$$
$$\mathcal{O}_3^{(5)} = [QQQH_d]_F \qquad \mathcal{O}_4^{(5)} = [QueH_d]_F$$
$$\mathcal{O}_5^{(5)} = [LLH_uH_u]_F \qquad \mathcal{O}_6^{(5)} = [LH_dH_uH_u]_F$$
$$\mathcal{O}_7^{(5)} = [H_uH_ue^*]_D \qquad \mathcal{O}_8^{(5)} = [H_u^*H_de]_D$$
$$\mathcal{O}_9^{(5)} = [QuL^*]_D \qquad \mathcal{O}_{10}^{(5)} = [ud^*e]_D \quad 3\times 1_k\times 1_l$$
$$\mathcal{O}_{11}^{(5)} = [QQd^*]_D \quad 3\times 3\times 1_l$$

# DM stability

Impose a $Z_2$ symmetry (unbroken)

Deshpande, Ma (1978)
E. Ma (2005)

$G_F$ symmetry unbroken

Battel (2011)
Deng, Boto, Ivanov, Silva (2025)

No impact on flavor structure

Double cover of $G_F$, accidental $Z_N$

Lavoura, Morisi, Valle (2012)

# DM stability

Instead of breaking A4 in two different directions

$$\langle \phi \rangle = (1,0,0)$$

Preserves "S" ($Z_2$)

$$\cancel{\langle \phi \rangle = (1,1,1)}$$

~~Preserves "T" ($Z_3$)~~

# DM stability

Instead of breaking A4 in two different directions

$$\langle\phi\rangle = (1,0,0)$$

Preserves "S" ($Z_2$)

$$\cancel{\langle\phi\rangle = (1,1,1)}$$

~~Preserves "T" ($Z_3$)~~

No TBM, but Z2 unbroken $\longrightarrow$ DM Stability

# DDM

Hirsch, Morisi, EP and Valle (2010)

| | $L_e$ | $L_\mu$ | $L_\tau$ | $l_e^c$ | $l_\mu^c$ | $l_\tau^c$ | $N_T$ | $N_4$ | $H$ | $\eta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $SU(2)$ | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |
| $A_4$ | 1 | $1'$ | $1''$ | 1 | $1''$ | $1'$ | 3 | 1 | 1 | 3 |

# DDM

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$$\langle \eta \rangle \sim (1,0,0)$$

# DDM

Hirsch, Morisi, EP and Valle (2010)

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$$\langle \eta \rangle \sim (1,0,0)$$

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} \xrightarrow{Z_2} \begin{pmatrix} T_1 \\ -T_2 \\ -T_3 \end{pmatrix}$$

# DDM

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$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} \xrightarrow{Z_2} \begin{pmatrix} T_1 \\ -T_2 \\ -T_3 \end{pmatrix}$$

Only 2 active RH neutrinos

$$m_{light} = 0$$

# DDM

## Inverted mass order

$$\theta_{13} = 0$$

$$m_\nu = \begin{pmatrix} y & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}$$

$$m_3 = 0$$

$$\begin{pmatrix} 0 \\ -c/b \\ 1 \end{pmatrix}$$

$m_{\beta\beta} \sim 0.03 - 0.05$ **eV**

# $A_4 \to Z_2$

$$\langle \eta \rangle \sim \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix} \longrightarrow \begin{pmatrix} N_1 \\ -N_2 \\ -N_3 \end{pmatrix} \qquad \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \longrightarrow \begin{pmatrix} \eta_1 \\ -\eta_2 \\ -\eta_3 \end{pmatrix}$$

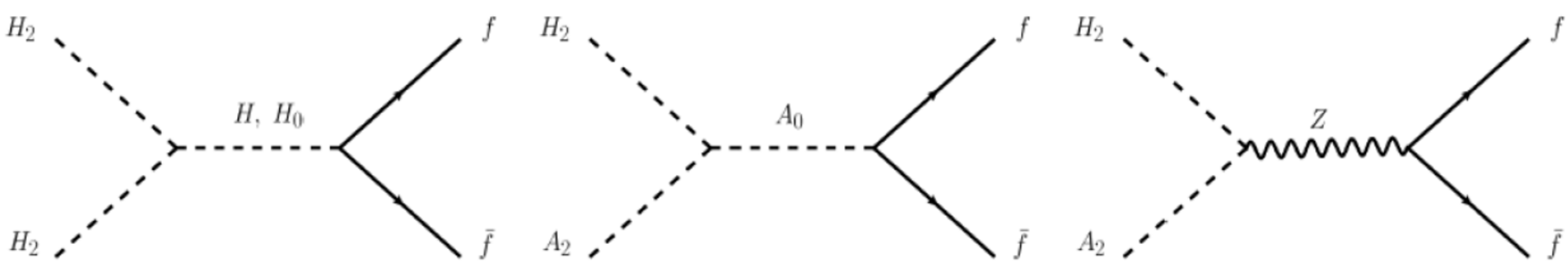
# $A_4 \to Z_2$

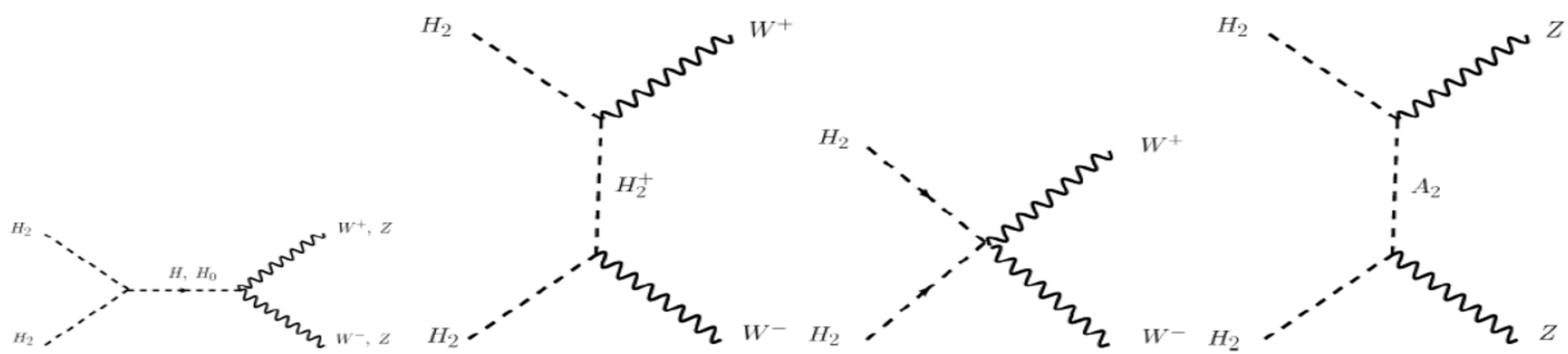
$$\langle \eta \rangle \sim \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$H = \begin{pmatrix} \tilde{H}_0^+ \\ (v_h + \tilde{H}_0 + i\tilde{A}_0)/\sqrt{2} \end{pmatrix}, \quad \eta_1 = \begin{pmatrix} \tilde{H}_1^+ \\ (v_\eta + \tilde{H}_1 + i\tilde{A}_1)/\sqrt{2} \end{pmatrix}$$ → even

$$\eta_2 = \begin{pmatrix} \tilde{H}_2^+ \\ (\tilde{H}_2 + i\tilde{A}_2)/\sqrt{2} \end{pmatrix}, \qquad \eta_3 = \begin{pmatrix} \tilde{H}_3^+ \\ (\tilde{H}_3 + i\tilde{A}_3)/\sqrt{2} \end{pmatrix}$$ → odd

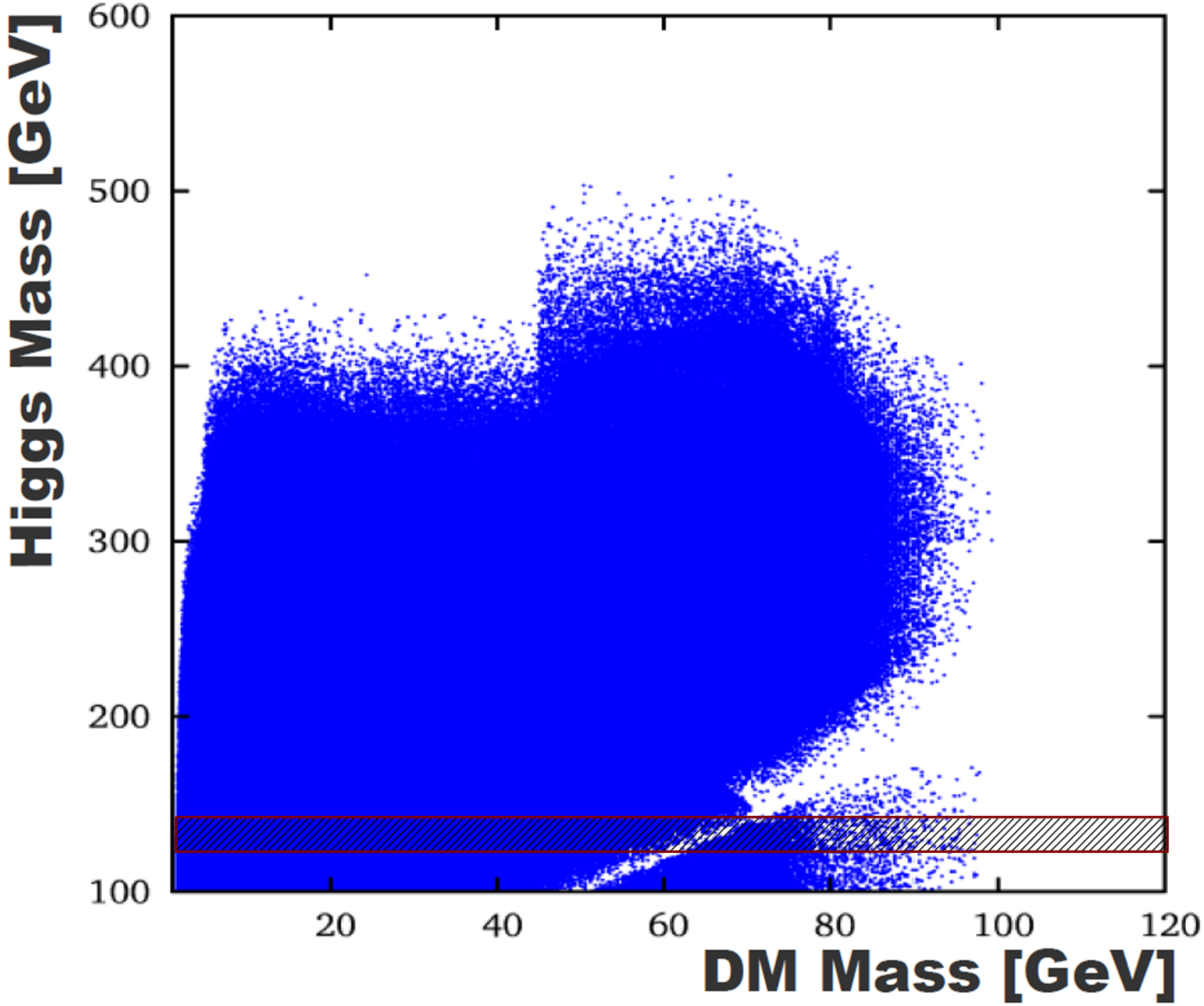
# DM annihilation channels



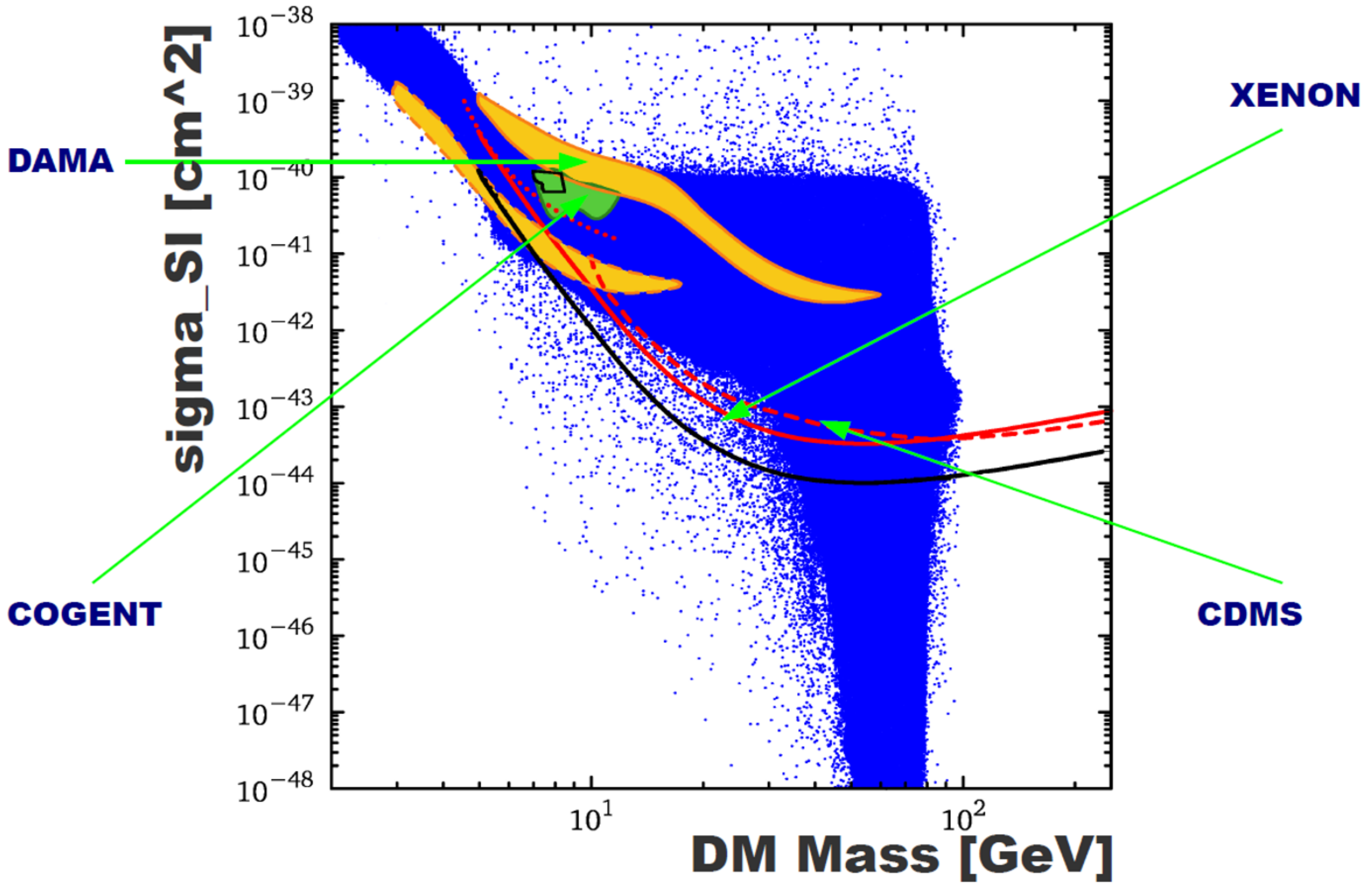

Boucenna, Hirsch, Morisi, EP, Taoso, Valle (2011)

# DDM predictions




Boucenna, Hirsch, Morisi, EP, Taoso, Valle (2011)

# DDM predictions




**... Direct Detection**

Boucenna, Hirsch, Morisi, EP, Taoso, Valle (2011)

# Fixing $\theta_{13}$

Not only with A4 but D4 the prediction is small or zero reactor mixing angle

Meloni, Morisi, EP (2011)

Meloni, Morisi, EP (2011)

Solution: breaking $A_4$ at the seesaw scale

Lamprea, EP (2015)

Ferro, de la Vega, EP (2019)

Predictions: Different zero textures

# $A_4$ beaking at the seesaw scale

Lamprea, EP (2015)
Ferro, de la Vega, EP (2019)

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

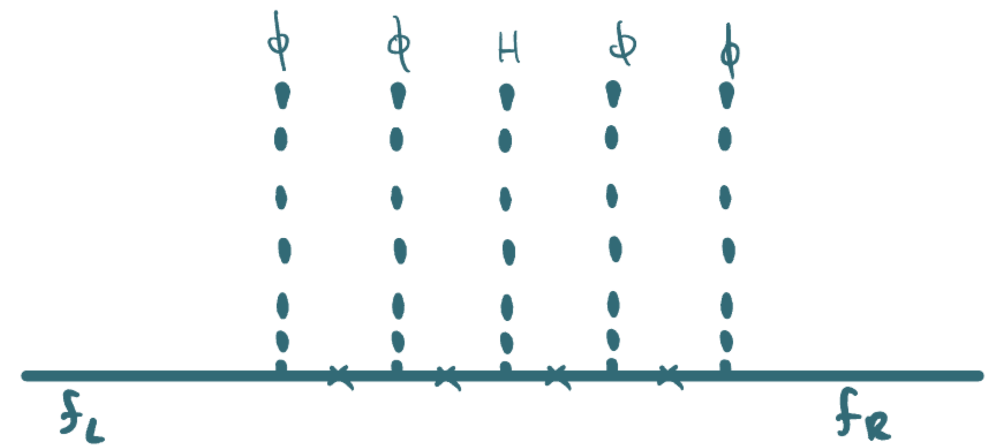
$$\bar{N}_T^c N_T \phi \qquad \bar{N}_T^c N_1 \phi \qquad \bar{N}_T^c N_5 \phi$$

| $L_e$ | $L_\mu$ | $L_\tau$ | $N_4$ | $N_5$ | Neutrino matrix | Type |
|---|---|---|---|---|---|---|
| $\mathbf{1}$ | $\mathbf{1}''$ | $\mathbf{1}'$ | $\mathbf{1}$ | $\mathbf{1}'$ | $\begin{pmatrix} X & 0 & X \\ 0 & 0 & X \\ X & X & X \end{pmatrix}$ | $B_3$ |
| $\mathbf{1}$ | $\mathbf{1}''$ | $\mathbf{1}'$ | $\mathbf{1}$ | $\mathbf{1}''$ | $\begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & 0 \end{pmatrix}$ | $B_4$ |
| $\mathbf{1}''$ | $\mathbf{1}$ | $\mathbf{1}'$ | $\mathbf{1}$ | $\mathbf{1}'$ | $\begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$ | $A_1$ |
| $\mathbf{1}''$ | $\mathbf{1}'$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}'$ | $\begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$ | $A_2$ |

# $\nu$ mass hierarchy

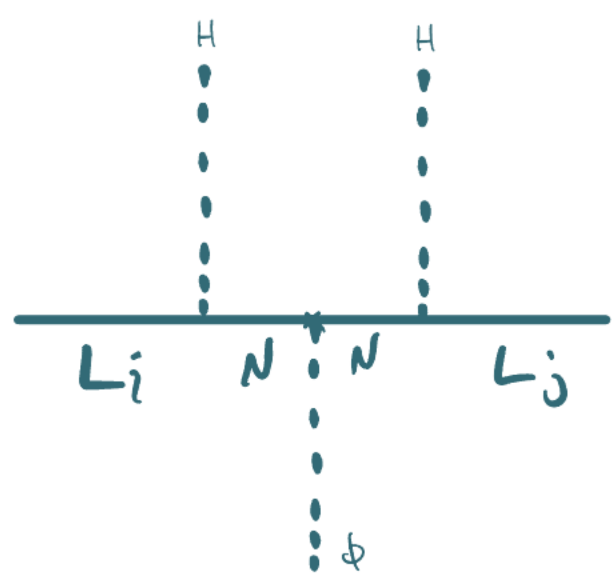
## Charged fermions hierarchy

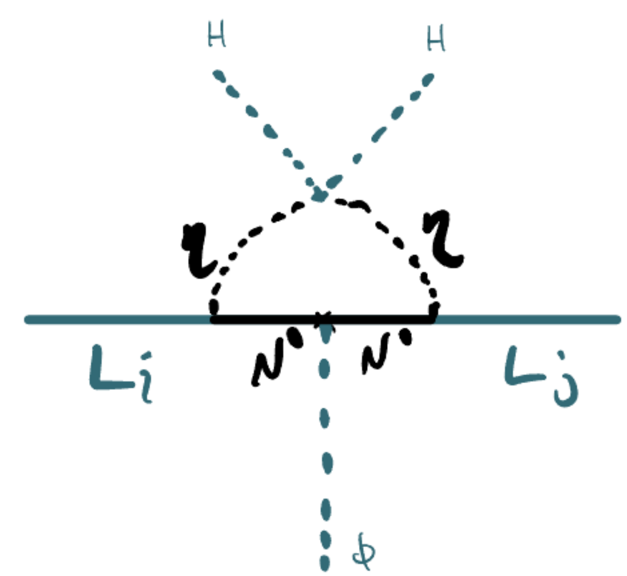
Froggatt, Nielsen (1979)




## One mechanism for each scale

Ivanov (2018)
Rojas, Srivastava, Valle (2019)
Aranda, Bonilla, EP (2019)




## Rank-1 matrices

# Minimal A4

| | $L_e$ | $L_\mu$ | $L_\tau$ | $l_e$ | $l_\mu$ | $l_\tau$ | $N_T$ | $H$ | $\eta$ |
|---|---|---|---|---|---|---|---|---|---|
| $SU(2)$ | 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 |

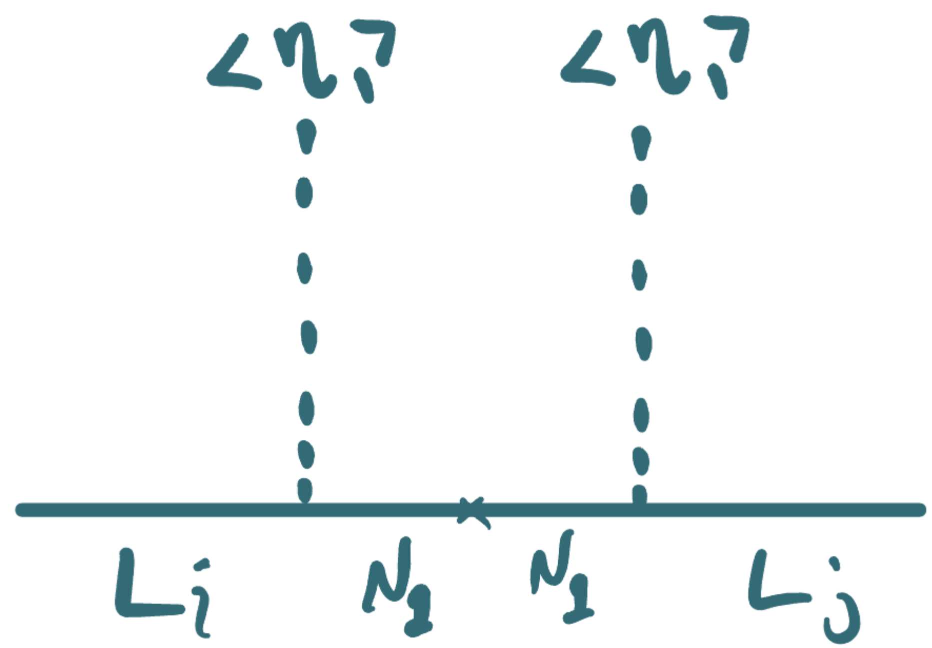
Bonilla, Herms, Medina, EP (2023)

$$A_4 \longrightarrow Z_2$$

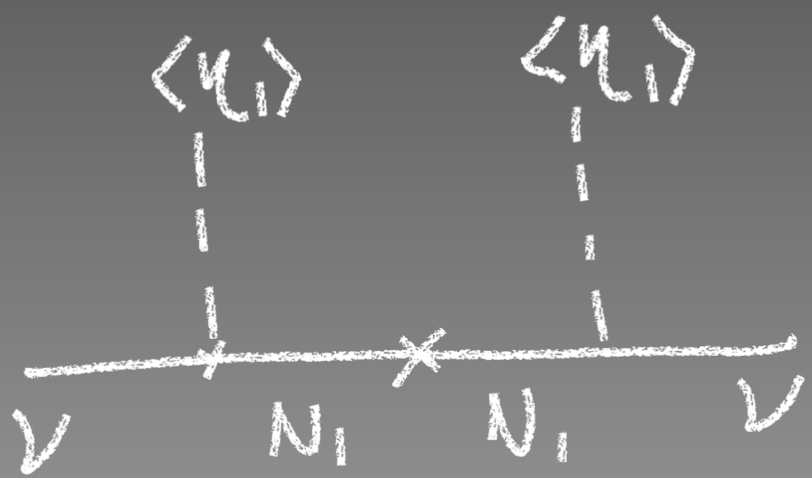
$$\langle \eta^0 \rangle = \begin{pmatrix} v_{\eta_1} \\ 0 \\ 0 \end{pmatrix}$$

Only $N_1$ is active

Rank-1 matrix

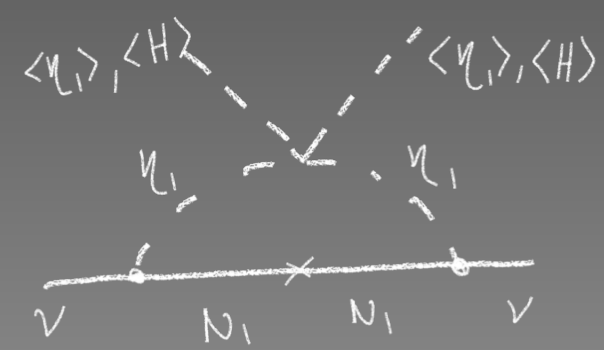


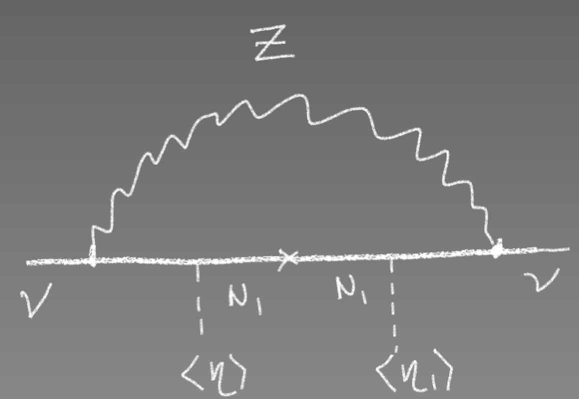
Bonilla, Herms, Medina, EP (2023)




$$M_\ell = \bar{M}_\ell$$

$$m_\nu = m_\nu^{\text{tree}} + m_\nu^{\text{1-loop}}$$

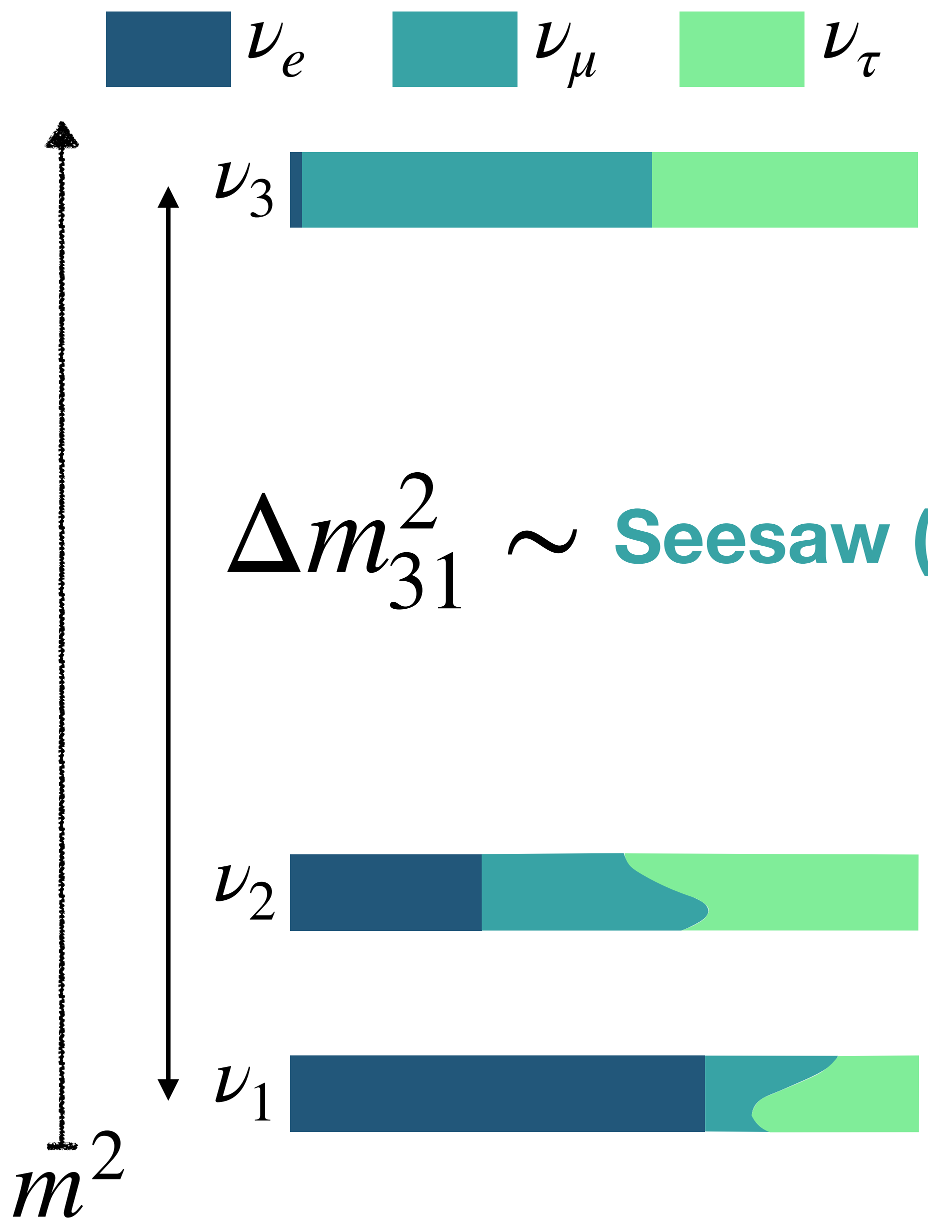



$$m_\nu^{\text{atm}} = m_\nu^{\text{tree}}$$

$$m_\nu^{\text{sol}} = m_\nu^{\text{1-loop}}$$

# Both mechanism share the same Yukawa couplings




## Neutrino Masses (NO)

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

$\boxed{H, \quad N_1, \quad \eta_1}$

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

$\boxed{N_2, \quad N_3, \quad \eta_2, \quad \eta_3}$

# CP-violation in the scalar sector is necessary to fit lepton mixing

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

$$\sin^2\theta^l_{12} \qquad \sin^2\theta^l_{23} \qquad \delta^{CP}$$

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

|  | $L_e$ | $L_\mu$ | $L_\tau$ | $l_e$ | $l_\mu$ | $l_\tau$ | $N_T$ | $H$ | $\eta$ |
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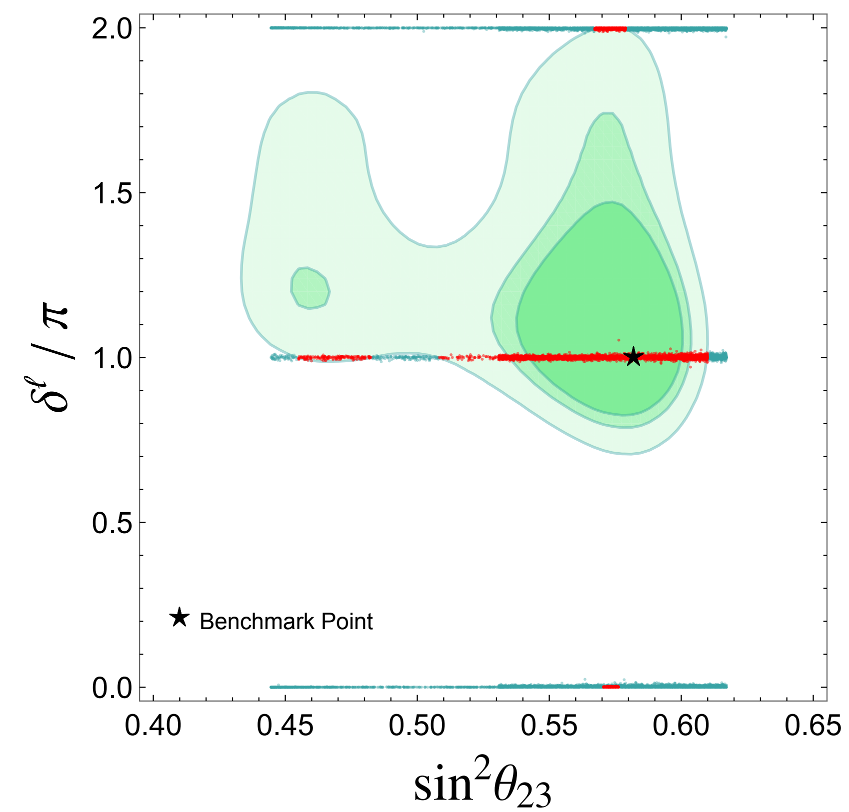


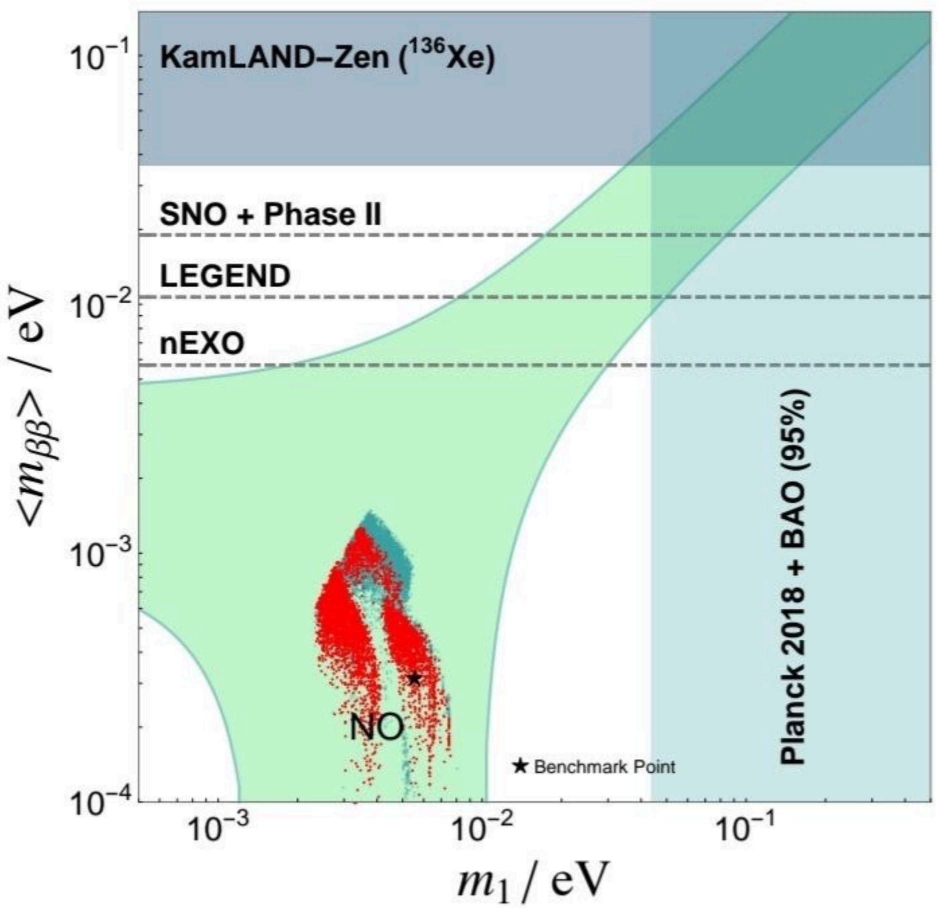


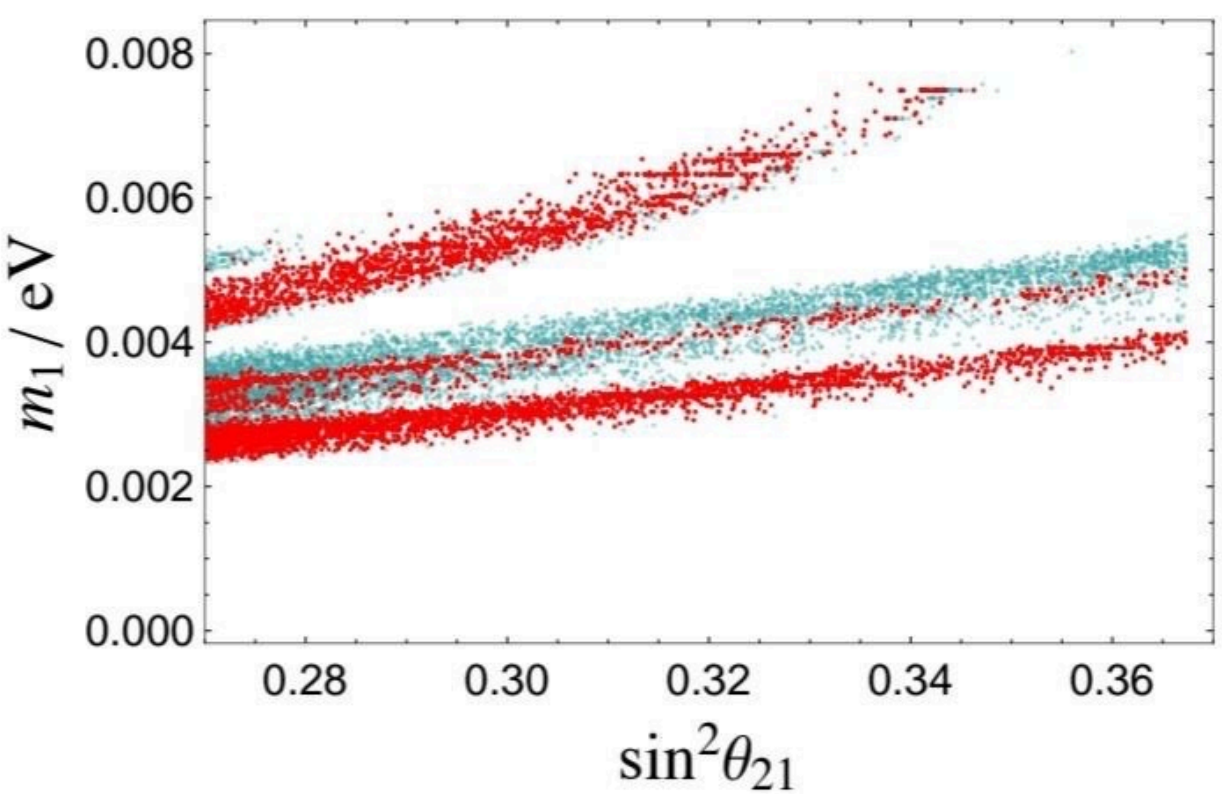

# Conclusions

- The minimal DDM model naturally explains DM stability and explain the hierarchy in the neutrino sector
- The Higgs potential needs to violate CP
- The model is severely constrain and can be ruled out soon