Workshop on Standard Model and Beyond

Corfu, Greece, August 30 – September 8, 2021

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

Débora Barreiros

debora.barreiros@tecnico.ulisboa.pt

CFTP/IST, U. Lisbon

In collaboration with: F. R. Joaquim, R. Srivastava and J. W. F. Valle

J. High Energ. Phys. 2021, 249 (2021) (arXiv: **2012.05189** [hep-ph])

Motivation

The Standard Model cannot explain:

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

Motivation

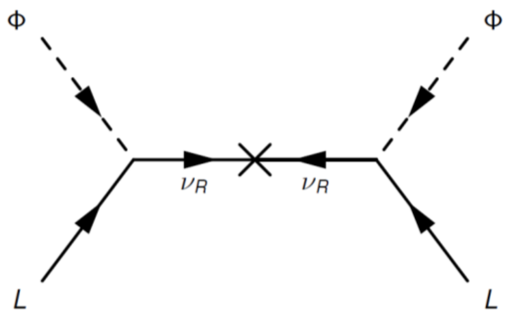
The Standard Model cannot explain:

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

Straightforward and **elegant** solutions:

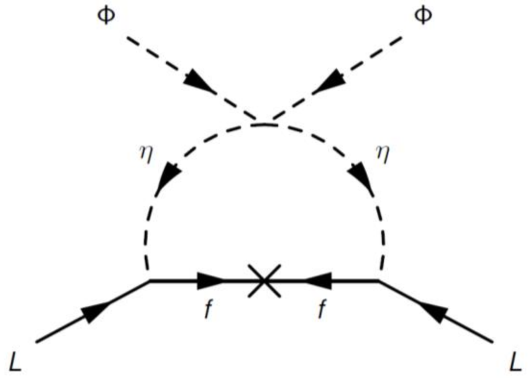
Type I Seesaw Model

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



Scotogenic Model

Ma (2006)



Motivation

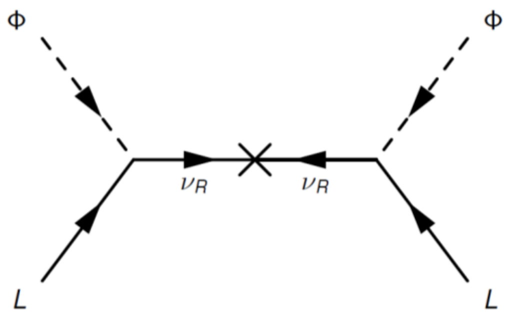
The Standard Model cannot explain:

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

Straightforward and **elegant** solutions:

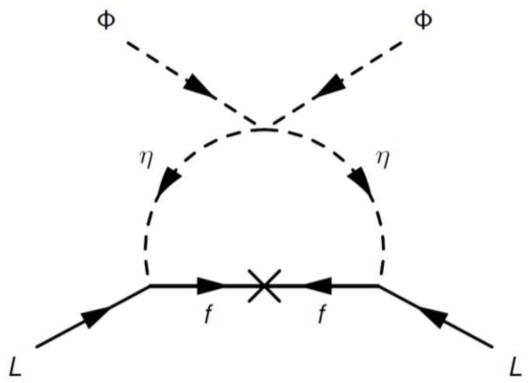
Type I Seesaw Model

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)

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
$\mathcal{Z}_2$	+	-	-
Multiplicity	1	1	1

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**

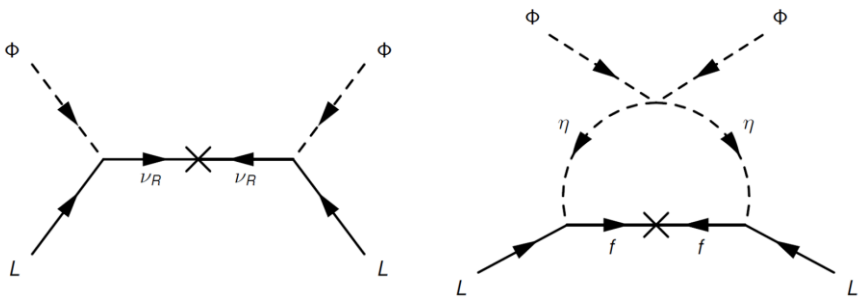
Rojas, Srivastava, Valle (2019)

Particle content:

	ν_R	η	f
$SU(2)_L$	1	2	1
$U(1)_Y$	0	1/2	0
$\mathcal{Z}_2$	+	-	-
Multiplicity	1	1	1

$$\mathcal{L} - \mathcal{L}_{SM} = -\overline{L}\mathbf{Y}_\nu^* \tilde{\Phi}\nu_R - \frac{1}{2}M_R\overline{\nu_R}\nu_R^c - \overline{L}\mathbf{Y}_f^*\tilde{\eta}f - \frac{1}{2}M_f\overline{f}f^c$$

Allowed diagrams:



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)

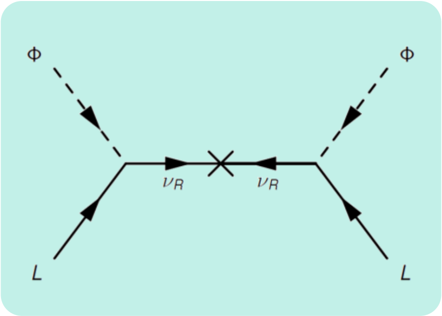
Particle content:

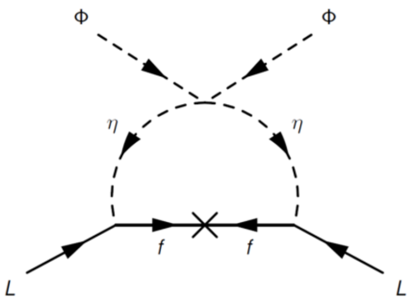
	ν_R	η	f
$SU(2)_L$	1	2	1
$U(1)_Y$	0	1/2	0
$\mathcal{Z}_2$	+	-	-
Multiplicity	1	1	1

$$\mathcal{L} - \mathcal{L}_{SM} = -\overline{L}\mathbf{Y}^*_\nu\tilde{\Phi}\nu_R - \frac{1}{2}M_R\overline{\nu_R}\nu^c_R - \overline{L}\mathbf{Y}^*_f\tilde{\eta}f - \frac{1}{2}M_f\overline{f}f^c$$

Generates the **atmospheric** neutrino mass scale

Allowed diagrams:





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:

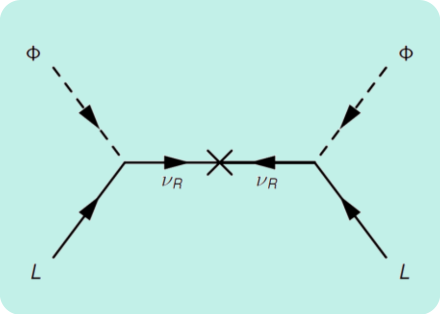
	ν_R	η	f
$SU(2)_L$	1	2	1
$U(1)_Y$	0	1/2	0
$\mathcal{Z}_2$	+	-	-
Multiplicity	1	1	1

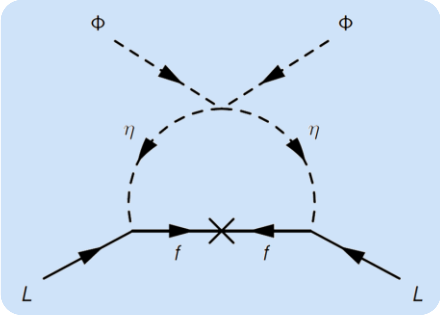
$$\mathcal{L} - \mathcal{L}_{SM} = -\bar{L}\mathbf{Y}_\nu^*\tilde{\Phi}\nu_R - \frac{1}{2}M_R\overline{\nu_R}\nu_R^c - \bar{L}\mathbf{Y}_f^*\tilde{\eta}f - \frac{1}{2}M_f\bar{f}f^c$$

Generates the **atmospheric** neutrino mass scale

Generates the **solar** neutrino mass scale

Allowed diagrams:





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
$\mathcal{Z}_2$	+	-	-
Multiplicity	1	1	1

$$\mathcal{L} - \mathcal{L}_{SM} = -\overline{L}\mathbf{Y}_\nu^* \tilde{\Phi}\nu_R - \frac{1}{2}M_R\overline{\nu_R}\nu_R^c - \overline{L}\mathbf{Y}_f^*\tilde{\eta}f - \frac{1}{2}M_f\overline{f}f^c$$

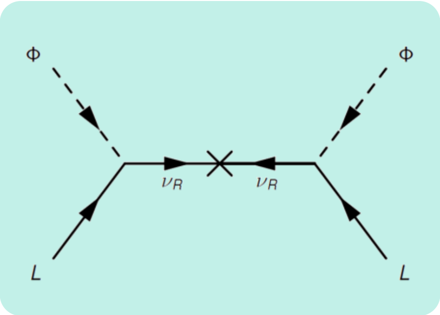
Generates the **atmospheric** neutrino mass scale

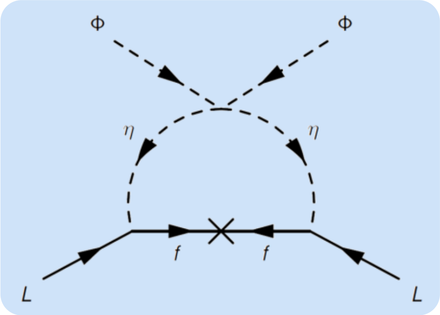
Generates the **solar** neutrino mass scale

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:





Simplest scoto-seesaw mechanism

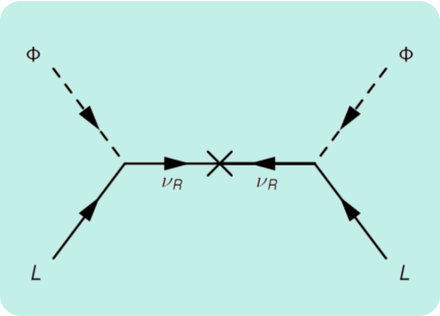
Simple and elegant model where the **atmospheric mass scale** arises at tree level from the **type-I seesaw mechanism** and the **solar mass scale** emerges radiatively through a **scotogenic loop**

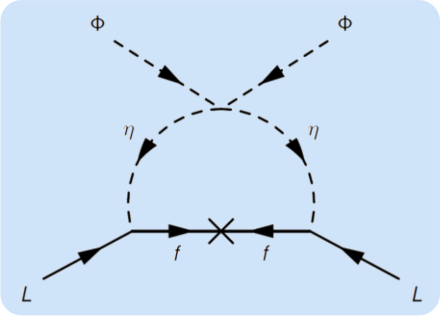
Rojas, Srivastava, Valle (2019)

Particle content:

	ν_R	η	f
$SU(2)_L$	1	2	1
$U(1)_Y$	0	1/2	0
$\mathcal{Z}_2$	+	-	-
Multiplicity	1	1	1

Allowed diagrams:





$$\mathcal{L} - \mathcal{L}_{SM} = -\overline{L}\mathbf{Y}_\nu^* \tilde{\Phi}\nu_R - \frac{1}{2}M_R\overline{\nu_R}\nu_R^c - \overline{L}\mathbf{Y}_f^*\tilde{\eta}f - \frac{1}{2}M_f\overline{f}f^c$$

Generates the **atmospheric** neutrino mass scale

Generates the **solar** neutrino mass scale

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

- 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**

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**: $\langle \sigma \rangle = ue^{i\theta}$

Adding spontaneous CP violation

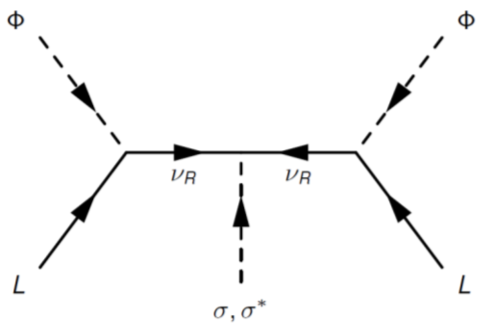
The number of parameters can be reduced by requiring the **Lagrangian to be CP symmetric** and invoking a **spontaneous origin** for **leptonic CP violation**

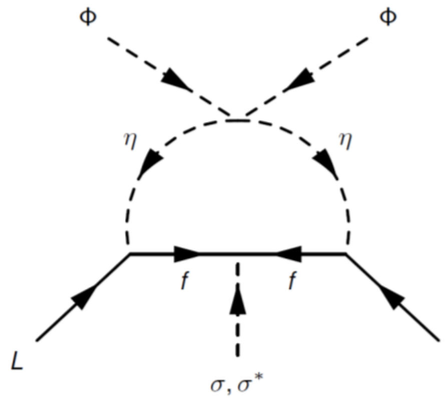
Introducing a **new scalar singlet** with **complex VEV**: $\langle\sigma\rangle = ue^{i\theta}$

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

SSB

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





Adding spontaneous CP violation

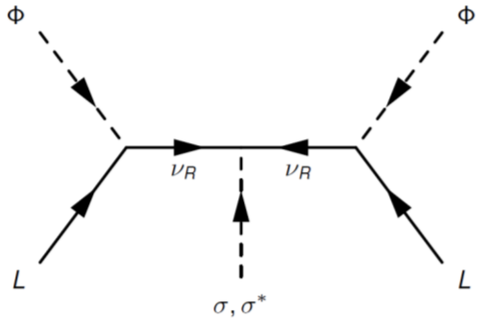
The number of parameters can be reduced by requiring the **Lagrangian to be CP symmetric** and invoking a **spontaneous origin** for **leptonic CP violation**

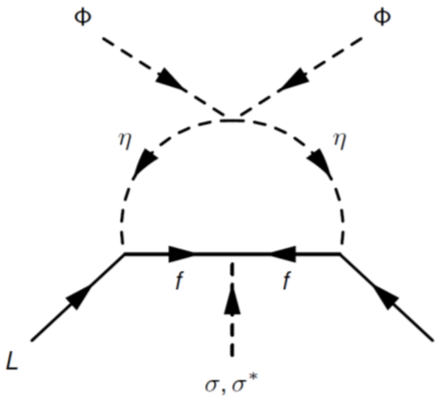
Introducing a **new scalar singlet** with **complex VEV**: $\langle\sigma\rangle = ue^{i\theta}$

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

SSB

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





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

Adding spontaneous CP violation

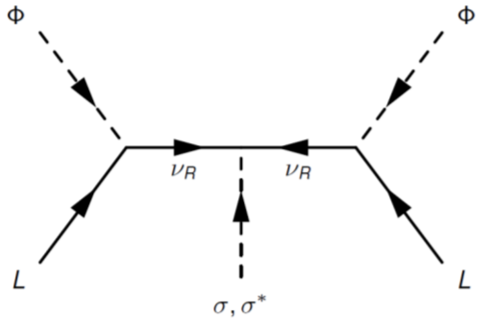
The number of parameters can be reduced by requiring the **Lagrangian to be CP symmetric** and invoking a **spontaneous origin** for **leptonic CP violation**

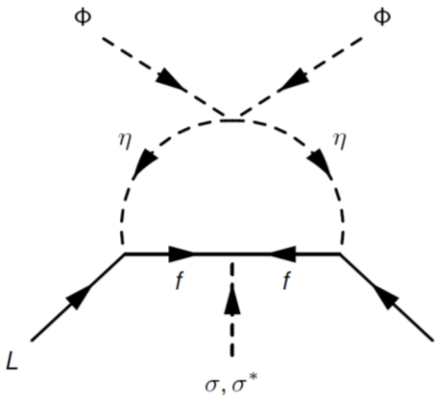
Introducing a **new scalar singlet** with **complex VEV**: $\langle\sigma\rangle = ue^{i\theta}$

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

SSB

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





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)

Adding spontaneous CP violation

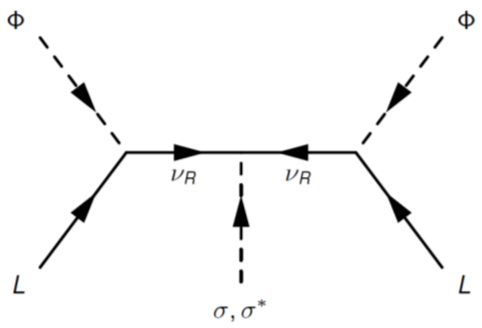
The number of parameters can be reduced by requiring the **Lagrangian to be CP symmetric** and invoking a **spontaneous origin** for **leptonic CP violation**

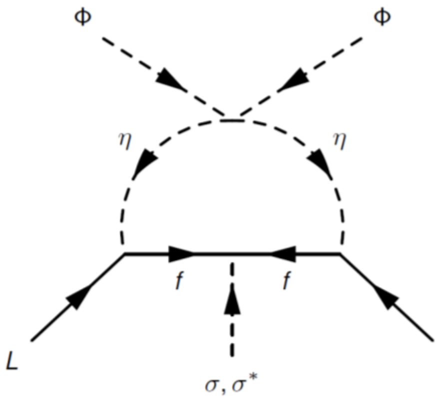
Introducing a **new scalar singlet** with **complex VEV**: $\langle \sigma \rangle = ue^{i\theta}$

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

SSB

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





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 $\mathbf{Y}_\nu$, $\mathbf{Y}_f$ and $\mathbf{Y}_\ell$ **realizable by minimal discrete flavour symmetry** in order to maximise predictability

Adding a discrete flavour symmetry

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

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

Particle content:

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

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

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

Adding a discrete flavour symmetry

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

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

Particle content:

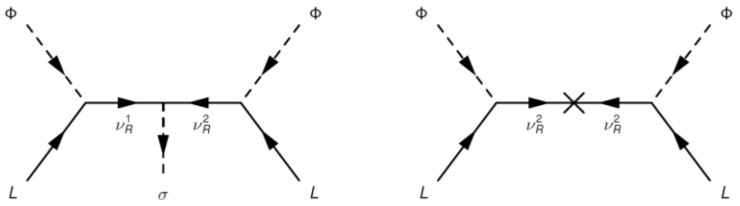
	Fields	$\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$	$\mathcal{Z}_8^{e-\tau *} \to \mathcal{Z}_2$
Fermions	L_e	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \to +1$
	L_μ	$(\mathbf{2}, -1/2)$	$\omega^0 \equiv 1 \to +1$
	L_τ	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \to +1$
	ν_R^1	$(\mathbf{1}, 0)$	$\omega^6 \equiv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

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

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

Contributions to neutrino masses:

- Tree level:



Adding a discrete flavour symmetry

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

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

Particle content:

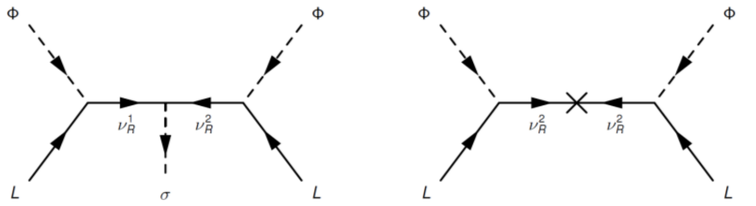
	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^{e-\tau *} \to \mathcal{Z}_2$
Fermions	L_e	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \to +1$
	L_μ	$(\mathbf{2}, -1/2)$	$\omega^0 \equiv 1 \to +1$
	L_τ	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \to +1$
	ν_R^1	$(\mathbf{1}, 0)$	$\omega^6 \equiv -i \to +1$
	ν_R^2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

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

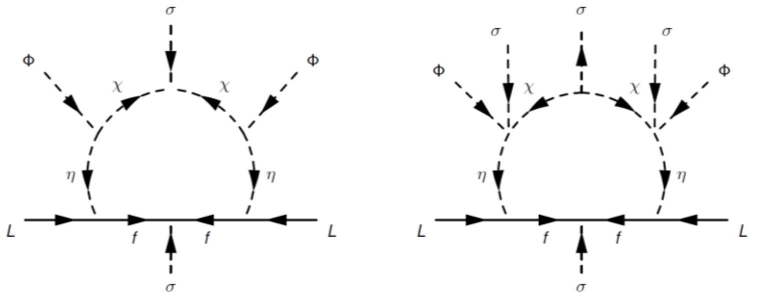
$^*\mathcal{Z}_8^{e-\mu}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments, with decoupled τ and e, respectively

Contributions to neutrino masses:

- Tree level:



- One loop:



Adding a discrete flavour symmetry

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

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

Particle content:

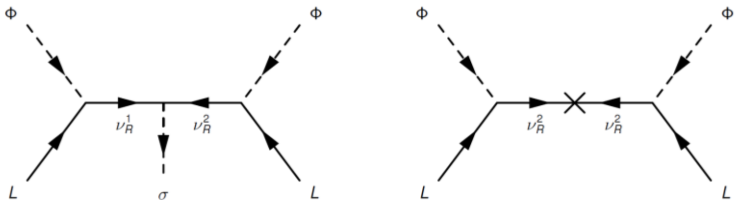
	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^{e-\tau\,*} \to \mathcal{Z}_2$
Fermions	L_e	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \to +1$
	L_μ	$(\mathbf{2}, -1/2)$	$\omega^0 \equiv 1 \to +1$
	L_τ	$(\mathbf{2}, -1/2)$	$\omega^6 \equiv -i \to +1$
	ν_R^1	$(\mathbf{1}, 0)$	$\omega^6 \equiv -i \to +1$
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

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

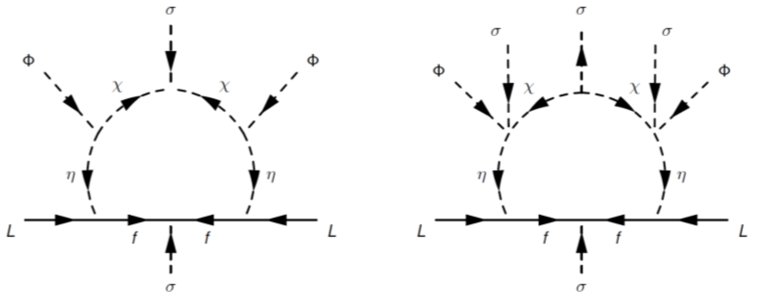
$^*\mathcal{Z}_8^{e-\mu}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments, with decoupled τ and e, respectively

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

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

Scalar Potential

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

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

Scalar sector

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

Scalar Potential

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

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

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

Scalar sector

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

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

Scalar Potential

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

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

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 $(m_\sigma'^4 - u^4\lambda_3'^2)/(4\lambda_3') > 0$

Scalar sector

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

Scalar Potential

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

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

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 ⇒ θ ≠ kπ is allowed!

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

Scalar sector

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

Scalar Potential

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

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

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 ⇒ $\theta \neq k\pi$ is allowed!

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

Other conclusions:

- $\boldsymbol{Z_8 \to Z_2}$ **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 $\eta^\pm$
- 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 $\mathcal{Z}_8^{e-\tau}$):

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

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

Low-energy constraints

Allowed Yukawa and mass matrices (for $\mathcal{Z}_8^{e-\tau}$):

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

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

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**

Low-energy constraints

Allowed Yukawa and mass matrices (for $\mathcal{Z}_8^{e-\tau}$):

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

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

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:

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

e.g. for $\mathcal{Z}_8^{e-\tau}$:

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

$(\mathbf{M}'_\nu)_{11} = 0$ for $\mathcal{Z}_8^{\mu-\tau}$ (decoupled **electron**)

$(\mathbf{M}'_\nu)_{22} = 0$ for $\mathcal{Z}_8^{e-\tau}$ (decoupled **muon**)

$(\mathbf{M}'_\nu)_{33} = 0$ for $\mathcal{Z}_8^{e-\mu}$ (decoupled **tau**)

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} (°)	34.3 ± 1.0	$31.4 \to 37.4$	34.3 ± 1.0	$31.4 \to 37.4$
θ_{23} (°)	$48.79^{+0.93}_{-1.25}$	$41.63 \to 51.32$	$48.79^{+1.04}_{-1.30}$	$41.88 \to 51.30$
θ_{13} (°)	$8.58^{+0.11}_{-0.15}$	$8.16 \to 8.94$	$8.63^{+0.11}_{-0.15}$	$8.21 \to 8.99$
δ/π	$1.20^{+0.23}_{-0.14}$	$0.8 \to 2.00$	1.54 ± 0.13	$1.14 \to 1.90$
Δm^2_{21} ($\times 10^{-5}$ eV^2)	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\|\Delta m^2_{31}\|$ ($\times 10^{-3}$ eV^2)	$2.56^{+0.03}_{-0.04}$	$2.46 \to 2.65$	2.46 ± 0.03	$2.37 \to 2.55$

Salas *et al.* (2020)

Normal Ordering (NO):

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

Inverted Ordering (IO):

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

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} (°)	34.3 ± 1.0	$31.4 \to 37.4$	34.3 ± 1.0	$31.4 \to 37.4$
θ_{23} (°)	$48.79^{+0.93}_{-1.25}$	$41.63 \to 51.32$	$48.79^{+1.04}_{-1.30}$	$41.88 \to 51.30$
θ_{13} (°)	$8.58^{+0.11}_{-0.15}$	$8.16 \to 8.94$	$8.63^{+0.11}_{-0.15}$	$8.21 \to 8.99$
δ/π	$1.20^{+0.23}_{-0.14}$	$0.8 \to 2.00$	1.54 ± 0.13	$1.14 \to 1.90$
Δm^2_{21} ($\times 10^{-5}$ eV^2)	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\lvert\Delta m^2_{31}\rvert$ ($\times 10^{-3}$ eV^2)	$2.56^{+0.03}_{-0.04}$	$2.46 \to 2.65$	2.46 ± 0.03	$2.37 \to 2.55$

Salas *et al.* (2020)

Normal Ordering (NO):

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

Inverted Ordering (IO):

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

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

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

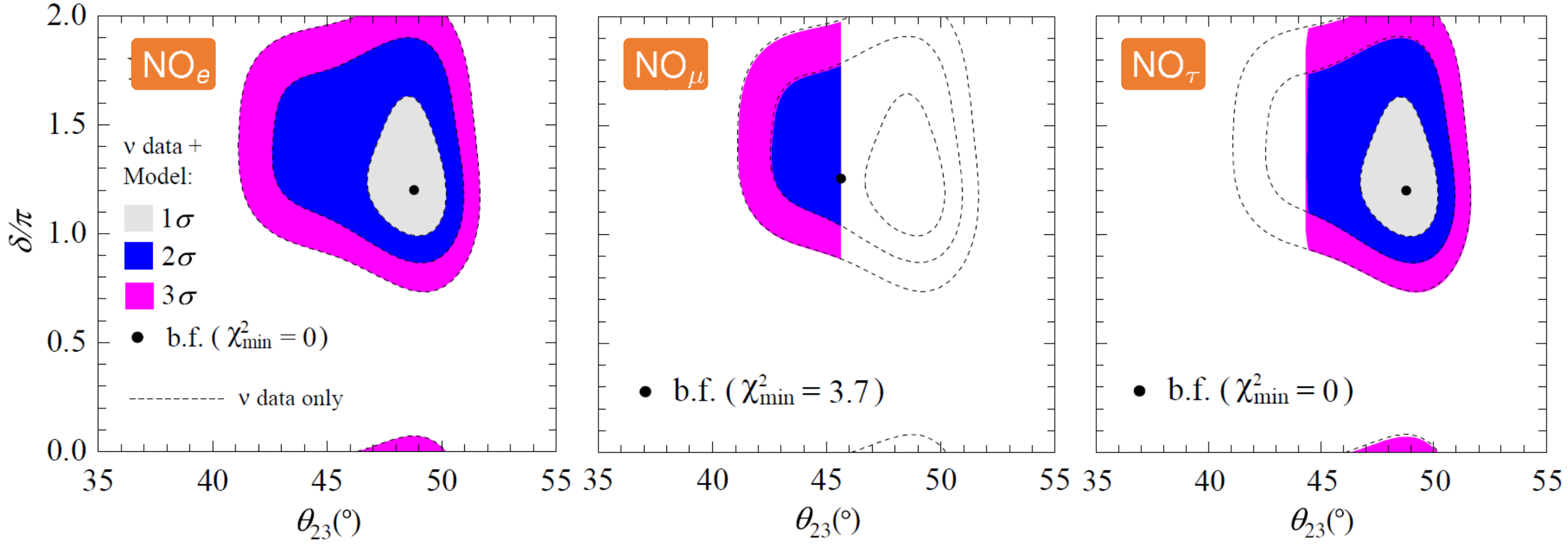
Lepton mixing (standard parametrisation): Rodejohann, Valle (2011)

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

Dirac phase: $\delta = \phi_{13} - \phi_{12} - \phi_{23}$ Majorana phases: ϕ_{13}, ϕ_{12}

θ_{23} and δ predictions

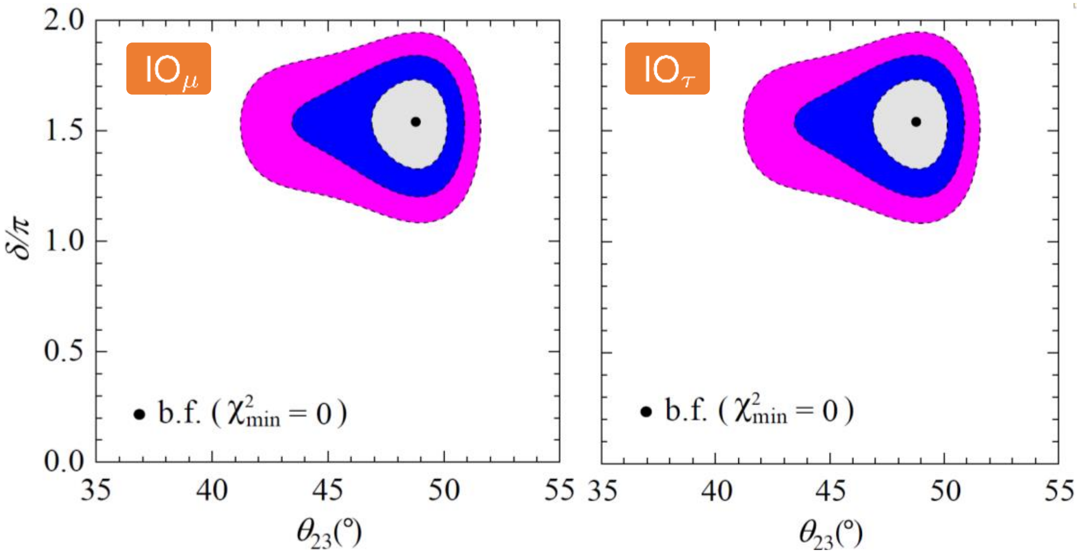
DB, F. R. Joaquim, R. Srivastava, J. W. F. Valle (2021)



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

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

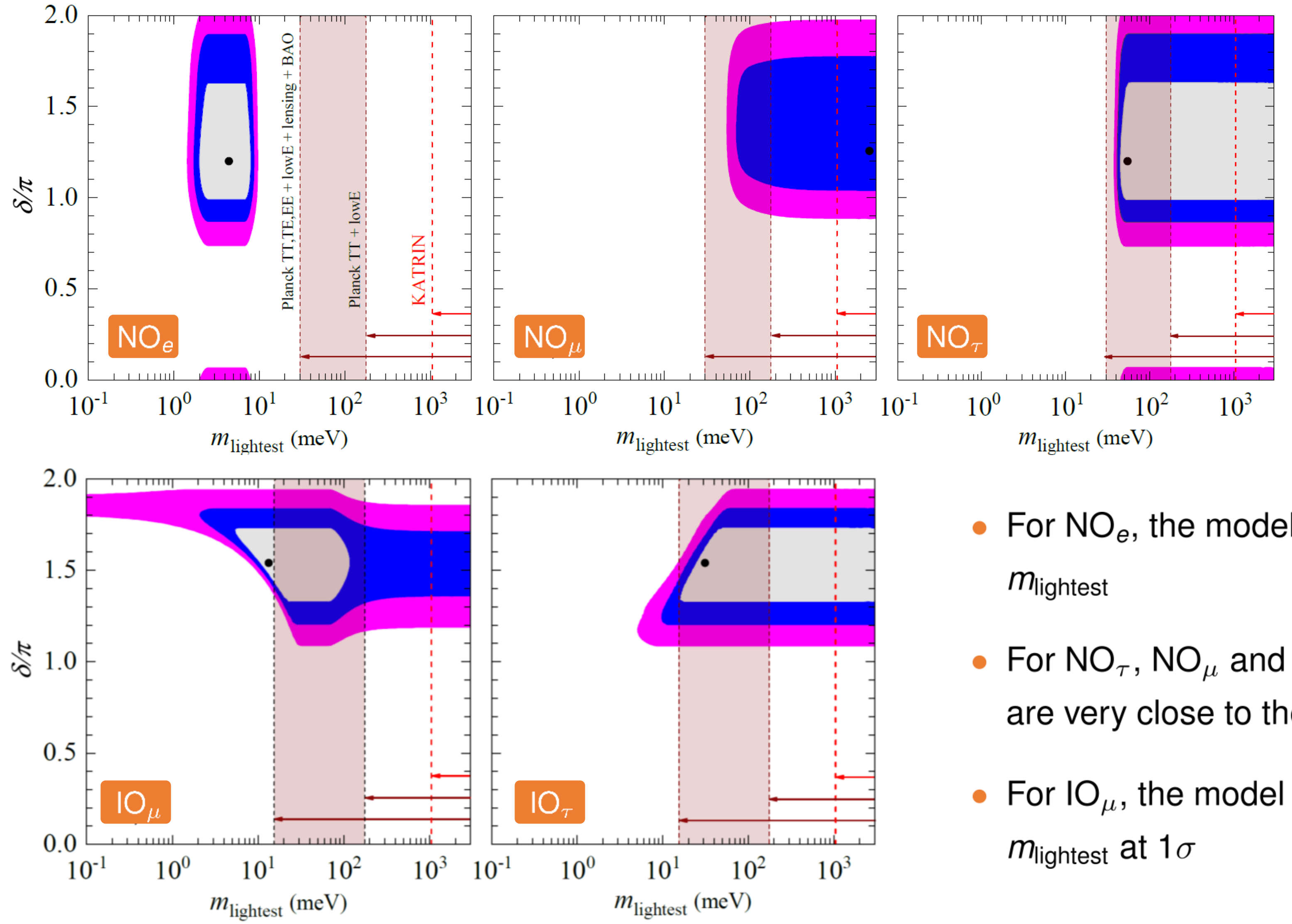
decoupled **tau**: $(\mathbf{M}'_\nu)_{33} = 0$



- 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$_\mu$ and IO$_\tau$ the model allowed regions coincide with the experimental ones
- NO$_\mu$ (NO$_\tau$) 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**: $(\mathbf{M}'_\nu)_{11} = 0$

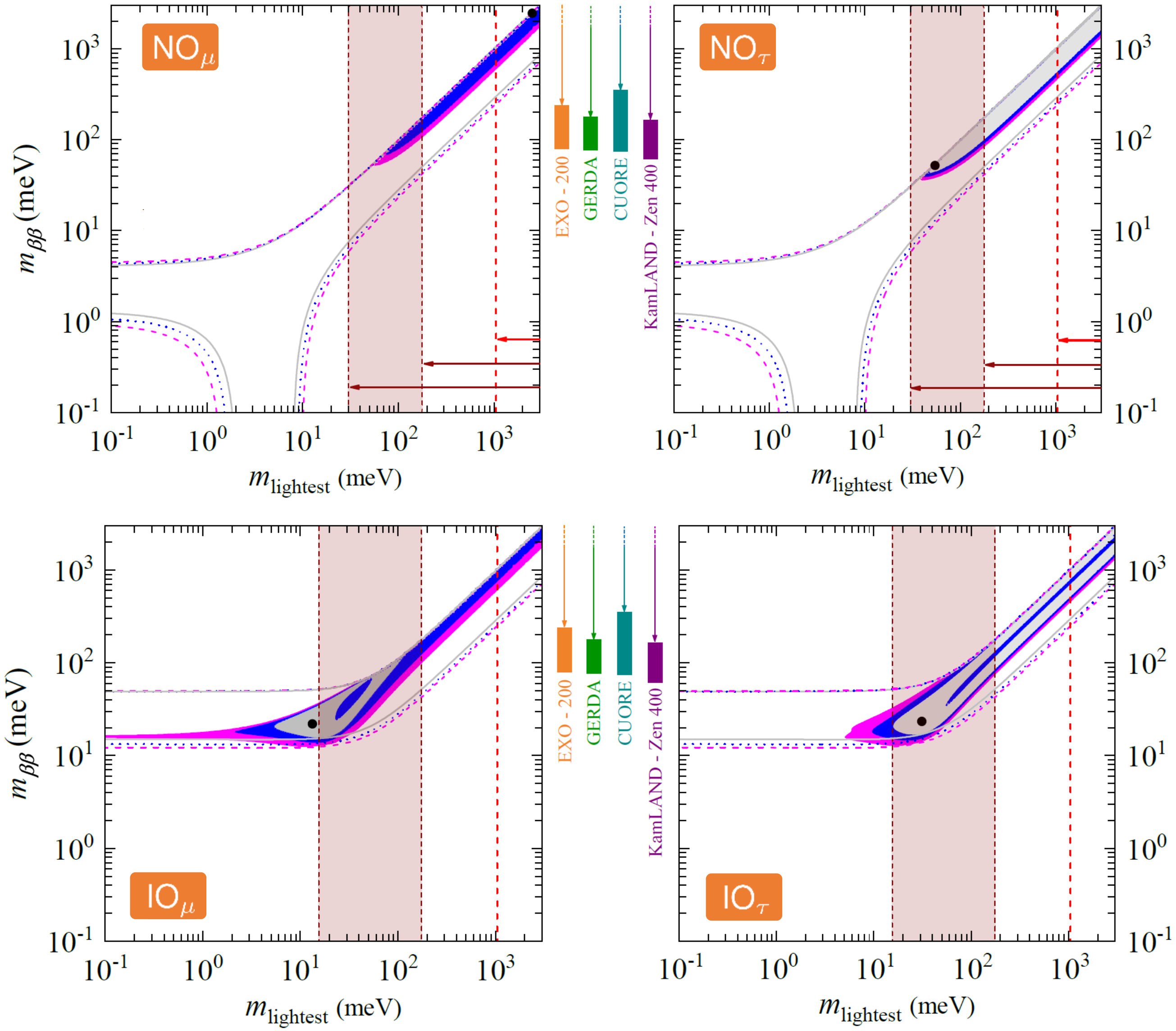
decoupled **muon**: $(\mathbf{M}'_\nu)_{22} = 0$

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

- For NO$_e$, the model establishes upper and lower bounds for $m_{\rm lightest}$
- For NO$_\tau$, NO$_\mu$ and IO$_\tau$ we get lower bounds for $m_{\rm lightest}$ which are very close to the cosmological and KATRIN bounds
- For IO$_\mu$, the model establishes upper and lower bounds for $m_{\rm lightest}$ 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

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

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

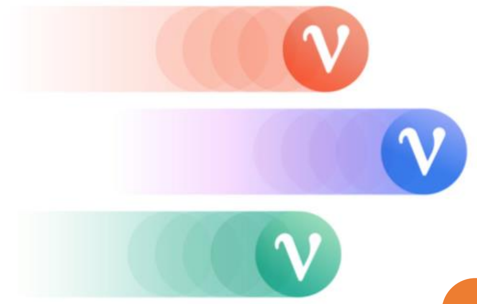
Concluding remarks

- 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 **0υββ-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 **0υββ-decay** experiments is required to test the model

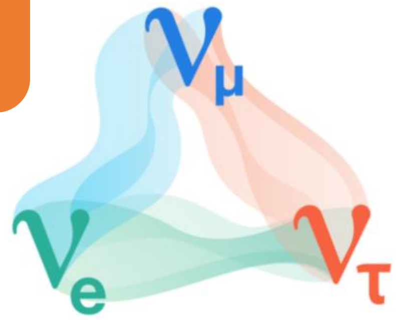
Concluding remarks

- 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** $\boldsymbol{Z_2}$ by the VEV of a new **complex scalar singlet** $\boldsymbol{\sigma}$
- 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** $\boldsymbol{\sigma}$ to $\boldsymbol{\nu_R}$ 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** $\boldsymbol{m_{\text{lightest}}}$ will be **fully tested** by near-future **0νββ-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 **0νββ-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: $\Phi = \begin{pmatrix} \phi^+ \\ \frac{v + \phi_{0R} + i\phi_{0I}}{\sqrt{2}} \end{pmatrix}, \; \eta = \begin{pmatrix} \eta^+ \\ \frac{v_\eta e^{i\theta_\eta} + \eta_{0R} + i\eta_{0I}}{\sqrt{2}} \end{pmatrix}, \; \chi = \frac{v_\chi + \chi_R + i\chi_I}{\sqrt{2}}, \; \sigma = \frac{u e^{i\theta} + \sigma_R + i\sigma_I}{\sqrt{2}}$

The Z_8 **symmetry is broken down to a dark Z_2 symmetry**, preventing the dark scalars to mix with the non-dark scalars

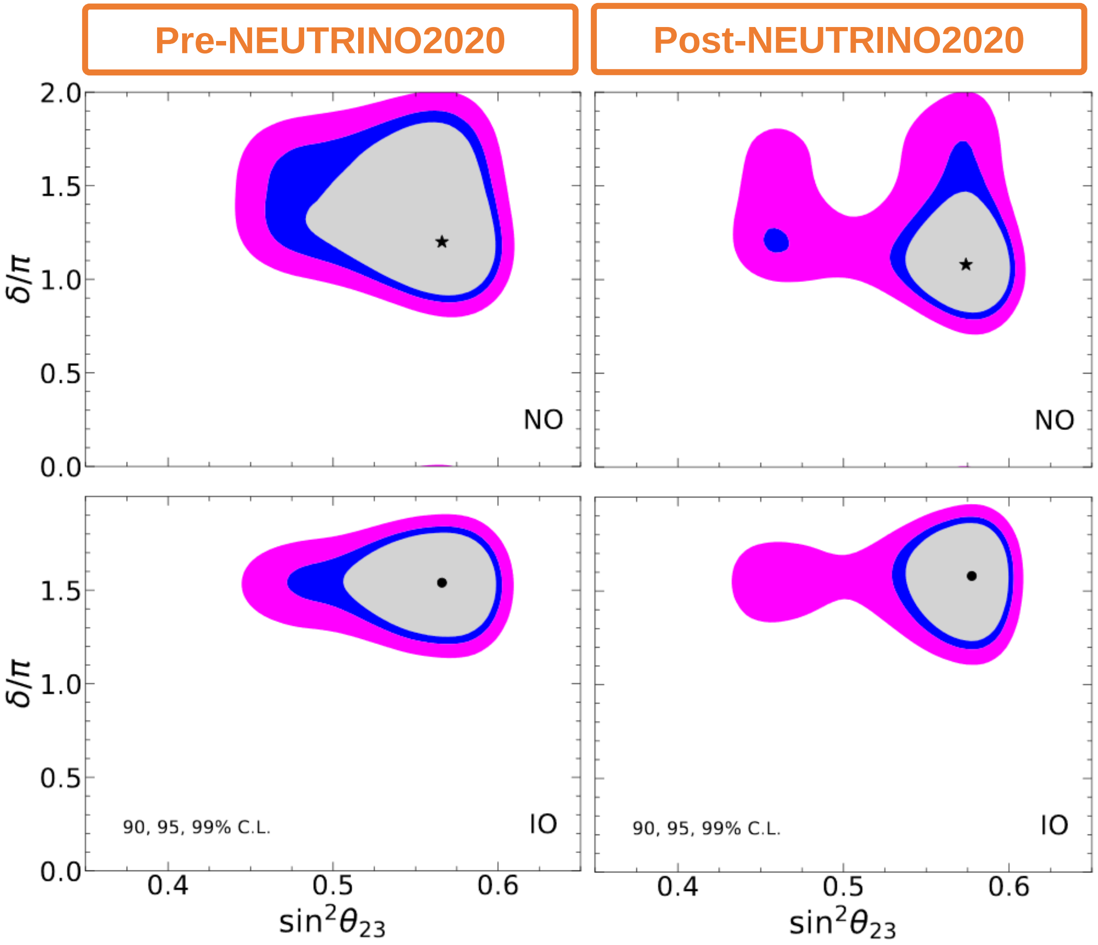
Scalar Masses:

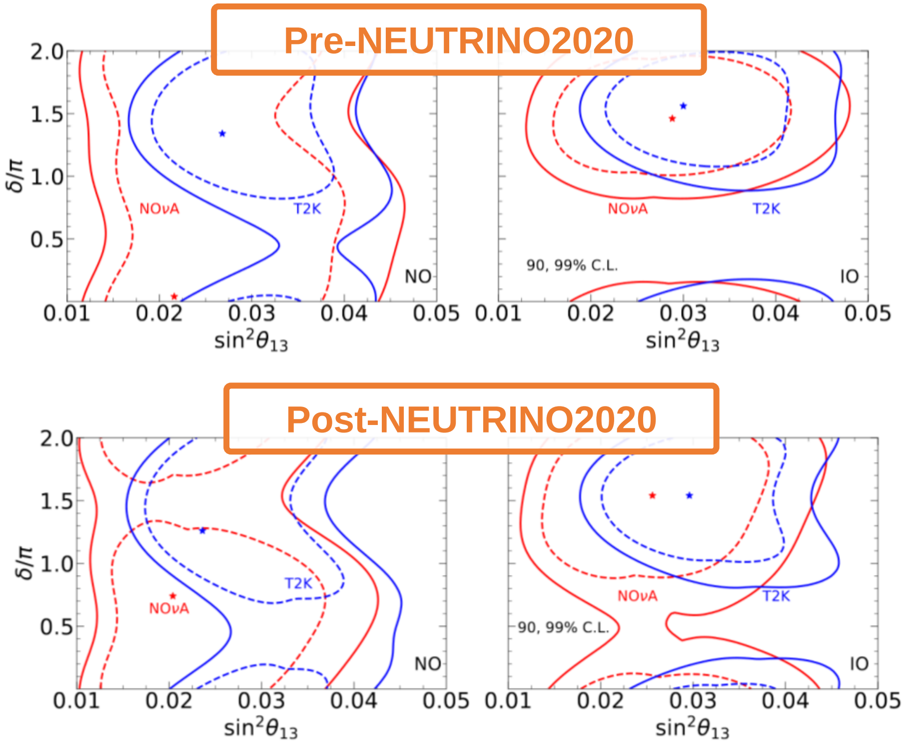
- $m_{\phi^+} = m_{\phi^-} = m_{\phi_{0I}} = 0$
- $m_{\eta^\pm}^2 = m_\eta^2 + \frac{\lambda_5}{2}v^2 + \frac{\lambda_8}{2}u^2$
- $\mathcal{M}_{\phi\sigma}^2 = \begin{pmatrix} v^2\lambda_1 & vu\lambda_6\cos\theta & vu\lambda_6\sin\theta \\ \cdot & u^2(\lambda^3 + \lambda_3')\cos^2\theta & u^2(\lambda_3 - 3\lambda_3')\cos\theta\sin\theta \\ \cdot & \cdot & u^2(\lambda^3 + \lambda_3')\sin^2\theta \end{pmatrix}$ → **$\phi - \sigma$ mixing** $(\phi_{0R}, \sigma_R, \sigma_I)$
- $\mathcal{M}_{\eta\chi}^2 = \begin{pmatrix} m_\eta^2 + \frac{\lambda_5+\lambda_5'}{2}v^2 + \frac{\lambda_8}{2}u^2 & v\left(\frac{\mu_2}{\sqrt{2}} + \frac{\lambda_{11}}{2}u\cos\theta\right) & 0 & -\frac{\lambda_{11}}{2}vu\sin\theta \\ \cdot & m_\chi^2 + \frac{\lambda_7}{2}v^2 + \frac{\lambda_{10}}{2}u^2 + \sqrt{2}u\lambda_{11}\cos\theta & \frac{\lambda_{11}}{2}vu\sin\theta & -\sqrt{2}\mu_1 u\sin\theta \\ \cdot & \cdot & m_\eta^2 + \frac{\lambda_5+\lambda_5'}{2}v^2 + \frac{\lambda_8}{2}u^2 & v\left(-\frac{\mu_2}{\sqrt{2}} + \frac{\lambda_{11}}{2}u\cos\theta\right) \\ \cdot & \cdot & \cdot & m_\chi^2 + \frac{\lambda_7}{2}v^2 + \frac{\lambda_{10}}{2}u^2 - \sqrt{2}u\lambda_{11}\cos\theta \end{pmatrix}$ → **$\eta - \chi$ mixing** $(\eta_{0R}, \chi_R, \eta_{0I}, \chi_I)$

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)