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Neutrino masses from simple scoto-seesaw model with spontaneous CP violation

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Motivation

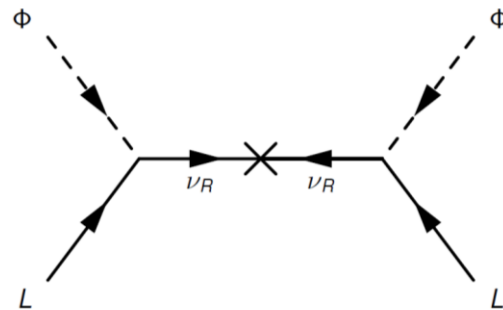
The Standard Model cannot explain:

- **Neutrino flavour oscillations** (imply existence of neutrino masses and lepton mixing)
- Observed **dark matter** abundance

Straightforward and **elegant** solutions:

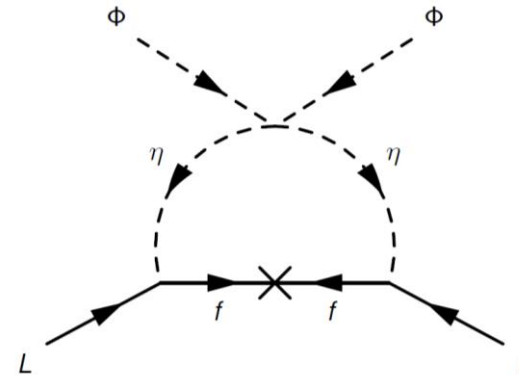
Type I Seesaw Model

Minkowski (1977), Gell-Mann *et al.* (1979), Yanagida (1979),
Glashow (1980), Mohapatra *et al.* (1980), Valle *et al.* (1980)



Scotogenic Model

Ma (2006)



Our solution:

Consider a model where **both mechanisms** contribute to neutrino masses with a **single discrete symmetry** to accommodate: **neutrino oscillation data**, **dark matter stability** and **spontaneous CP violation**

Simplest scoto-seesaw mechanism

Simple and elegant model where the **atmospheric mass scale** arises at tree level from the **type-I seesaw mechanism** and the **solar mass scale** emerges radiatively through a **scotogenic loop**

Rojas, Srivastava, Valle (2019)

Particle content:

	ν_R	η	f
$SU(2)_L$	1	2	1
$U(1)_Y$	0	1/2	0
Z_2	+	-	-
Multiplicity	1	1	1

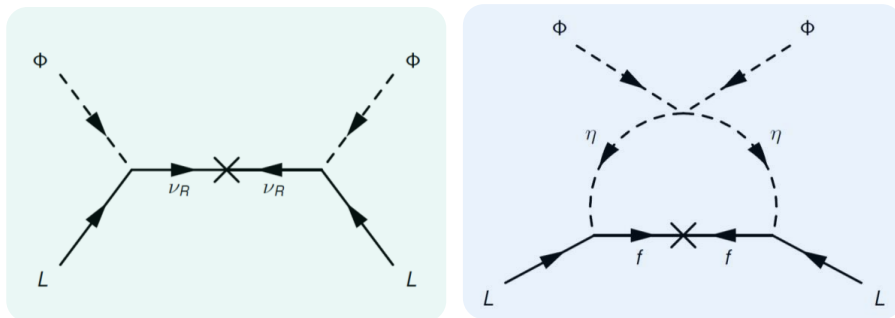
$$\mathcal{L} - \mathcal{L}_{\text{SM}} = \underbrace{-\bar{L}\mathbf{Y}_\nu^* \tilde{\Phi} \nu_R - \frac{1}{2} M_R \bar{\nu}_R \nu_R^c}_{\text{Generates the atmospheric neutrino mass scale}} - \underbrace{\bar{L}\mathbf{Y}_f^* \tilde{\eta} f - \frac{1}{2} M_f \bar{f} f^c}_{\text{Generates the solar neutrino mass scale}}$$

Generates the **atmospheric** neutrino mass scale

Generates the **solar** neutrino mass scale

Effective neutrino mass:
$$\mathbf{M}_\nu = -v^2 \frac{\mathbf{Y}_\nu \mathbf{Y}_\nu^T}{M_R} + \mathcal{F}(M_f, m_{\eta_R}, m_{\eta_I}) M_f \mathbf{Y}_f \mathbf{Y}_f^T$$

Allowed diagrams:



- Predicts **one massless neutrino**
- Accommodates **neutrino oscillation** and **LFV data**
- Provides a viable **WIMP dark matter candidate**
- **But lacks in predictivity!**

Adding spontaneous CP violation

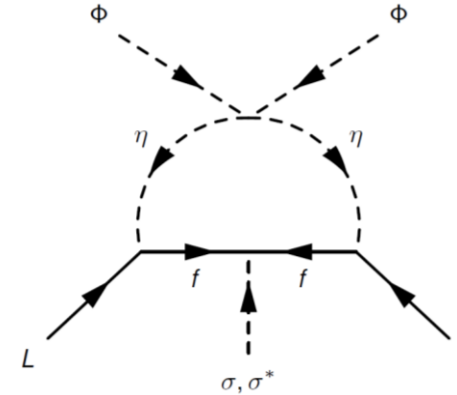
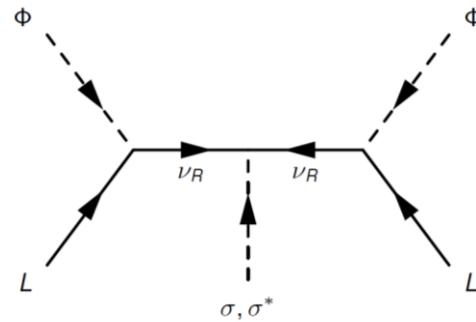
The number of parameters can be reduced by requiring the **Lagrangian to be CP symmetric** and invoking a **spontaneous origin** for leptonic CP violation

Introducing a **new scalar singlet** with **complex VEV**: $\langle \sigma \rangle = ue^{i\theta}$

$$\frac{1}{2}(y_R\sigma + \tilde{y}_R\sigma^*)\overline{\nu}_R\nu_R^c + \frac{1}{2}(y_f\sigma + \tilde{y}_f\sigma^*)\bar{f}f^c + \text{H.c.}$$

SSB

$$|M_R|e^{i\theta_R}\overline{\nu}_R\nu_R^c + |M_f|e^{i\theta_f}\bar{f}f^c + \text{H.c.}$$



At the effective level: $\mathbf{M}_\nu = -v^2 e^{i(\theta_f - \theta_R)} \frac{\mathbf{Y}_\nu \mathbf{Y}_\nu^T}{|M_R|} + \mathcal{F}(|M_f|, m_{\eta_R}, m_{\eta_I}) |M_f| \mathbf{Y}_f \mathbf{Y}_f^T$

- CPV is transmitted to the neutrino sector provided that $\theta \neq k\pi$ ($k \in \mathbb{Z}$) and $y_{R,f} \neq \tilde{y}_{R,f}$
- A minimal scalar potential which allows to implement SCPV must contain a phase sensitive term of the type $\sigma^4 + \text{H.c.}$

Branco *et al.* (1999, 2003)

The minimal scoto-seesaw model provides a template for neutrino masses, dark matter and SCPV!

Adding a discrete flavour symmetry

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)

Consider the most restrictive textures for \mathbf{Y}_ν , \mathbf{Y}_f and \mathbf{Y}_ℓ **realizable by minimal discrete flavour symmetry** in order to maximise predictability

Particle content:

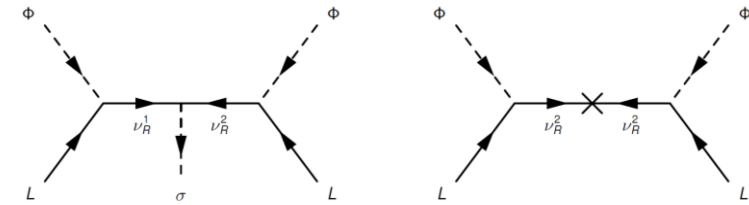
	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^{e-\tau*} \rightarrow \mathcal{Z}_2$
Fermions	L_e	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \rightarrow +1$
	L_μ	$(\mathbf{2}, -1/2)$	$\omega^0 \equiv 1 \rightarrow +1$
	L_τ	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \rightarrow +1$
	ν_R^1	$(\mathbf{1}, 0)$	$\omega^6 \equiv -i \rightarrow +1$
	ν_R^2	$(\mathbf{1}, 0)$	$\omega^0 \equiv 1 \rightarrow +1$
	f	$(\mathbf{1}, 0)$	$\omega^3 \rightarrow -1$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$\omega^0 \equiv 1 \rightarrow +1$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \equiv i \rightarrow +1$
	η	$(\mathbf{2}, 1/2)$	$\omega^5 \rightarrow -1$
	χ	$(\mathbf{1}, 0)$	$\omega^3 \rightarrow -1$

$$\langle \Phi \rangle = v, \langle \sigma \rangle = ue^{i\theta}, \langle \eta \rangle = \langle \chi \rangle = 0$$

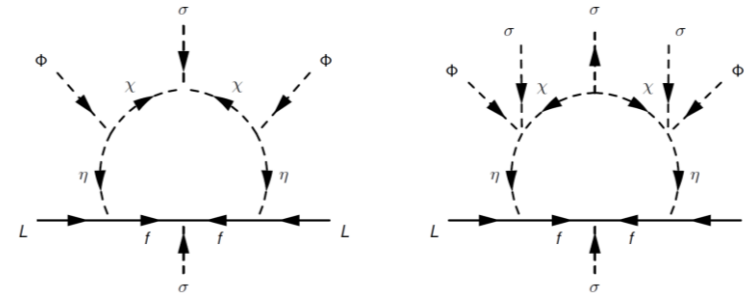
* $\mathcal{Z}_8^{e-\mu}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments, with decoupled τ and e , respectively

Contributions to neutrino masses:

• Tree level:



• One loop:



Allowed Yukawa and mass matrices:

$$\mathbf{Y}_\nu = \begin{pmatrix} x_1 & 0 \\ 0 & x_2 \\ x_3 & 0 \end{pmatrix} \quad \mathbf{M}_R = \begin{pmatrix} 0 & M_{12} e^{-i\theta} \\ M_{12} e^{-i\theta} & M_{22} \end{pmatrix} \quad \mathbf{Y}_f = \begin{pmatrix} y_1 \\ 0 \\ y_2 \end{pmatrix} \quad \mathbf{Y}_\ell = \begin{pmatrix} w_1 & 0 & w_2 \\ 0 & w_3 & 0 \\ w_4 & 0 & w_5 \end{pmatrix}$$

Scalar sector

Scalar Potential

$$\begin{aligned}
 V = & m_\Phi^2 \Phi^\dagger \Phi + m_\eta^2 \eta^\dagger \eta + m_\sigma^2 \sigma^* \sigma + m_\chi^2 \chi^* \chi + \frac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2} (\eta^\dagger \eta)^2 + \frac{\lambda_3}{2} (\sigma^* \sigma)^2 \\
 & + \frac{\lambda_4}{2} (\chi^* \chi)^2 + \lambda_5 (\Phi^\dagger \Phi) (\eta^\dagger \eta) + \lambda'_5 (\Phi^\dagger \eta) (\eta^\dagger \Phi) + \lambda_6 (\Phi^\dagger \Phi) (\sigma^* \sigma) + \lambda_7 (\Phi^\dagger \Phi) (\chi^* \chi) \\
 & + \lambda_8 (\eta^\dagger \eta) (\sigma^* \sigma) + \lambda_9 (\eta^\dagger \eta) (\chi^* \chi) + \lambda_{10} (\sigma^* \sigma) (\chi^* \chi) \\
 & + \left(\frac{\lambda'_3}{4} \sigma^4 + \frac{m_\sigma'^2}{2} \sigma^2 + \mu_1 \chi^2 \sigma + \mu_2 \eta^\dagger \Phi \chi^* + \lambda_{11} \eta^\dagger \Phi \sigma \chi + \text{H.c.} \right)
 \end{aligned}$$



From the minimisation conditions for $\langle \Phi \rangle = v$, $\langle \sigma \rangle = u e^{i\theta}$, $\langle \eta \rangle = \langle \chi \rangle = 0$

CP violating solution:

$$m_\Phi^2 = -\frac{\lambda_1}{2} v^2 - \frac{\lambda_6}{2} u^2, \quad m_\sigma^2 = -\frac{\lambda_6}{2} v^2 - \frac{\lambda_3 - \lambda'_3}{2} u^2, \quad \cos(2\theta) = -\frac{m_\sigma'^2}{u^2 \lambda'_3}$$

corresponds to the global minimum for $(m_\sigma'^4 - u^4 \lambda_3'^2)/(4\lambda_3') > 0$

Existence of a non-zero vacuum phase at the potential global minimum $\Rightarrow \theta \neq k\pi$ is allowed!

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)

	Fields	SU(2) _L \otimes U(1) _Y	$Z_8^{e-\tau} \rightarrow Z_2$
Fermions	L_e	(2, -1/2)	$\omega^6 \equiv -i \rightarrow +1$
	L_μ	(2, -1/2)	$\omega^0 \equiv 1 \rightarrow +1$
	L_τ	(2, -1/2)	$\omega^6 \equiv -i \rightarrow +1$
	ν_R^1	(1, 0)	$\omega^6 \equiv -i \rightarrow +1$
	ν_R^2	(1, 0)	$\omega^0 \equiv 1 \rightarrow +1$
	f	(1, 0)	$\omega^3 \rightarrow -1$
Scalars	Φ	(2, 1/2)	$\omega^0 \equiv 1 \rightarrow +1$
	σ	(1, 0)	$\omega^2 \equiv i \rightarrow +1$
	η	(2, 1/2)	$\omega^5 \rightarrow -1$
	χ	(1, 0)	$\omega^3 \rightarrow -1$

Other conclusions:

- $Z_8 \rightarrow Z_2$ after SSB, preventing the neutral dark scalars to mix with the neutral non-dark scalars:
 - $\phi - \sigma$ mixing
 - $\eta - \chi$ mixing
 - degenerate dark charged scalars η^\pm
- The lightest of the mass eigenstates resulting from the $\eta - \chi$ mixing is a **dark matter candidate** along with the dark fermion f

Low-energy constraints

Allowed Yukawa and mass matrices (for $Z_8^{e-\tau}$):

$$\mathbf{Y}_\nu = \begin{pmatrix} x_1 & 0 \\ 0 & x_2 \\ x_3 & 0 \end{pmatrix} \quad \mathbf{M}_R = \begin{pmatrix} 0 & M_{12} e^{-i\theta} \\ M_{12} e^{-i\theta} & M_{22} \end{pmatrix} \quad \mathbf{Y}_f = \begin{pmatrix} y_1 \\ 0 \\ y_2 \end{pmatrix} \quad \mathbf{Y}_\ell = \begin{pmatrix} w_1 & 0 & w_2 \\ 0 & w_3 & 0 \\ w_4 & 0 & w_5 \end{pmatrix}$$

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)

At the effective level:

$$\mathbf{M}_\nu = -v^2 \mathbf{Y}_\nu \mathbf{M}_R^{-1} \mathbf{Y}_\nu^T + \mathcal{F}(M_f, m_{S_i}) M_f \mathbf{Y}_f \mathbf{Y}_f^T$$

$$= \begin{pmatrix} \mathcal{F}(M_f, m_{S_i}) M_f y_1^2 + \frac{v^2 M_{22}}{M_{12}^2} x_1^2 e^{i\theta} & -\frac{v^2}{M_{12}} x_1 x_2 & \mathcal{F}(M_f, m_{S_i}) M_f y_1 y_2 + \frac{v^2 M_{22}}{M_{12}^2} x_1 x_3 e^{i\theta} \\ \cdot & 0 & -\frac{v^2}{M_{12}} x_2 x_3 \\ \cdot & \cdot & \mathcal{F}(M_f, m_{S_i}) M_f y_2^2 + \frac{v^2 M_{22}}{M_{12}^2} x_3^2 e^{i\theta} \end{pmatrix}$$

- A **zero** in the effective neutrino mass matrix arises as a result of the imposed symmetry
- Contribution of the scotogenic loop is crucial to ensure the **existence of CPV**

In the charged-lepton mass basis:

$$\mathbf{M}'_\nu = \mathbf{U}_\ell^T \mathbf{M}_\nu \mathbf{U}_\ell = \mathbf{U}^* \text{diag}(m_1, m_2, m_3) \mathbf{U}^\dagger$$

$(\mathbf{M}'_\nu)_{11} = 0$ for $Z_8^{\mu-\tau}$
(decoupled **electron**)

$(\mathbf{M}'_\nu)_{22} = 0$ for $Z_8^{e-\tau}$
(decoupled **muon**)

$(\mathbf{M}'_\nu)_{33} = 0$ for $Z_8^{e-\mu}$
(decoupled **tau**)

e.g. for $Z_8^{e-\tau}$:

$$\mathbf{U}_\ell = \begin{pmatrix} \cos \theta_\ell & 0 & \sin \theta_\ell \\ 0 & 1 & 0 \\ -\sin \theta_\ell & 0 & \cos \theta_\ell \end{pmatrix}$$

Neutrino oscillation data

Global fit of neutrino oscillation data:

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
θ_{12} ($^\circ$)	34.3 ± 1.0	$31.4 \rightarrow 37.4$	34.3 ± 1.0	$31.4 \rightarrow 37.4$
θ_{23} ($^\circ$)	$48.79^{+0.93}_{-1.25}$	$41.63 \rightarrow 51.32$	$48.79^{+1.04}_{-1.30}$	$41.88 \rightarrow 51.30$
θ_{13} ($^\circ$)	$8.58^{+0.11}_{-0.15}$	$8.16 \rightarrow 8.94$	$8.63^{+0.11}_{-0.15}$	$8.21 \rightarrow 8.99$
δ/π	$1.20^{+0.23}_{-0.14}$	$0.8 \rightarrow 2.00$	1.54 ± 0.13	$1.14 \rightarrow 1.90$
Δm_{21}^2 ($\times 10^{-5}$ eV 2)	$7.50^{+0.22}_{-0.20}$	$6.94 \rightarrow 8.14$	$7.50^{+0.22}_{-0.20}$	$6.94 \rightarrow 8.14$
$ \Delta m_{31}^2 $ ($\times 10^{-3}$ eV 2)	$2.56^{+0.03}_{-0.04}$	$2.46 \rightarrow 2.65$	2.46 ± 0.03	$2.37 \rightarrow 2.55$

Salas et al. (2020)

Normal Ordering (NO):

- $m_1 = m_{\text{lightest}}$
- $m_2 = \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2}$
- $m_3 = \sqrt{m_{\text{lightest}}^2 + \Delta m_{31}^2}$

Inverted Ordering (IO):

- $m_3 = m_{\text{lightest}}$
- $m_1 = \sqrt{m_{\text{lightest}}^2 + |\Delta m_{21}^2|}$
- $m_2 = \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2 + |\Delta m_{31}^2|}$

$$(\mathbf{M}'_{\nu})_{ii} = (\mathbf{U}^* \text{diag}(m_1, m_2, m_3) \mathbf{U}^\dagger)_{ii} = 0$$



Corresponds to **two low-energy constraints**, testable against **neutrino data!**

Lepton mixing (standard parametrisation): Rodejohann, Valle (2011)

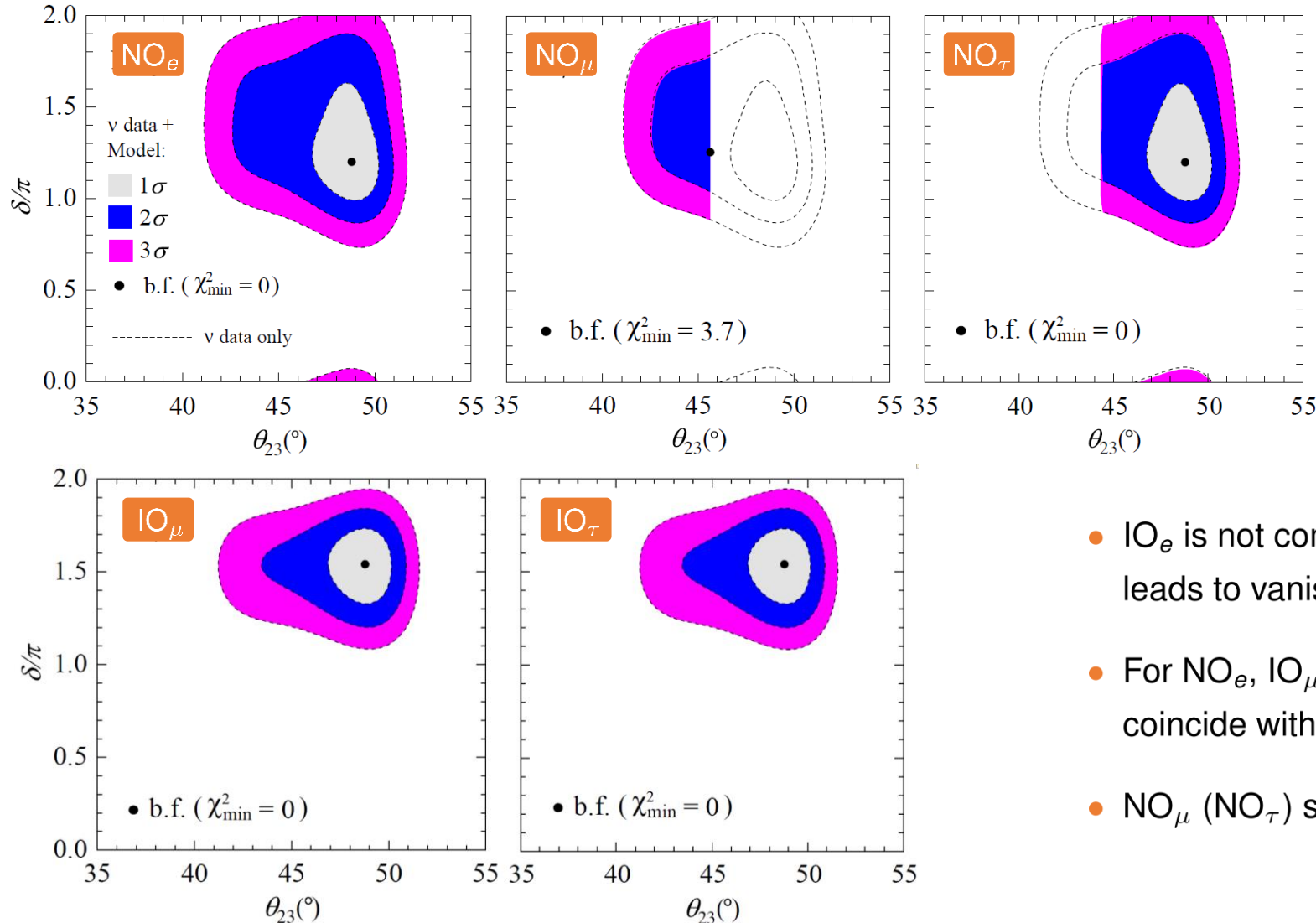
$$\mathbf{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{-i\phi_{12}} & s_{13}e^{-i\phi_{13}} \\ -s_{12}c_{23}e^{i\phi_{12}} - c_{12}s_{13}s_{23}e^{-i(\phi_{23}-\phi_{13})} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{-i(\phi_{12}+\phi_{23}-\phi_{13})} & c_{13}s_{23}e^{-i\phi_{23}} \\ s_{12}s_{23}e^{i(\phi_{12}+\phi_{23})} - c_{12}s_{13}c_{23}e^{i\phi_{13}} & -c_{12}s_{23}e^{i\phi_{23}} - s_{12}s_{13}c_{23}e^{-i(\phi_{12}-\phi_{13})} & c_{13}c_{23} \end{pmatrix}$$

Dirac phase: $\delta = \phi_{13} - \phi_{12} - \phi_{23}$

Majorana phases: ϕ_{13}, ϕ_{12}

θ_{23} and δ predictions

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)

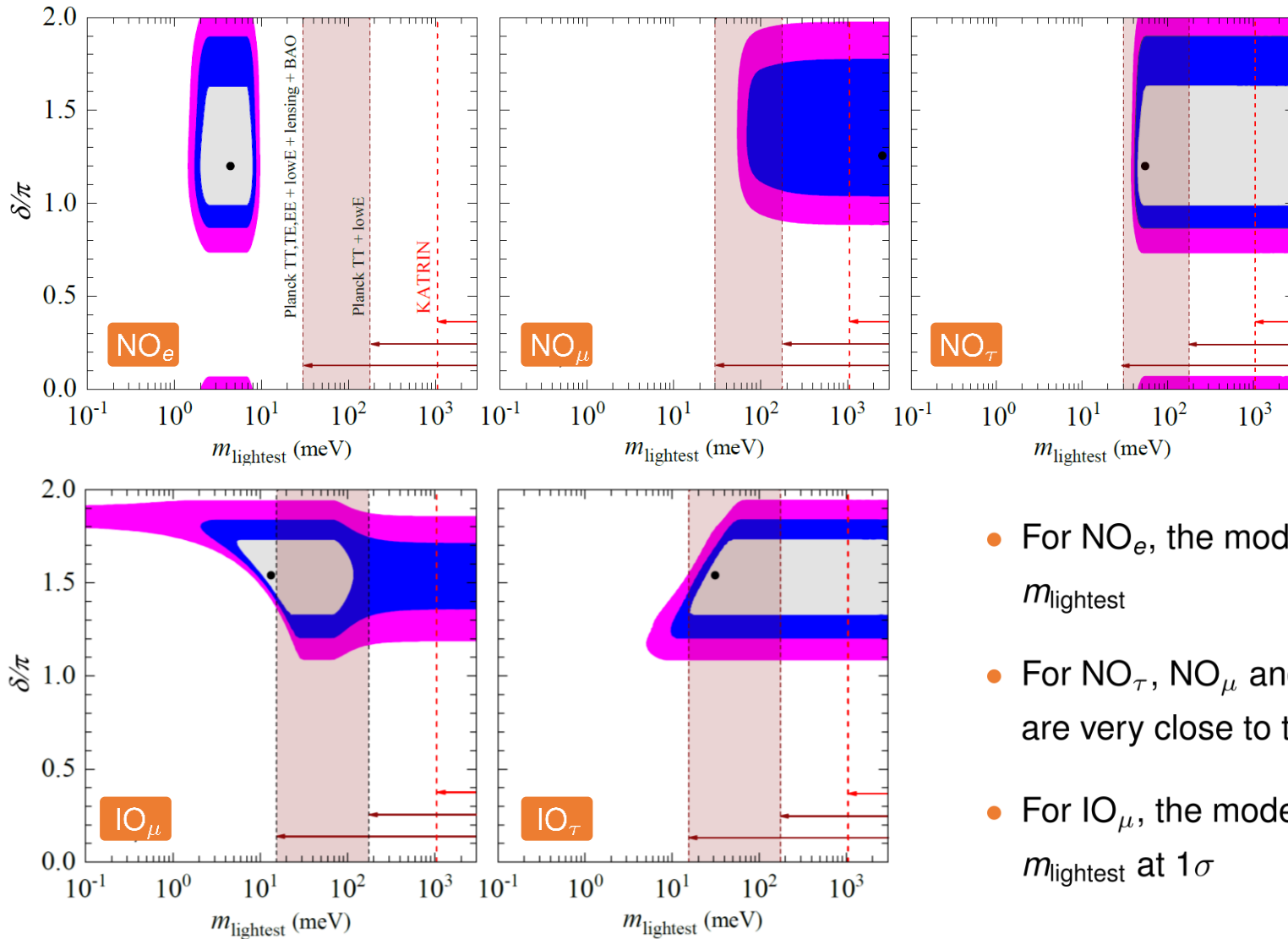


decoupled **electron**: $(\mathbf{M}'_{\nu})_{11} = 0$
 decoupled **muon**: $(\mathbf{M}'_{\nu})_{22} = 0$
 decoupled **tau**: $(\mathbf{M}'_{\nu})_{33} = 0$

- IO_e is not compatible with data since $(\mathbf{M}'_{\nu})_{11} = 0$ leads to vanishing $0\nu\beta\beta$ decay rate
- For NO_e, IO _{μ} and IO _{τ} the model allowed regions coincide with the experimental ones
- NO _{μ} (NO _{τ}) selects the first (second) octant for θ_{23}

Constraints on the lightest neutrino mass

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)

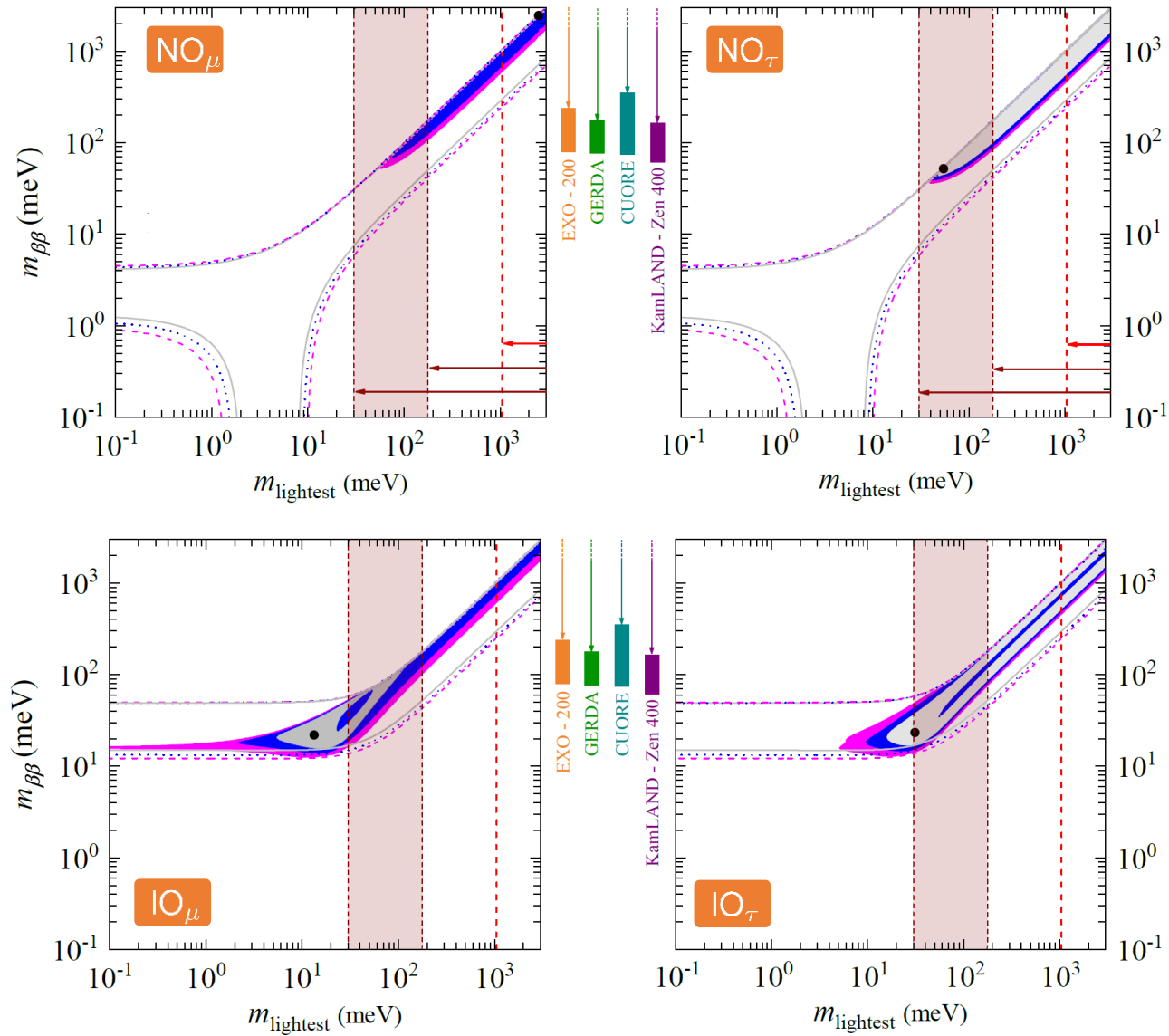


decoupled **electron**: $(\mathbf{M}'_{\nu})_{11} = 0$
 decoupled **muon**: $(\mathbf{M}'_{\nu})_{22} = 0$
 decoupled **tau**: $(\mathbf{M}'_{\nu})_{33} = 0$

- For NO_e , the model establishes upper and lower bounds for m_{lightest}
- For NO_τ , NO_μ and IO_τ we get lower bounds for m_{lightest} which are very close to the cosmological and KATRIN bounds
- For IO_μ , the model establishes upper and lower bounds for m_{lightest} at 1σ

Constraints on $m_{\beta\beta}$

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)



$m_{\beta\beta}$ in terms of low-energy parameters

$$\text{NO: } m_{\beta\beta} = \left| c_{12}^2 c_{13}^2 m_{\text{lightest}} + s_{12}^2 c_{13}^2 \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2} e^{2i\phi_{12}} \right|$$

$$\text{IO: } m_{\beta\beta} = \left| c_{12}^2 c_{13}^2 \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2} + s_{12}^2 c_{13}^2 \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2} + |\Delta m_{31}^2| e^{2i\phi_{12}} + s_{13}^2 m_{\text{lightest}} e^{2i\phi_{13}} \right|$$

- NO_e predicts $m_{\beta\beta} = 0$, allowed by neutrino oscillation data and $m_{\beta\beta}$ current experimental limits
- In all remaining cases the model establishes a lower bound on $m_{\beta\beta}$
- Current KamLAND bound nearly excludes the NO cases

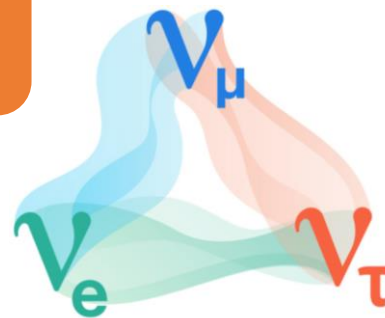
Concluding remarks

- We propose a **simple scoto-seesaw model** where **neutrino masses**, **lepton flavour structure**, **dark matter stability** and **spontaneous CP violation** are accommodated with a single **Z_8 flavour symmetry**
- This symmetry is **broken down to dark Z_2** by the VEV of a new **complex scalar singlet σ**
- The complex VEV of σ is the **unique source of leptonic CP violation**, arising **spontaneously**
- The generated CP violation is **successfully** transmitted to the leptonic sector via **couplings of σ to ν_R and f**
- The Z_8 symmetry leads to **low-energy constraints**, which translate into a **neutrino texture** that can be tested against neutrino experimental data
- For **NO**, the **predicted ranges on m_{lightest}** will be **fully tested** by near future **$0\nu\beta\beta$ -decay** experiments and by improved neutrino mass sensitivities from **cosmology** and **β decay**
- For **IO**, better determination of the **Dirac phase** from neutrino oscillations and further improvement in expected sensitivities from upcoming **$0\nu\beta\beta$ -decay** experiments is required to test the model

Thank you!



Backup slides



Scalar sector of the Z_8 model

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)

Scalar Potential

$$V = m_\phi^2 \Phi^\dagger \Phi + m_\eta^2 \eta^\dagger \eta + m_\sigma^2 \sigma^* \sigma + m_\chi^2 \chi^* \chi + \frac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2} (\eta^\dagger \eta)^2 + \frac{\lambda_3}{2} (\sigma^* \sigma)^2 + \frac{\lambda_4}{2} (\chi^* \chi)^2 + \lambda_5 (\Phi^\dagger \Phi) (\eta^\dagger \eta) + \lambda'_5 (\Phi^\dagger \eta) (\eta^\dagger \Phi) + \lambda_6 (\Phi^\dagger \Phi) (\sigma^* \sigma) + \lambda_7 (\Phi^\dagger \Phi) (\chi^* \chi) + \lambda_8 (\eta^\dagger \eta) (\sigma^* \sigma) + \lambda_9 (\eta^\dagger \eta) (\chi^* \chi) + \lambda_{10} (\sigma^* \sigma) (\chi^* \chi) + \left(\frac{\lambda'_3}{4} \sigma^4 + \frac{m_\sigma'^2}{2} \sigma^2 + \mu_1 \chi^2 \sigma + \mu_2 \eta^\dagger \Phi \chi^* + \lambda_{11} \eta^\dagger \Phi \sigma \chi + \text{H.c.} \right)$$

Our scalars: $\Phi = \begin{pmatrix} \phi^+ \\ \frac{v + \phi_{0R} + i\phi_{0I}}{\sqrt{2}} \end{pmatrix}$, $\eta = \begin{pmatrix} \eta^+ \\ \frac{v_\eta e^{i\theta_\eta} + \eta_{0R} + i\eta_{0I}}{\sqrt{2}} \end{pmatrix}$, $\chi = \frac{v_\chi + \chi_R + i\chi_I}{\sqrt{2}}$, $\sigma = \frac{u e^{i\theta} + \sigma_R + i\sigma_I}{\sqrt{2}}$

Scalar Masses:

- $m_{\phi^+} = m_{\phi^-} = m_{\phi_{0I}} = 0$
- $m_{\eta^\pm}^2 = m_\eta^2 + \frac{\lambda_5}{2} v^2 + \frac{\lambda_8}{2} u^2$

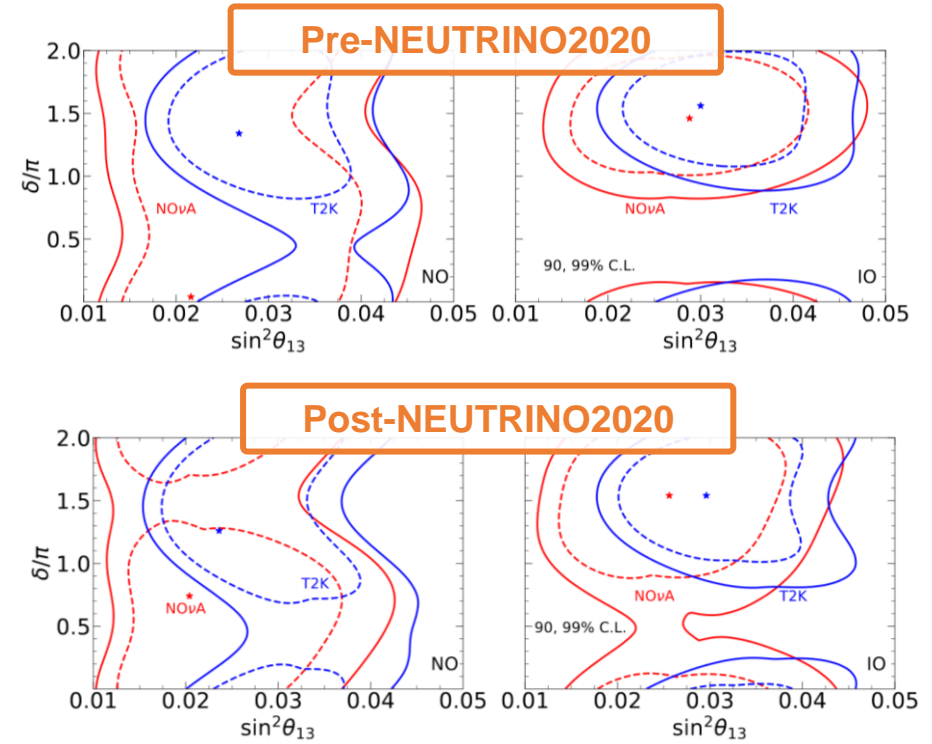
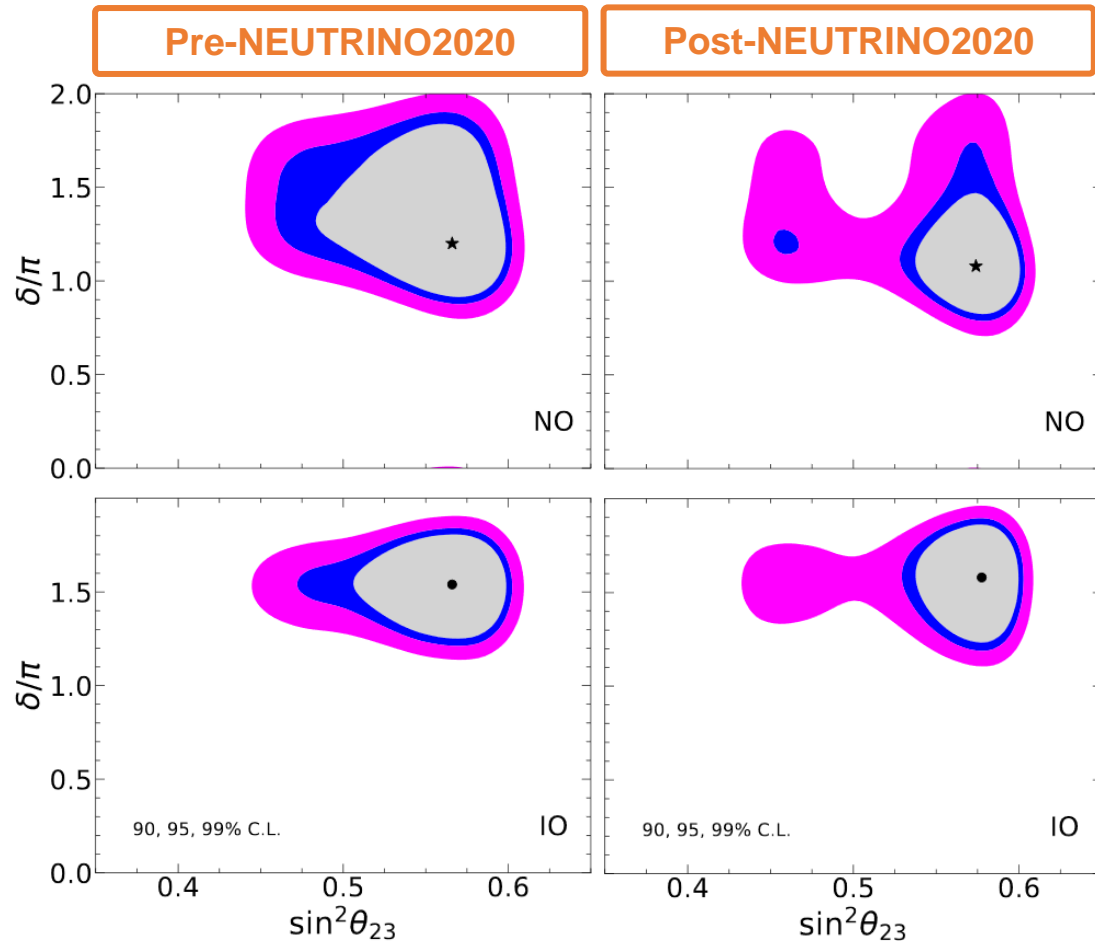
$$\mathcal{M}_{\phi\sigma}^2 = \begin{pmatrix} v^2 \lambda_1 & v u \lambda_6 \cos \theta & v u \lambda_6 \sin \theta \\ \cdot & u^2 (\lambda_3 + \lambda'_3) \cos^2 \theta & u^2 (\lambda_3 - 3\lambda'_3) \cos \theta \sin \theta \\ \cdot & \cdot & u^2 (\lambda_3 + \lambda'_3) \sin^2 \theta \end{pmatrix} \longrightarrow \begin{matrix} \phi - \sigma \text{ mixing} \\ (\phi_{0R}, \sigma_R, \sigma_I) \end{matrix}$$

$$\mathcal{M}_{\eta\chi}^2 = \begin{pmatrix} m_\eta^2 + \frac{\lambda_5 + \lambda'_5}{2} v^2 + \frac{\lambda_8}{2} u^2 & v \left(\frac{\mu_2}{\sqrt{2}} + \frac{\lambda_{11}}{2} u \cos \theta \right) & 0 & -\frac{\lambda_{11}}{2} v u \sin \theta \\ \cdot & m_\chi^2 + \frac{\lambda_7}{2} v^2 + \frac{\lambda_{10}}{2} u^2 + \sqrt{2} u \lambda_{11} \cos \theta & \frac{\lambda_{11}}{2} v u \sin \theta & -\sqrt{2} \mu_1 u \sin \theta \\ \cdot & \cdot & m_\eta^2 + \frac{\lambda_5 + \lambda'_5}{2} v^2 + \frac{\lambda_8}{2} u^2 & v \left(-\frac{\mu_2}{\sqrt{2}} + \frac{\lambda_{11}}{2} u \cos \theta \right) \\ \cdot & \cdot & \cdot & m_\chi^2 + \frac{\lambda_7}{2} v^2 + \frac{\lambda_{10}}{2} u^2 - \sqrt{2} u \lambda_{11} \cos \theta \end{pmatrix} \longrightarrow \begin{matrix} \eta - \chi \text{ mixing} \\ (\eta_{0R}, \chi_R, \eta_{0I}, \chi_I) \end{matrix}$$

Lightest of the $\mathcal{M}_{\eta\chi}$ eigenstates is a dark matter candidate along with the dark fermion f

Present status of neutrino oscillation data

Salas *et al.* (2020)



- Best fit remains for **NO** with **reduced significance** (2.7σ)
- Mild **preference** for the **second octant** of θ_{23}
- δ is pushed towards **CP conservation** for **NO**
- δ remains close to **maximal CP violation** for **IO**

θ_{23} and δ predictions

DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)

