Absolute neutrino mass and dark matter stability from flavour

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WARNING!

Model-building!

(hopefully not the case)

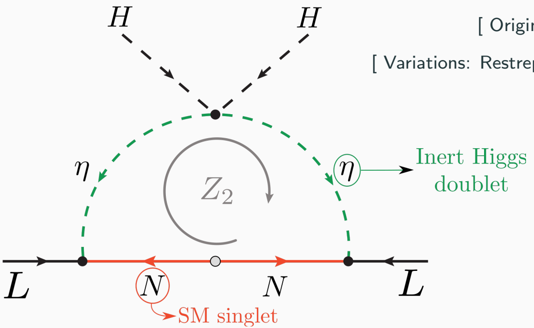
Motivation

- We still fail to understand the structure of the flavour sector
- Non-abelian discrete flavour symmetries can help us with current data and anticipate future results
- Explain neutrino masses, dark matter stability together with flavour in the lepton sector
- Produce testable prediction

Scotogenic in a nut-shell

Radiative mass generation $\Longrightarrow$ naturally **suppressed** neutrino masses

Tree-level is forbidden by the Z_2 symmetry $\Longrightarrow$ stable **DM candidate**



[Original: Ma (2006)]

[Variations: Restrepo et al (2013)]

We promote Z_2 to the non-abelian $\Sigma(81)$

$\Sigma(81)$ **symmetry**

- Discrete subgroup of $U(3)$ with 9 singlets $(\mathbf{1}_{ij})$ and 4 complex triplets $(\mathbf{3}_{A,B,C,D})$
- Very attractive property!! Some representations form a closed set under the group tensor products

$\Longrightarrow$ We have automatically two sectors:

Visible sector: $\{\mathbf{1}_{ij},\ \mathbf{3}_D,\ \bar{\mathbf{3}}_D\}$ is closed.

Dark sector: $\{\mathbf{3}_{A,B,C},\ \bar{\mathbf{3}}_{A,B,C}\}$

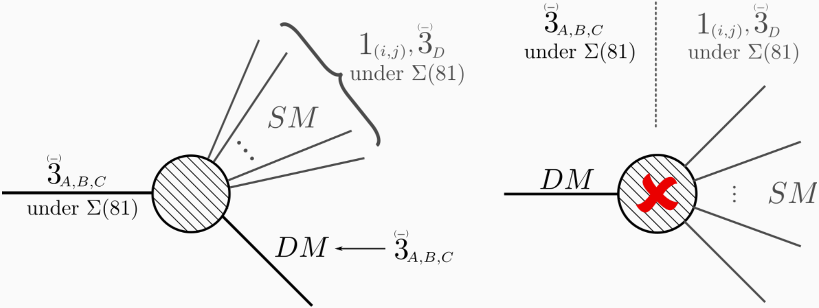
Not the only possibility: S_4, T', $\Sigma(32)$, ...

[On discrete symmetries: Ishimori et al, book 2012 (ed.2)]

[Other works on $\Sigma(81)$: Ma (2006); Ma (2007); BenTov, Zee (2013); Hagedorn et al (2018)]

DM stability

Visible sector: $\{\mathbf{1}_{ij},\ \mathbf{3}_D,\ \bar{\mathbf{3}}_D\}$, Dark sector: $\{\mathbf{3}_{A,B,C},\ \bar{\mathbf{3}}_{A,B,C}\}$



Lightest dark sector particle is automatically stable.

Non-abelian version of the stability mechanism shown in general by Bonilla et al (2020).

The model

Particle content

	Fields	$\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$	$\Sigma(81)$
Visible	L	$(\mathbf{1}, \mathbf{2}, -1/2)$	$\mathbf{3}_D$
	e_R	$(\mathbf{1}, \mathbf{1}, -1)$	$\bar{\mathbf{3}}_D$
	H	$(\mathbf{1}, \mathbf{2}, 1/2)$	$\bar{\mathbf{3}}_D$
Dark	$N_{L,R}$	$(\mathbf{1}, \mathbf{1}, 0)$	$\mathbf{3}_A$
	η	$(\mathbf{1}, \mathbf{2}, 1/2)$	$\mathbf{3}_A$
	ϕ	$(\mathbf{1}, \mathbf{2}, 1/2)$	$\bar{\mathbf{3}}_A$

- SM fields transform under the subgroup $\Rightarrow$ closed
- **BSM particles** are in the dark sector, i.e. outside the subgroup $\Rightarrow$ the lightest is a **stable dark matter** candidate
- Similar to a *flavoured* 3HDM

Charged lepton masses

$$\begin{aligned}\mathcal{L}_Y^V &= Y_1^e \sum_{i=1}^{3} \bar{L}_i \ell_{R_i} H_i \\ &+ Y_2^e \left(\bar{L}_1 \ell_{R_3} H_2 + \bar{L}_2 \ell_{R_1} H_3 + \bar{L}_3 \ell_{R_2} H_1\right) \\ &+ Y_3^e \left(\bar{L}_1 \ell_{R_2} H_3 + \bar{L}_2 \ell_{R_3} H_1 + \bar{L}_3 \ell_{R_1} H_2\right) \\ &+ \text{h.c.}\end{aligned}$$

$$M_e = \frac{1}{\sqrt{2}} \begin{pmatrix} Y_1^e\, v1 & Y_3^e\, v3 & Y_2^e\, v2 \\ Y_2^e\, v3 & Y_1^e\, v2 & Y_3^e\, v1 \\ Y_3^e\, v2 & Y_2^e\, v1 & Y_1^e\, v3 \end{pmatrix}$$

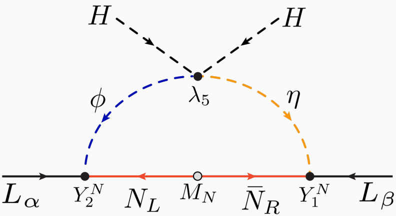
The strong hierarchy in the charged leptons

$\Downarrow$

Strong hierarchy between the VEVs

Neutrino masses

$$\begin{aligned}
\mathcal{L}_{\mathrm{Y}}^{D} &= M_N \left(\bar{N}_{L_1} N_{R_1} + \bar{N}_{L_2} N_{R_2} + \bar{N}_{L_3} N_{R_3}\right) \\
&+ Y_1^N \left(L_1 \bar{N}_{R_2} \eta_1 + L_2 \bar{N}_{R_3} \eta_2 + L_3 \bar{N}_{R_1} \eta_3\right) \\
&+ Y_2^N \left(L_1 N_{L_1} \phi_2 + L_2 N_{L_2} \phi_3 + L_3 N_{L_3} \phi_1\right) \\
&+ \text{h.c.}
\end{aligned}$$



$$\begin{aligned}
\mathcal{V}_\nu &= \lambda_5^{(1)} \left[(H_1\eta_2^\dagger)(H_1\phi_1^\dagger) + (H_2\eta_3^\dagger)(H_2\phi_2^\dagger) + (H_3\eta_1^\dagger)(H_3\phi_3^\dagger)\right] \\
&+ \lambda_5^{(2)} \left[(H_1\eta_1^\dagger)(H_2\phi_3^\dagger) + (H_1\eta_3^\dagger)(H_3\phi_2^\dagger) + (H_2\eta_2^\dagger)(H_3\phi_1^\dagger)\right] \\
&+ \text{h.c.}
\end{aligned}$$

Note that given the flavour structure some of the entries of $(M_\nu)_{\alpha\beta}$ are not realised!

Neutrino masses

- Like for charged leptons, there is a clear pattern in the mass matrix $\Rightarrow$ **flavour predictions**
- The diagonal-less is protected by the symmetry

$$M_\nu \sim \frac{1}{2}\begin{pmatrix} 0 & C_1 v_3^2 + C_2 v_1 v_2 & C_1 v_2^2 + C_2 v_1 v_3 \\ C_1 v_3^2 + C_2 v_1 v_2 & 0 & C_1 v_1^2 + C_2 v_2 v_3 \\ C_1 v_2^2 + C_2 v_1 v_3 & C_1 v_1^2 + C_2 v_2 v_3 & 0 \end{pmatrix}$$

Results and predictions

Neutrino mass scale

$$A = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix} \text{ diagonalised by: } \quad U^T A\, U = \text{diagonal}(m_1, m_2, m_3)$$

It fulfils the relation,

$$\frac{1}{2}\left[Tr(A^\dagger A)\right]^2 = Tr\left[(A^\dagger A)^2\right] ,$$

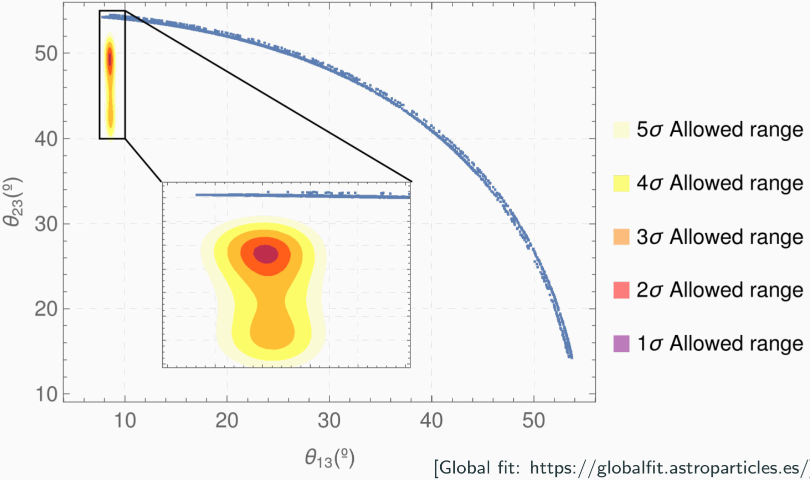
which translates to $m_3^{\text{NO}} = m_1^{\text{NO}} + m_2^{\text{NO}}$ and $m_2^{\text{IO}} = m_1^{\text{IO}} + m_3^{\text{IO}}$

$$m_{\text{lightest}}^{\text{NO}} \approx 2.8 \times 10^{-2} \text{ eV}$$

$$m_{\text{lightest}}^{\text{IO}} \approx 7.5 \times 10^{-4} \text{ eV}$$

Mixing predictions (Normal Ordering)

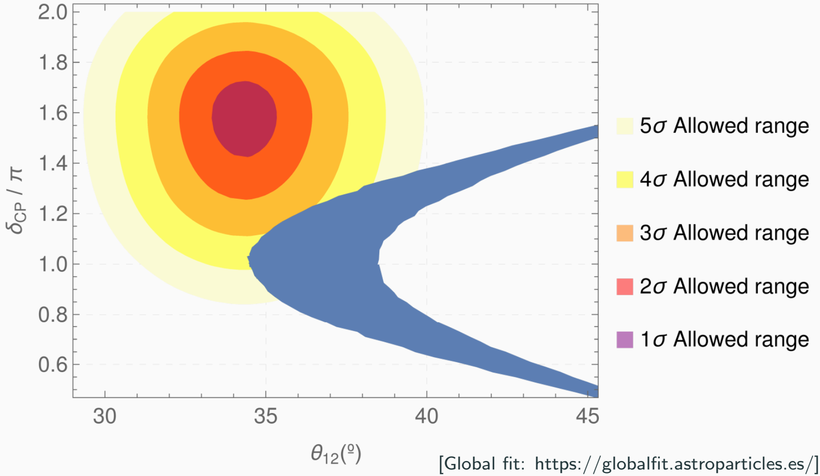
The model is not compatible with NO!



[Global fit: https://globalfit.astroparticles.es/]

Mixing predictions (Inverted Ordering)

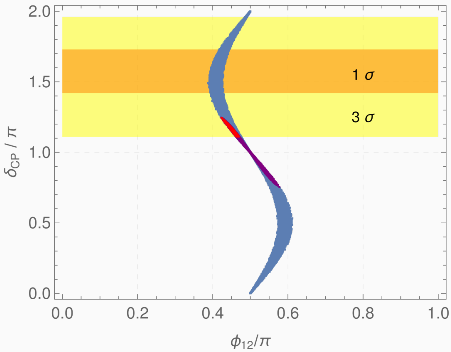
- Strong correlation between solar and δ_{CP}
- **Testable prediction!** New releases of Nova/T2K results

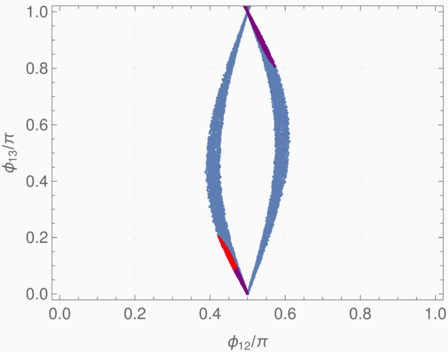


[Global fit: https://globalfit.astroparticles.es/]

CP phases

- Strong correlation between the three phases
- Only δ_{CP} is constrained, but Majorana phases are important for $0\nu\beta\beta$





Blue: θ_{12}, δ free. Purple: θ_{12} in 3σ, δ free. Red: θ_{12}, δ in 3σ

[Global fit: https://globalfit.astroparticles.es/]

Neutrinoless double beta decay

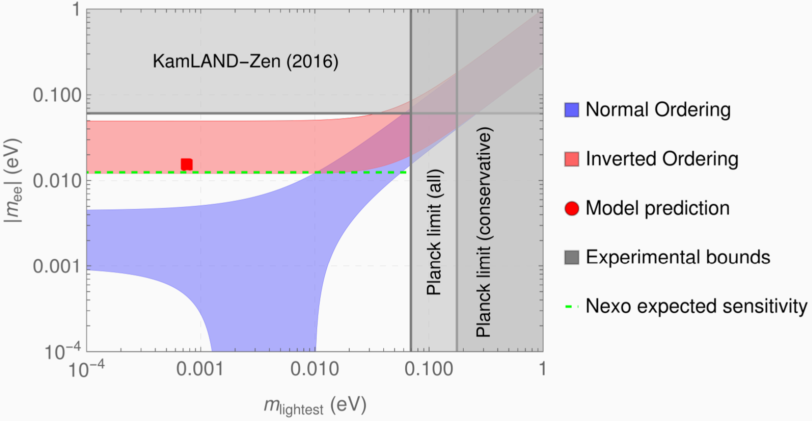
Inverted Ordering prediction

Absolute neutrino scale prediction

Majorana phases correlation

$\Longrightarrow$ **Strong prediction for** $0\nu\beta\beta$

$|m_{ee}| \approx 0.018$ eV



Summary

- All the *nice things* of the Scotogenic model + flavour predictions

- $\Sigma(81)$ symmetry does everything:
  $\Longrightarrow$ Radiative mass + DM stability + Flavour

- Strong **flavour predictions**:
  - Inverted Ordering
  - Absolute neutrino mass scale, $m_\nu \approx 7.5 \times 10^{-4}$ eV
  - Strong correlation between θ_{12} and δ_{CP} falsifiable in the close future
  - Correlations between the three CP phases
  - $0\nu\beta\beta$ prediction, $|m_{ee}| \approx 0.018$ eV

- Other models connecting flavour and dark matter stability

Backup

Diagonalising the matrices

- Charged Lepton masses: $\hat{M}_e = U_\ell^\dagger M_e V_\ell$

  with $L \to U_\ell\, L, \quad \ell_R \to V_\ell\, \ell_R\,, \quad \hat{M}_e = \mathrm{diag}(m_e, m_\mu, m_\tau)$

- Neutrino masses: $U_\nu^T\, M_\nu\, U_\nu \,=\, \mathrm{diag}(m_1, m_2, m_3)$

  $(M_\nu)_{\alpha\beta} = \frac{1}{16\pi^2}\,(Y_1^N)_{\beta ij}\,(Y_2^N)_{\alpha ij}\, M_N \sum_{X=R,I} \sigma_X\,(U_X^\alpha)_{1i}\,(U_X^\alpha)_{i2}\, B_0(0, M_N, m_{X_i}^2)$

$U_{\mathrm{lep}} = U_\ell^\dagger\, U_\nu$ with the usual definition

$U_{\mathrm{lep}} = P(\delta_1, \delta_2, \delta_3)\, U_{23}(\theta_{23}, \phi_{23})\, U_{13}(\theta_{13}, \phi_{13})\, U_{12}(\theta_{12}, \phi_{12}).$

Dark matter

- Flavour structure $\Longrightarrow$ **three independent scotogenic mechanisms**
- Three component dark matter: lightest CP-odd/even scalar or the fermionic singlet for each scotogenic
- Both scalar and fermionic DM scenarios compatible with the observed **DM relic density** and DD constraints
- The scalar candidate can achieve this more easily with masses around 500 GeV
- The fermionic candidate requires large Yukawas and leads to some tension with existing bounds from lepton flavour violation

[DM in the Scotogenic model have been widely studied, for example 2108.05103]

Soft-breaking terms

We add the dimension 2 soft-breaking terms $\mathcal{V}_{\text{soft}} = \mu^2_{ij}\, H_i^\dagger H_j$.

- $\mathcal{V}_{\text{soft}}$ is not needed to break $\Sigma(81)$, but to move away from the very restrictive VEV alignments

- Similar to add flavon fields, but without new extra physical degrees of freedom

- Suppress strong FCNCs (like in 3HDMs)

    - We can rotate to the Higgs basis $H = \sum_i \frac{v_i}{v} H_i \longrightarrow$ only one H with VEV, the orthogonal ones are VEV-less

    - Diagonal terms proportional to μ : can be taken to be arbitrarily large suppressing FCNCs

[Georgi, Nanopoulos (1979)]