Absolute ν mass and DM stability from flavour

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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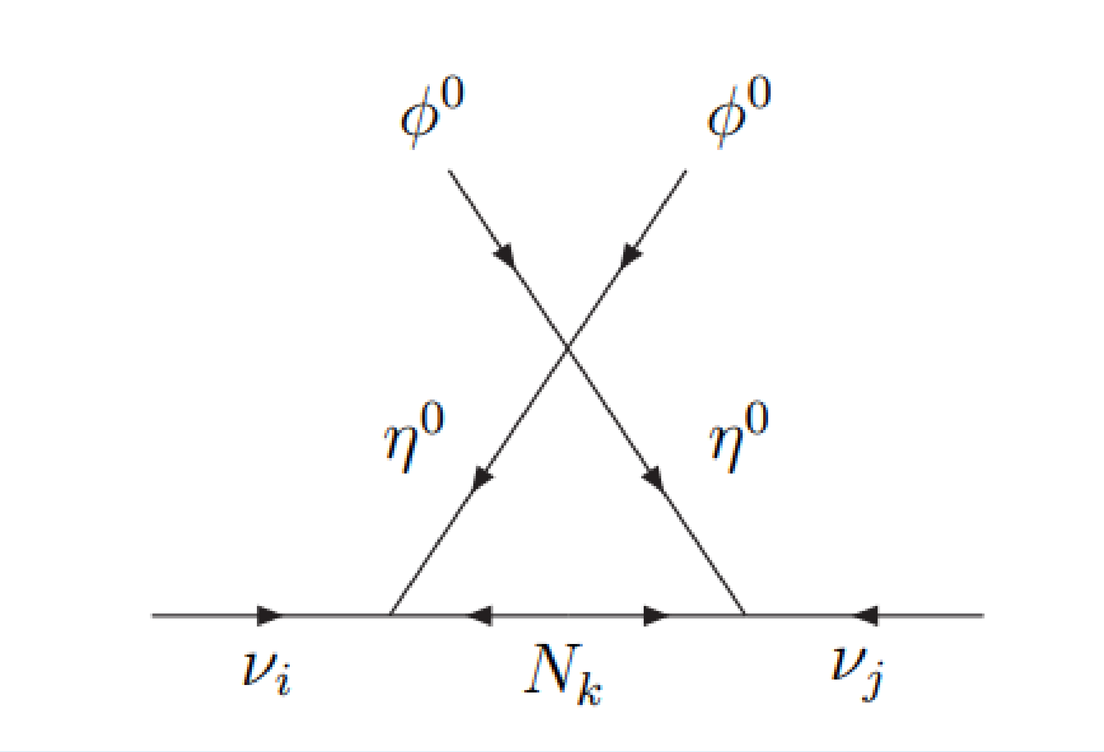
Flavoured scotogenic: $\Sigma(81)$

- Scotogenic framework: hep-ph/0601225 by Ernest Ma
- Neutrino masses come at the 1-loop level. The lightest particle running in the loop is stabilized by a Z2 symmetry.
- We promote the Z2 symmetry to a non-Abelian group $\Sigma(81)$.



Σ(81) group

- Why Σ(81)?
- Nice property: some representations form a close set under the group tensor products. We call these 'visible representations' (as opposed to 'dark representations')

Visible representations: $\{1_{ij}, 3_D, \overline{3}_D\}$,

$$1_{ij} \times 3_D(\overline{3}_D) = 3_D(\overline{3}_D),$$
$$3_D(\overline{3}_D) \times 3_D(\overline{3}_D) = \overline{3}_D(3_D),$$
$$3_D(\overline{3}_D) \times \overline{3}_D(3_D) = 1_{ij}$$

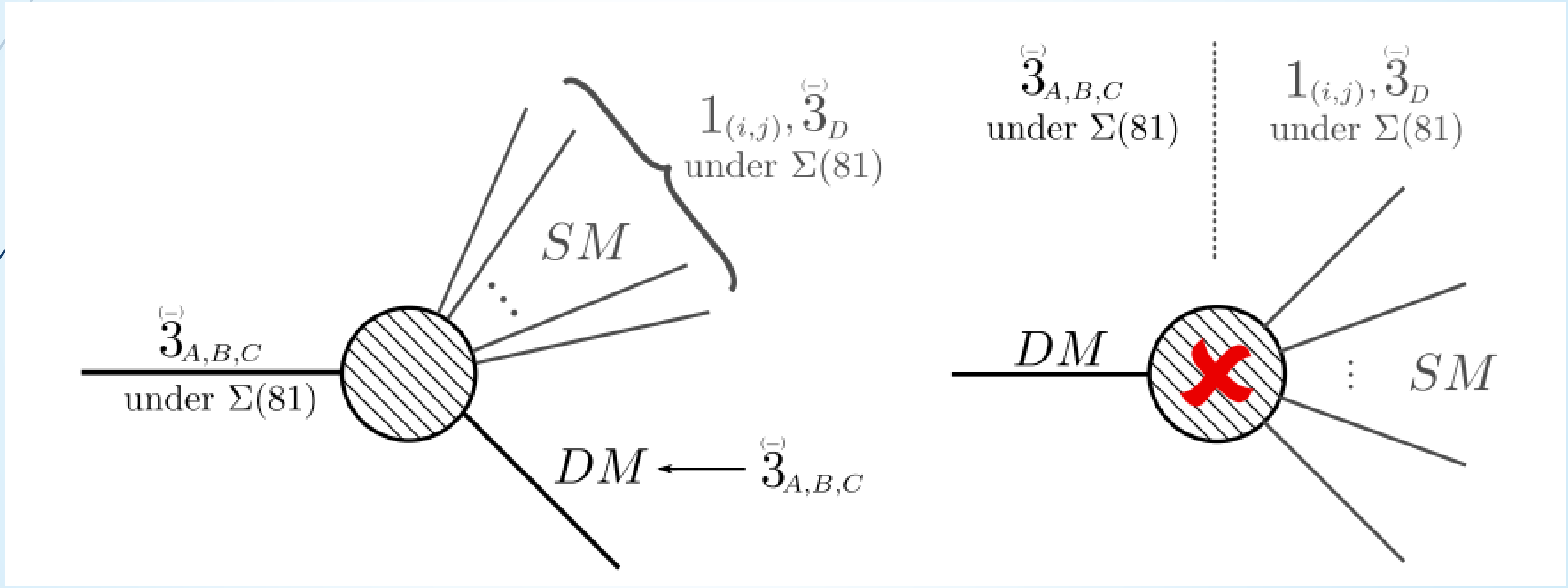
Closed set

Dark representations: $\{3_A, \overline{3}_A, 3_B, \overline{3}_B, 3_C, \overline{3}_C\}$,

Not a closed set

DM stability

- Non-abelian version of the stability mechanism shown in 1812.01599. Lightest dark sector particle is stable.



- Not the only group with this property
- Additional features: SM in triplets, leads to strong predictions in mixing angles, neutrino masses and $\nu 0ee$. No need of extra symmetries or flavons.

The UV complete model

	Fields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$\Sigma(81)$
Visible	L	$(\mathbf{1}, \mathbf{2}, -1/2)$	$\mathbf{3}_D$
	ℓ_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 is visible, new particles are dark sector. Lightest is DM.
- No new SSB scalar apart from the Higgs doublet.
- Flavoured 3HDM

Charged lepton masses

- SM mechanism + flavour

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

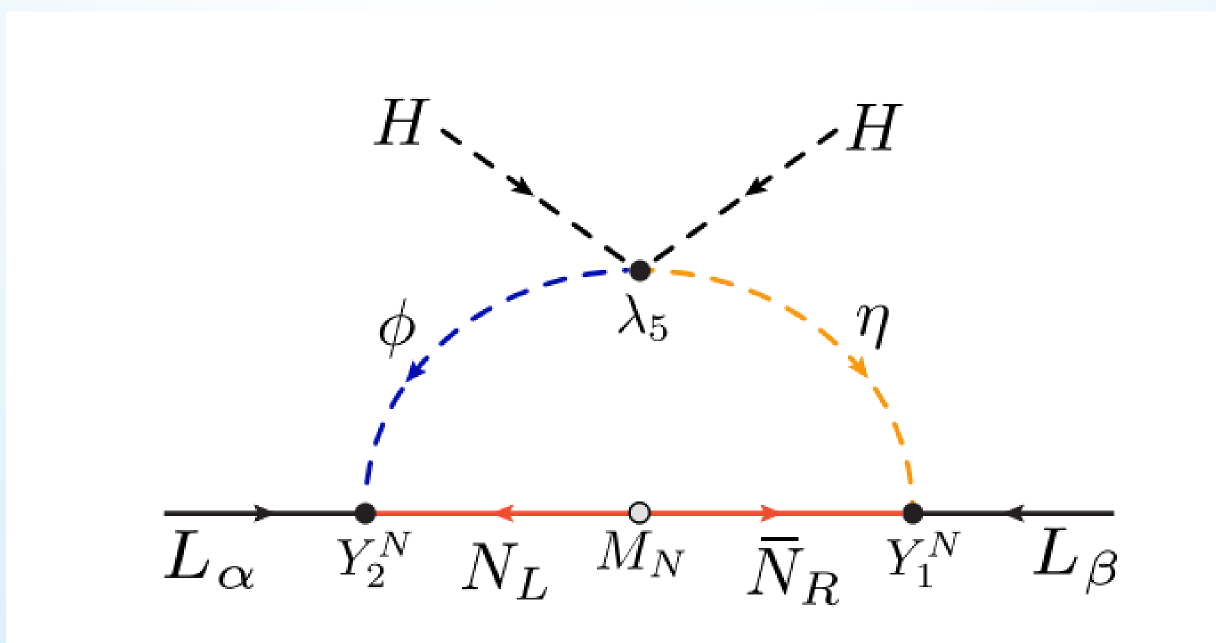
$$
M_e = \frac{1}{\sqrt{2}} \begin{pmatrix} Y_1^e\, v1 & Y_3^e\, v3 & Y_2^e\, v2 \\ Y_2^e\, v3 & Y_1^e\, v2 & Y_3^e\, v1 \\ Y_3^e\, v2 & Y_2^e\, v1 & Y_1^e\, v3 \end{pmatrix}
$$

Neutrino masses

- Scotogenic mechanism hep-ph/0601225 (+ flavour). No need of 'ad hoc' Z_2 stabilizing symmetry: flavour does it for you.

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

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



Neutrino masses

- There is a clear pattern in both mass matrices: flavour predictions!
- The diagonaless neutrino texture is **NOT** a prediction of $\Sigma(81)$. We could generate them by adding different triplets to the model. But in this setup the 0s are symmetry protected.

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

Neutrino mass scale

- Consider a diagonal-less Majorana neutrino mass matrix

$$A = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix}, \qquad \text{with } a, b, c \in \mathbb{C}$$

- Diagonalized as usual as

$$U^T A U = m_d = \text{diagonal}(m_1, m_2, m_3)$$
$$U^\dagger A^\dagger A U = m_d^2 ,$$

- We can compute the traces of $A^\dagger A$ and $(A^\dagger A)^2$ and noti

$$\frac{1}{2}\left[Tr(A^\dagger A\right.$$

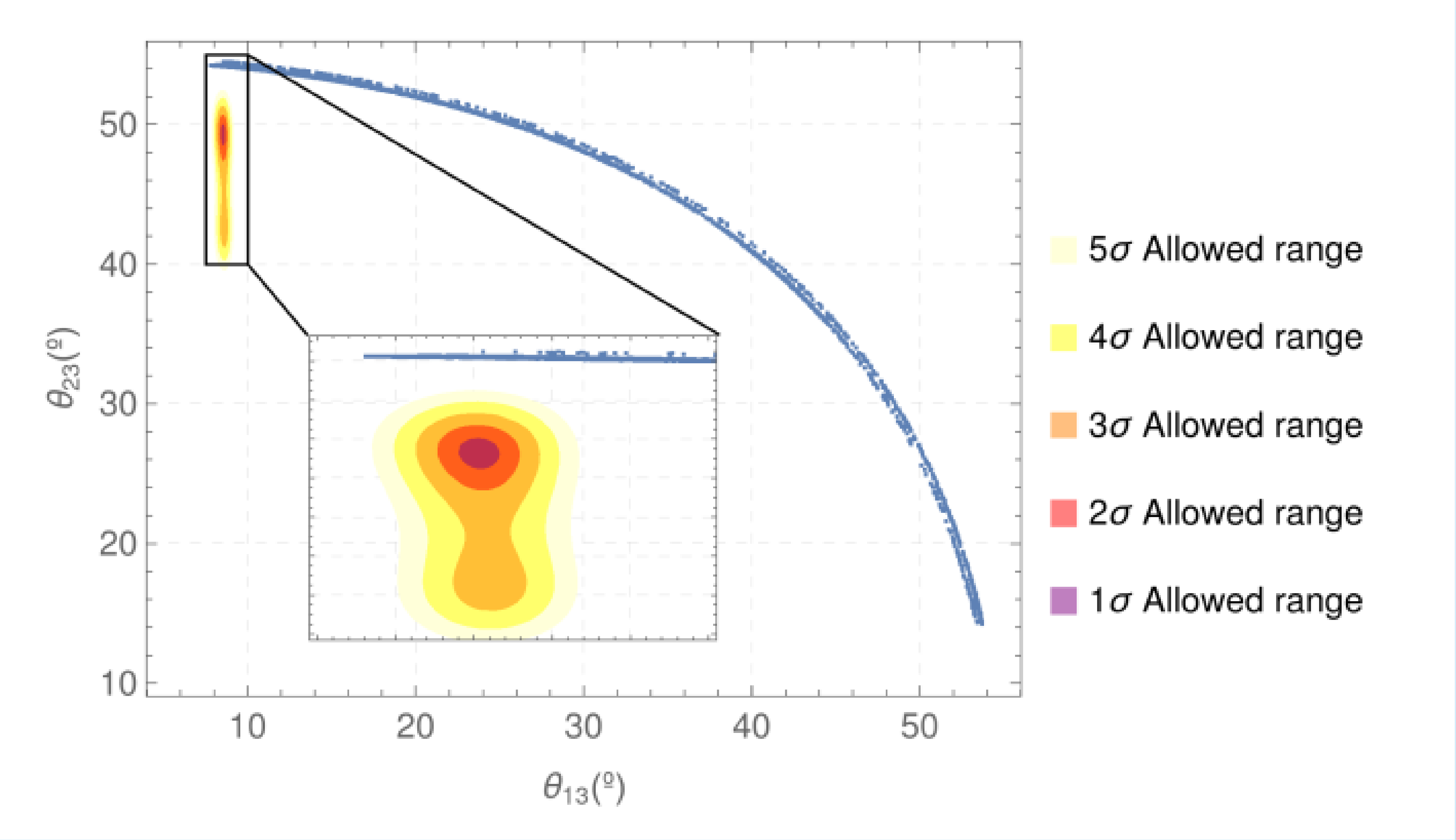
$$m_{\text{lightest}}^{\text{NO}} \approx 2.8 \times 10^{-2}\,\text{eV}\,,$$
$$m_{\text{lightest}}^{\text{IO}} \approx 7.5 \times 10^{-4}\,\text{eV}\,.$$

$$m_3^{\text{NO}} = m_1^{\text{NO}} + m_2^{\text{NO}}\,,$$
$$m_2^{\text{IO}} = m_1^{\text{IO}} + m_3^{\text{IO}}\,,$$

$$m_{\text{heaviest}}$$

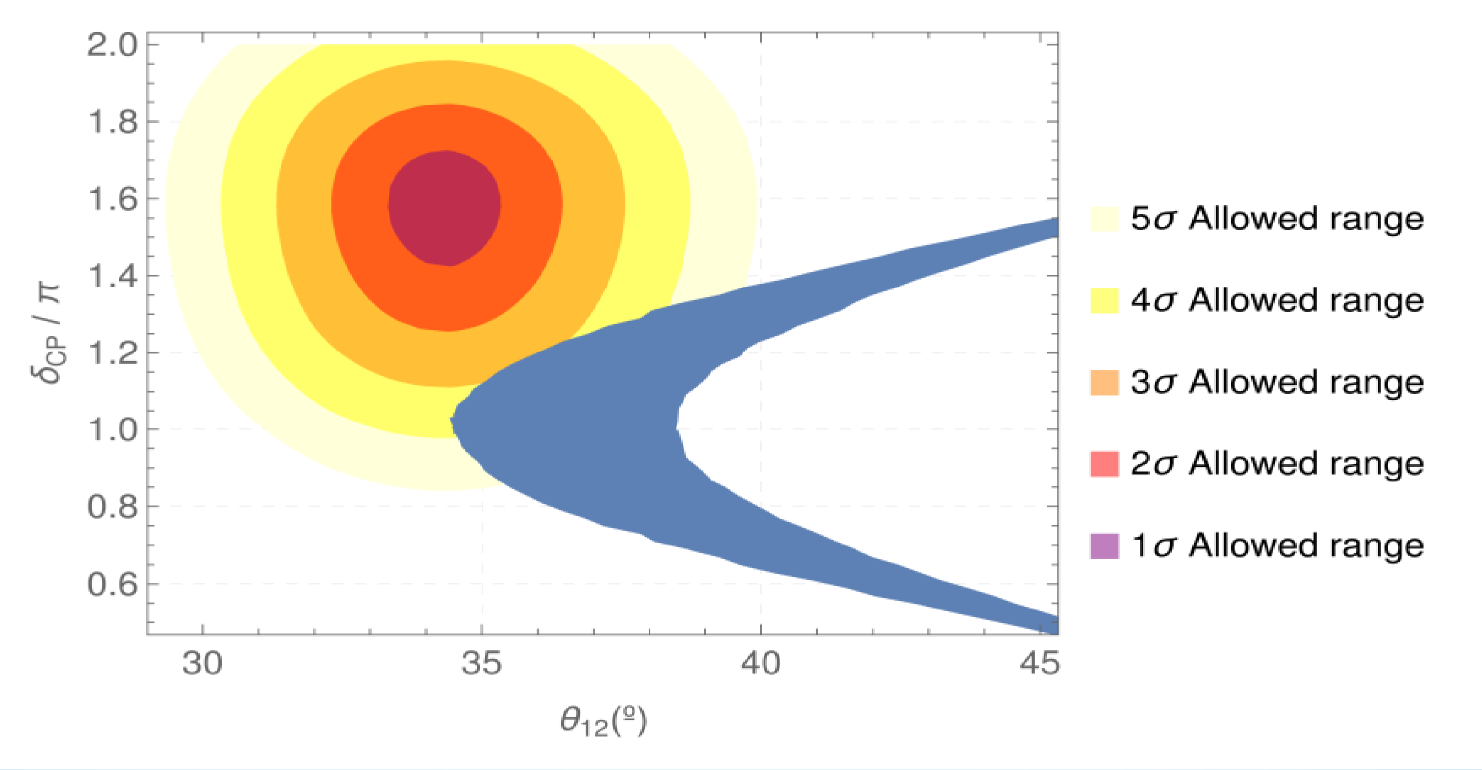
Mixing predictions

- If NO is assumed, a strong but ruled out correlation between θ_{13} and θ_{23} appears. The model is <u>not</u> compatible with NO!



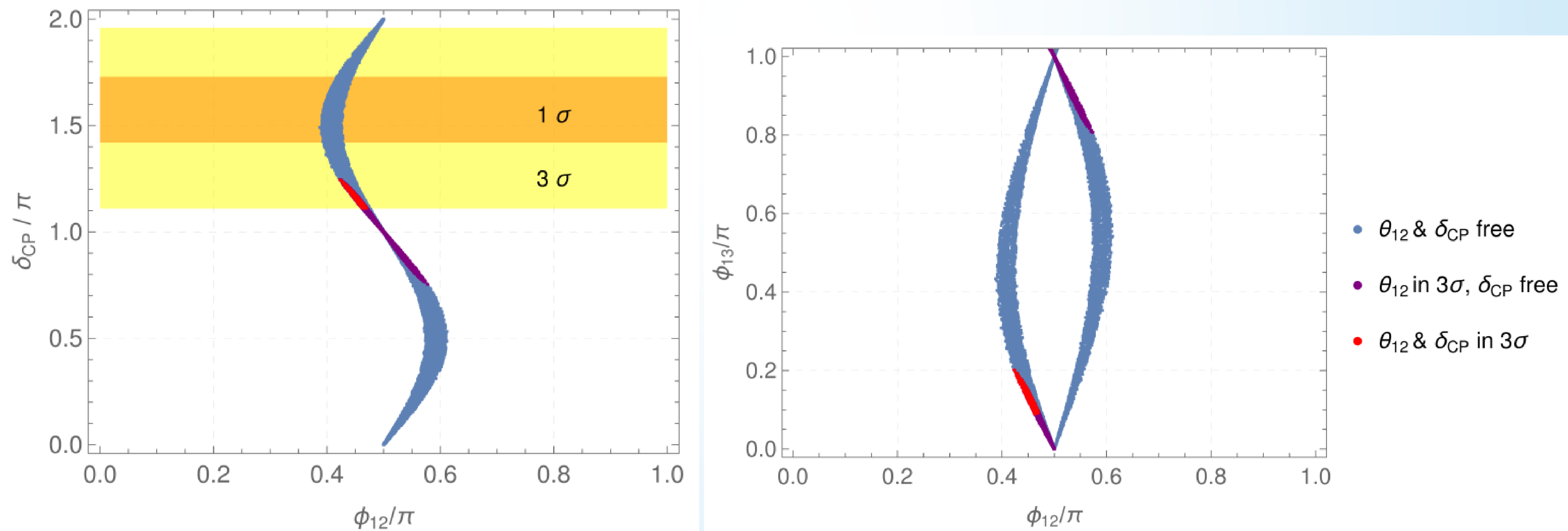
Mixing predictions

- If instead we take IO we find a number of predictions:
- θ_{13} and θ_{23} can be fitted (no predictive pattern)
- Strong correlation θ_{12} vs δ_{CP}. 3σ tension if we believe δ_{CP} measurements, but best fit θ_{12} if we allow $\delta_{CP} \sim \pi$. **Testable prediction!** Stay tuned to Nova/T2K results (see Mariam's talk)



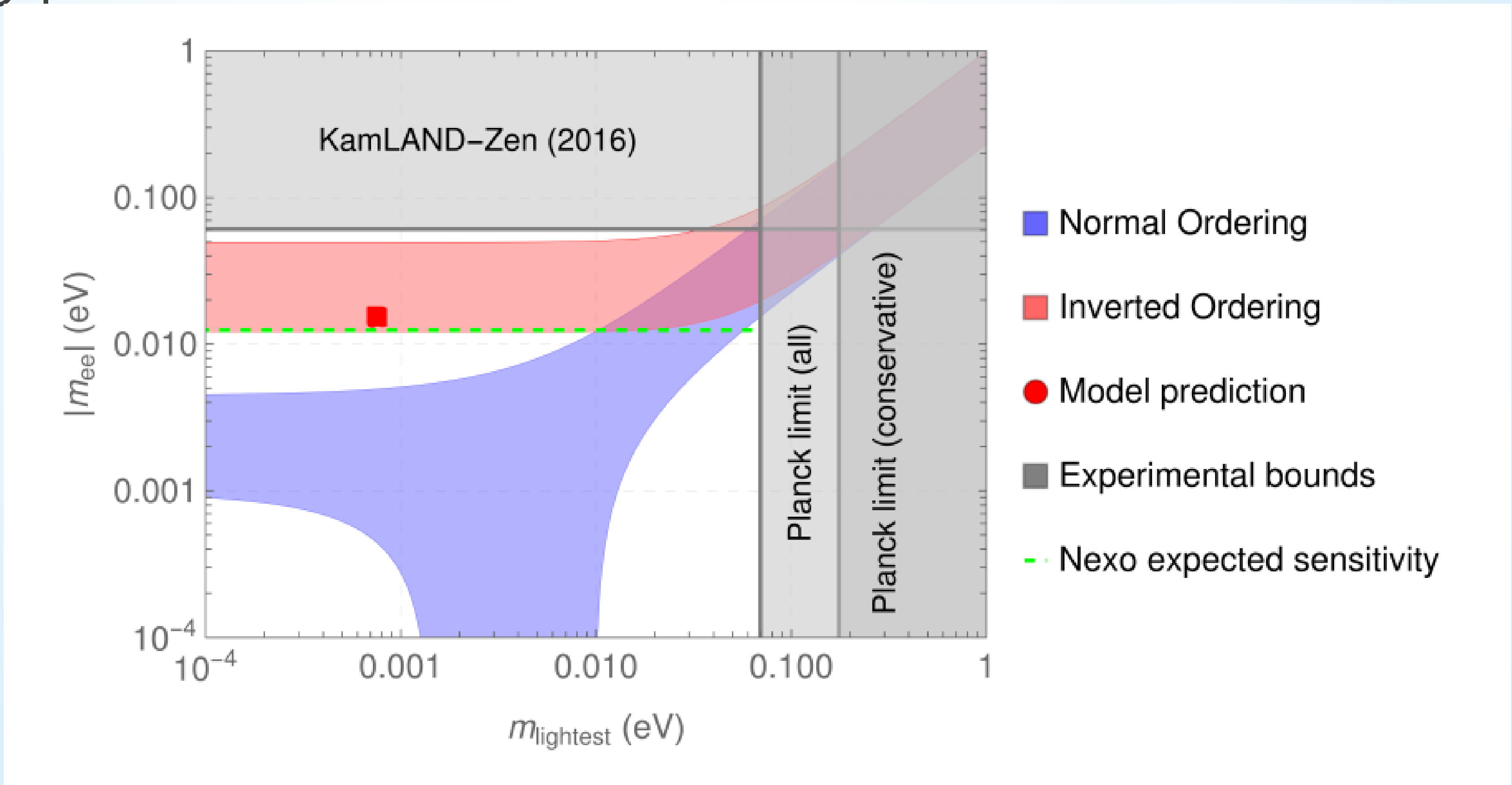
CP Violating phases

- Strong correlation between the three
- Only δ_{CP} is constrained by oscillation experiments
- But ϕ_{12} and ϕ_{13} are relevant for $\nu 0ee$



Neutrinoless double beta decay

- Ordering is predicted
- Absolute neutrino scale is predicted
- Majorana phases are correlated
- Strong prediction for $\nu 0ee$!



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Conclusions

- Minimal model:
  - Scotogenic field content
  - Multipurpose $\Sigma(81)$ symmetry does all: DM stabiltiy & flavour
  - Strong flavour predictions:
    - Inverted Ordering
    - Neutrino mass $m_{\text{light}} \approx 10^{-4}$ eV
    - Testable correlation between θ_{12} and δ_{CP}
    - Correlations between CPV phases
    - $|m_{ee}| \approx 0.018$ eV

Thank you for your attention!

Backup: Neutrino mass scale

- Consider a diagonal-less Majorana neutrino mass matrix

$$A = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix}, \qquad \text{with } a,\, b,\, c \in \mathbb{C}$$

$$Tr(A^\dagger A) = 2(|a|^2 + |b|^2 + |c|^2) = m_1^2 + m_2^2 + m_3^2\,,$$
$$Tr\left[(A^\dagger A)^2\right] = 2(|a|^2 + |b|^2 + |c|^2)^2 = m_1^4 + m_2^4 + m_3^4\,.$$

$$m_3^2 = (m_1 \pm m_2)^2$$

$$m_3^{\mathrm{NO}} = m_1^{\mathrm{NO}} + m_2^{\mathrm{NO}}\,,$$
$$m_2^{\mathrm{IO}} = m_1^{\mathrm{IO}} + m_3^{\mathrm{IO}}\,,$$

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

$$\frac{1}{2}\sum m_i = m_{\text{heaviest}}$$

Back up: Sigma(81)

$$\mathbf{1}_{(k,l)} \times \mathbf{3}_D(\bar{\mathbf{3}}_D) = \mathbf{3}_D(\bar{\mathbf{3}}_D)\,, \quad \mathbf{3}_D \times \mathbf{3}_D = \bar{\mathbf{3}}_D + \bar{\mathbf{3}}_D + \bar{\mathbf{3}}_D\,, \quad \mathbf{3}_D \times \bar{\mathbf{3}}_D = \mathbf{1}_{(k,l)}$$

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}_{\mathbf{3}_D} \otimes \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}_{\bar{\mathbf{3}}_D} = \sum_{k=0,1,2} [(x_1y_1 + \omega^{2k}x_2y_2 + \omega^k x_3y_3)_{\mathbf{1}_{(k,0)}} \oplus (x_2y_3 + \omega^{2k}x_3y_1 + \omega^k x_1y_2)_{\mathbf{1}_{(k,2)}} \oplus (x_3y_2 + \omega^{2k}x_1y_3 + \omega^k x_2y_1)_{\mathbf{1}_{(k,1)}}].$$

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}_{\mathbf{3}_D} \otimes \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}_{\mathbf{3}_D} = \begin{pmatrix} x_1y_1 \\ x_2y_2 \\ x_3y_3 \end{pmatrix}_{\bar{\mathbf{3}}_D} \oplus \begin{pmatrix} x_2y_3 \\ x_3y_1 \\ x_1y_2 \end{pmatrix}_{\bar{\mathbf{3}}_D} \oplus \begin{pmatrix} x_3y_2 \\ x_1y_3 \\ x_2y_1 \end{pmatrix}_{\bar{\mathbf{3}}_D},$$

$$(x)_{\mathbf{1}_{(k,0)}} \otimes \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}_{\mathbf{3}(\bar{\mathbf{3}})_D} = \begin{pmatrix} xy_1 \\ \omega^k xy_2 \\ \omega^{2k} xy_3 \end{pmatrix}_{\mathbf{3}(\bar{\mathbf{3}})_D}$$

$$(x)_{\mathbf{1}_{(k,1)}} \otimes \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}_{\mathbf{3}(\bar{\mathbf{3}})_D} = \begin{pmatrix} xy_3 \\ \omega^k xy_1 \\ \omega^{2k} xy_2 \end{pmatrix}_{\mathbf{3}(\bar{\mathbf{3}})_D}$$

$$(x)_{\mathbf{1}_{(k,2)}} \otimes \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}_{\mathbf{3}(\bar{\mathbf{3}})_D} = \begin{pmatrix} xy_2 \\ \omega^k xy_3 \\ \omega^{2k} xy_1 \end{pmatrix}_{\mathbf{3}(\bar{\mathbf{3}})_D}$$

Back up: other scoto groups

S4: doublets and singlet in visible reps, triplets in dark reps visible reps, triplete en dark rep ?

T': triplets and singlets in visible reps, doublets in dark ☑

Sigma(18) doublets and singlets in visible reps, more doublets in dark reps ?

Sigma(32) and Sigma(50) Complicated but visible doublets. ✗